Reading the "Paradoxical Book of Bell:"
A Case Study in Theology and Science.

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Thesis submitted to the University of Nottingham
for the degree of Doctor of Philosophy

September 2018

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Abstract

John Bell's 1964 paper, "On the Einstein Podolsky Rosen Paradox," written to explore Einstein's contention that quantum theory is incomplete, has been cited extensively by theologians to support the contention that the quantum world evidences supraluminal connections. It is the centrepiece of Kirk Wegter-McNelly's *The Entangled God: Divine Relationality and Quantum Physics*. Bell's paper has been the focus of continuous research in theoretical and experimental physics since its publication in 1964 but while theologians overwhelmingly interpret Bell's paper to support the nonlocality of the quantum world, the meanings drawn by quantum physicists and philosophers of science from the results of the experiments done to test the mathematical expression that lies at the paper's heart are varied and contradictory. I explore the content, context and usages of Bell's paper, showing how complex the making of scientific meaning is. I outline the multifarious interpretations of Bell's paper by physicists, philosophers of science and theologians demonstrating that the various conclusions drawn from the experimental violations of his inequality, by those who believe them significant, whilst being cogent, rational and based upon scientific considerations, are not scientifically mandated but follow from the starting philosophical assumptions of physicists and philosophers of science and/or from the preconceptions they hold about the nature of science. I contend that interpretations of Bell's paper will be thus inevitably multiple and that this epistemological plurality is both inescapable and irreducible. I show that while the final answer to what the experimental violations mean remains elusive this does not hinder their technological fruitfulness. I suggest philosophical and theological resources by which the fact of this potent epistemological multiplicity, seen theologically as a sign of our situatedness and creaturehood, can

be explored rather than resisted. I note that Philip Clayton's "tracing of lines" and Bernard d'Espagnat's "fabricated ontology" offer conceptual possibilities in this regard.

Reading the "Paradoxical Book of Bell:"[1]
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Acknowledgements

I should like to thank Professor Richard Bell, my supervisor, for his unstinting encouragement, enthusiasm and support, which has been invaluable throughout my period of study. I am grateful for the love and support of my husband, Adrian and my children, Felicity, James, Michael and Ffion and the encouragement of colleagues particularly, Dawn, Paul and Caroline.

I dedicate this thesis to the parishioners of the parishes of Charlton Musgrove, Cucklington and Stoke Trister with Bayford in Somerset whose life I was privileged to share as I began this project and to my late parents, David and Mary Penberthy who made it possible.

[1] Marek Żukowski, "On the Paradoxical Book of Bell," *Studies in History and Philosophy of Modern Physics* 36 (2005):566.

Reading the "Paradoxical Book of Bell:"[2]
A Case Study in Theology and Science

Table of Contents

[2] Żukowski, "On the Paradoxical Book of Bell."

Reading the "Paradoxical Book of Bell:"[3] A Case Study in Theology and Science

Abbreviations

BA:
David Bohm, and Yakir Aharonov. "Discussion of Experimental Proof for the Paradox of Einstein, Rosen and Podolsky." *Physical Review* 108, no. 4, (1957):1070-76.

Bell 1964:
John S Bell. "On the Einstein-Podolsky-Rosen Paradox." *Physics* 1, (1964):195-200.

CHSH:
John F Clauser, Michael A. Horne, Abner Shimony and Richard Holt. "Proposed Experiment to Test Local Hidden-Variable Theories." *Physical Review Letters* 23, no.15 (1969):880-84.

EPR:
Albert Einstein, Boris Podolsky and Nathan Rosen. "Can Quantum-Mechanical Description of Physical Reality be Considered Complete?" *Physical Review* 47 (1935):777-780.

FC:
Stuart J Freedman and John F Clauser. "Experimental Test of Local Hidden-Variable Theories" *Physical Review Letters* 28, no. 14, (1972):938-41.

KC:
Carl A. Kocher and Eugene D. Commins. "Polarization Correlation of Photons Emitted in an Atomic Cascade" *Physical Review Letters* 18, no. 15 (1967):575-77.

KW-M:
Kirk Wegter-McNelly. *The Entangled God: Divine Relationality and Quantum Physics*, Routledge Studies in Religion, New York, London: Routledge, (2011).

WS:

C.S. Wu, and I. Shaknov. "The Angular Correlation of Scattered Annihilation Radiation," *Physical Review* 77, no. 1, (1950):136.

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[3] Żukowski, "On the Paradoxical Book of Bell."

"Theology is not to incorporate indifferently each new philosophical or scientific-theory. As these findings become part of the intellectual culture of the time, however, theologians must understand them and test their value in bringing out from Christian belief some of the possibilities which have not yet been realized.[1]

Pope John Paul II, 1st June 1988.

Introduction

Telling the whole story

When addressing the theologians and scientists gathered at the Papal Summer residence in Rome in September 1988, Pope John Paul II enjoined them to understand scientific theories before reflecting on them theologically. In this thesis, I follow Pope John Paul II's advice, although I seek to understand, not a scientific theory, but one particular scientific paper, "On the Einstein-Podolsky-Rosen Paradox"[2] [Bell 1964] and then ask what possibilities paying attention to this paper can draw out from Christian belief. This thesis is therefore a case study. At the heart of it is a short, six page paper written in 1964 by the CERN[3] physicist, John Bell, while on sabbatical, and published in a short-lived obscure journal, *Physics.* This paper has been called "the most profound discovery of science."[4] It is still generating new science: experiments are still being done to test the mathematical relationship that lies at its heart and new areas of research such as

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[1] Pope John Paul II. "To the Reverend George V. Coyne." *Physics, Philosophy and Theology: A Common Quest for Understanding.* (1988) m1-m14.:m10 [sic]

[2] Bell 1964

[3] Conseil Européen pour la recherche nucleaire (European Organisation for Nuclear Research.)

[4] Henry P Stapp. "Bell's Theorem and World Process." *Il Nuovo Cimento* 29B, no. 2 (1975):270-76.p.271

quantum cryptography and quantum teleportation flow from it. In this short paper Bell outlines one small mathematical inequality,[5] having first set it within its scientific context. In writing the paper, Bell stepped into the controversy over whether quantum mechanics is a complete theory, as Bohr held or whether incomplete as Einstein thought. While the majority of physicists in the twentieth century agreed with Bohr, there were those who, like Einstein, thought that a scientific theory should be able to give an account of everything that counted as reality for that theory without depending on the results of experiments conducted by scientists. Quantum theory, even in cosmology, is framed in terms of the probabilities of what will happen when human beings take experimental actions. This has been a moot point since the beginnings of quantum theory and there have been many attempts to provide instead a theory that describes an undergirding reality independent of human action. John Bell noticed that nonlocality, i.e. instantaneous causal connections between the theory's posited particles that exceed the speed of light, was a feature of one of these theories, David Bohm's[6] and derived a mathematical expression in order to discriminate between the results of

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[5] An inequality is like an equation but where an equation relates terms by an equals sign, =, an inequality relates terms by a 'greater than, " ≥, or "less than,"≤, sign.
[6] David Bohm. "A Suggested Interpretation of Quantum Theory in Terms of "Hidden Variables" I." *Physical Review* 85, no. 2 (1952):166-79.; David Bohm. "A Suggested Interpretation of Quantum Theory in Terms of "Hidden" Variables II." *Physical Review* 85, no. 2 (1952):180-93. Like Einstein, Louis de Broglie was troubled by quantum theory and, in 1923, developed the Pilot Wave theory, positing particles with definite locations, guided through space by waves. These papers of Bohm developed de Broglie's theory, featuring real particles guided by a wave but included between particles, instantaneous action at a distance that restored causality but did not respect the speed of light. As the de Broglie-Bohm theory adds features not included in quantum theory but retains exactly the same predictions, it is known as a "hidden variable" theory.

experiments that respected locality[7] and those that didn't. In this context, nonlocality means a change in one experimental outcome caused by an action taken at a physical distance beyond a time frame within which it is possible for light to travel. The importance of Bell's paper lies in the fact that it offered a way of making it possible to discriminate experimentally between Bohm's theory and standard quantum mechanics. This was previously thought impossible since Bohm's theory, while restoring causality to quantum theory, made exactly the same predictions as standard quantum theory. Thus Bell's paper held out the hope of closing the long running dispute between Einstein and Bohr as to the nature of quantum theory.

The case study on this paper has three stages. Firstly, following Pope John Paul II's stricture to understand, I shall explore Bell 1964, its context, its text, its scientific repercussions and how it is understood today within the scientific community. I will note the wide range of differing and contradictory interpretations of the implications of Bell 1964 and the inability of scientists and philosophers of science to come to any consensus. Secondly, I will survey those theologians who have already written about Bell's paper and reflect on their understanding of its implications. I will explore how well they have understood it before they have put it to use. Finally, I will suggest that the widely differing interpretations of Bell 1964 by scientists and philosophers of science is dictated by the differing philosophical and scientific assumptions they bring to the debate and that this plurality of interpretations is therefore irreducible, given that there is no means by which to adjudicate definitively between these differing philosophical stances. I will go on to suggest that this conclusion, drawn from the close study of one scientific paper and its aftermath exemplifies the implications of a specific area of Christian belief,

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[7] The crux of the debate amongst scientists and philosophers of science is whether or not this is the only way in which to interpret the implications of the experiments done to test Bell's inequality.

namely what it is to be created, what it is to be a creature for whom a God's eye view is not available.

My methodological commitment in this thesis will be to pay attention. Paying attention is one of Paul Janz's theological virtues.[8] By attentiveness Janz means a commitment to "allowing speakers and writers with whom one is engaging to *speak for themselves.*"[9] Paying attention to Bell 1964 so as to reflect on what this slice of human experience might hold for us theologically demands a proper and sustained engagement with the specifics of the human experience it represents. Paying attention to Bell 1964 means paying attention to why he wrote the paper, to the context out of which he wrote and the situation into which he wrote. Attentiveness to John Bell's work means starting with a close and situated reading of his 1964 paper[10] within its own context and then surveying what, in terms reminiscent[11] of Deleuze and Guattari's,[12] it "did" next and is still doing.[13]
I will show how paying attention to the whole range of the specific particularities of Bell's work in its historical context and its subsequent

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[8] Paul. D Janz. *God, the Mind's Desire. Reference, Reason and Christian Thinking*. Cambridge: CUP, (2004).p.3
[9] Janz, *God, the Mind's Desire. Reference, Reason and Christian Thinking*. p.48
[10] This has not been done before in a theological context. Previously, theologians, have concentrated on what they think Bell's work means rather than what Bell wrote. Even Wegter-McNelly fails to quote Bell's original inequality.
[11] "Reminiscent" because although they may have approved of my intention to ask what John Bell's paper gave rise to, they would abhor asking what it means. Gilles Deleuze, and Félix Guattari, *A Thousand Plateaus. Capitalism and Schizophrenia.* trans. Brian Massumi. Minneapolis: University of Minnesota Press, (1987).p.4
[12] Deleuze and Guattari's work on immanence and on science as one of the three great form of thought will inform my reflection in Chapter Eight on what it is to be created.
[13] "It is thus no longer appropriate to ask what a text means, what it says, the structure of it's interiority, how to interpret or decipher it. Instead, one must ask what it does," Elizabeth Grosz. "A Thousand Tiny Sexes: Feminism and Rhizomatics." *Topoi* 12 (1993):167-79.p.173 referring to Deleuze, and Guattari. *A Thousand Plateaus. Capitalism and Schizophrenia*.p.4

effects and interpretations enables a proper appreciation of what Bell achieved and of why it is still so potent today. It is this thorough appreciation of Bell 1964 in its own terms that provides a solid basis for respectful theological reflection and showcases a fruitful methodology for an attentive interdisciplinary interaction between theology and science.

Paying Attention: Interdisciplinary Methodology & Sources

In this case study in the field of theology and science, in which I shall be paying attention to "the paradoxical book of Bell,"[14] I will be "ventur[ing] into a borderland"[15] in the field of science and religion between theology, philosophy, physics and the history and philosophy of science. Just as Einstein said that any good scientist will be an "unscrupulous opportunist,"[16] with regard to her choice of epistemology, choosing whichever suits the task in hand, to pay attention well, I shall be an "unscrupulous opportunist" with regard to the differing methodologies needed to undertake this case study. While, it is important for theologians who step outside of the thought world of theology, and for any scholar who undertakes any interdisciplinary project, to pay proper attention to the assumptions, tools and methodologies of the discipline with which they are interacting, it is also important to use the tools from their own familiar tool box. I shall 'unscrupulously' borrow tools from various academic fields that will aid in my paying proper attention to "the paradoxical book of Bell."[17] In the first four chapters I will don the garments of a historian of science and, because the centre of this case study is a paper, I shall also utilise the tools of a biblical critic and a reception

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[14] Żukowski. "On the Paradoxical Book of Bell."
[15] Michela Massimi. *Pauli's Exclusion Principle: The Origin and Validation of a Scientific Principle*. Cambridge: CUP, (2005).p.6
[16] Albert Einstein. "Reply to Criticisms." in *Albert Einstein Philosopher-Scientist*. ed. Paul Arthur Schilpp. New York: MJF Books, (1970).p.684
[17] Żukowski. "On the Paradoxical Book of Bell."

historian.[18] As a biblical critic, I shall write a commentary on Bell 1964 and on a selection of other papers as necessary. I shall explore Bell's paper, outline its context, both conceptual and historical, and explore what Bell was intending by it. To this, I shall add the tools of a reception historian. Once published, a text has a life of its own. Reception history seeks to chart how the text has been received, understood and put to use beyond its original author and audience. Reception history stems from the work of the philosopher, Hans-Georg Gadamer[19] who, foreswearing the attempt to find *the* one truth of a text's meaning, opened up the possibility of appreciating the significance of how a text is perceived at different times, in different contexts and from different perspectives. In chapters one and two, I shall explore Bell 1964 and the 1935 paper by Albert Einstein, Boris Podolsky and Nathan Rosen with which Bell engaged, EPR.[20] The narrative continues in chapter three and four as I sketch out how Bell's mathematical inequality was adapted and how it stimulated both experiments and further areas of theory and research. In the fifth, sixth and seventh chapters, I shall detail Bell 1964's reception history in detail. While the first four chapters will be diachronic, following a narrative thread across time, in chapter five, I turn to a synchronic survey of paying attention to how Bell's work is understood today by theoretical and experimental physicists and by philosophers of science then turning in chapters six and seven to a diachronic survey of Bell 1964's reception amongst theologians and theistic philosophers.

In the first five chapters, I am providing an analysis and survey of Bell 1964, its experimental violations and its interpretation by physicists,

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[18] For this insight, I am grateful to Dr Mark Harris.
[19] Jonathan Roberts. "Introduction." to *The Oxford Handbook of the Reception History of the Bible*. ed. Michael Lieb, Emma Mason, and Christopher Rowland. Oxford: Oxford University Press, (2011).p.1
[20] Albert Einstein, Boris Podolsky and Nathan Rosen. "Can Quantum-Mechanical Description of Physical Reality be Considered Complete?" *Physical Review* 47 (1935):777-780.

philosophers of science and mathematicians culled from a wide range of sources. Understanding in this depth is vital for any proper demonstration of why, how and in what way Bell 1964 is significant for theology. It ensures that I pay attention properly to Bell's work before I reflect upon those who have engaged with it theologically so as to be able to reflect on their work cogently. The first five chapters have the nature of what in scientific terms would be a review article. It is an overview of the origin and text of Bell 1964 with an account of what experimental and conceptual fruit it engendered and an overview of how scientists, mathematicians and philosophers of science understand Bell 1964 today. In doing interdisciplinary work, there are cross-disciplinary achievements to be won however and in this thesis I have gained two. Wearing the hat of a historian of science, I have discovered the very first citation of Bell 1964, in a book by the French philosopher, Bernard d'Espagnat,[21] and found that L.R. Kasday was the first person to note that the problem with Bell's ideal experiment is the failure of the joint probability assumption.[22]

However, there is a caveat, there is a further area worthy of attention which I note here but will not address despite it being an area vital for a study that pays complete attention to Bell 1964. Scientific papers, like Bell 1964, are not neutral vehicles for meaning, they cannot be divorced from the socio-economic, political and cultural backgrounds, frameworks and commitments from which the scientists who write them, the institutions that pay the scientists and resource the provision of the technology with which experiments are conducted come. They cannot be divorced from the socio-economic, political and cultural backgrounds, frameworks and commitments of those who sit

[21] Bernard d'Espagnat. *Conceptions De La Physique Contemporaine* Paris: Hermann, (1965).p.149. It was thought that the first citations of Bell 1964 were in 1968.

[22] L. R. Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons," in *Foundations of Quantum Mechanics. (Proceedings of the International School of Physics "Enrico Fermi, Course IL)*. ed. Bernard d'Espagnat. London: Academic Press, (1971).p.200

on the boards of the journals who print them or of those who act as referees for the boards of the journals who print them, or from the socio-economic, political and cultural backgrounds, frameworks and commitments of the librarians who choose which journals to stock. While I shall not attend to the socio-economic, political and cultural backgrounds, frameworks and commitments of Bell and those who in whatever way impact on his work, like a sailor who only sails one route, I am aware of the wider ocean and a fuller case study than that which I am attempting would need to attend to these wider contexts in order to pay proper attention to Bell 1964 and understand it as fully as Pope John Paul II asked. The work of Bruno Latour,[23] Peter Galison[24] and Lisa Stenmark[25] would be important in this regard.

This overview of Bell 1964, the consideration of what it led to both in terms of practical effects and theoretical understanding and its reception history amongst philosophers of science and scientists, both theoretical and experimental, is followed in chapters six and seven by a diachronic survey of its reception history amongst theologians and theistic philosophers starting with its first mentions in a theological context in 1977.[26] I consider how theologians who have paid attention to Bell 1964 understand its meaning. This survey of how theologians to date have grappled with Bell's work is the first such overview.

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[23] Bruno Latour and S Woolgar. *Laboratory Life: The Social Construction of Scientific Facts*. Beverley Hills, CA: Sage, (1979).
[24] Peter Galison, *How Experiments End*. Chicago: University of Chicago Press (1987).
[25] Lisa L. Stenmark. "Feminist Philosophies of Science: Towards a Prophetic Epistemology." in *The Blackwell Companion to Science and Christianity.* Malden, MA & Oxford: Wiley Blackwell, (2012).; Lisa L. Stenmark. *Religion, Science and Democracy. A Disputational Friendship* Lanham, Boulder, New York & Plymouth, UK: Lexington Books, (2013).
[26] Patrick A. Heelan S.J."Quantum Relativity and the Cosmic Observer" in *Cosmology, History and Theology*. ed. Wolfgang Yourgrau, and Allen D. Breck, New York: Plenum Press, (1977).p.29 & Charles Hartshorne, "The Neglect of Relative Predicates in Modern Philosophy," *American Philosophical Quarterly* 14, no. 4 (1977):309-18.p.317

In chapter eight I begin to "test the value" of how paying attention to Bell 1964 and its reception history can enrich our understanding of a particular aspect of the Christian faith. I will suggest that the irreducible plurality of interpretations of what Bell's work means exemplifies the inescapable situatedness of our thinking and reflection, and can be made sense of theologically by exploring the nature of our creaturehood.[27] I will give an overview of what can be learned from this case study and suggest theological resources that would enable a richer engagement with what has been gleaned.

As I navigate this journey, borrowing tools from a variety of theological disciplines, it will be important to note what of sort of literary sources I shall use. For the first part of the case study, when I will be laying out an account of Bell 1964, its context and to what uses it was subsequently put, I will use scientific papers, books and conference proceedings as the primary sources. I shall be using also papers and books written by philosophers of science. In some cases, when they have been part of the thinking of those whom I am studying, these will be primary sources, whereas those that I consult to aid my own reflection will count as secondary sources. Other secondary sources will be the papers and books I consult written by historians of science. Care will need to be taken when consulting history of science books or papers that have been written by scientists. If they were participants in the events related, some of what they say will count as a primary source. The difficulty comes when scientists write as historians of science or as theologians because, unlike professional historians of science, they are not always careful about the historical appropriateness of the terms they use, denoting something by a term by which it is later known and thereby anachronistically importing later assumptions or ascriptions back into the telling of an earlier story. Theodore Arabatzis' history of the electron is an illuminating

[27] This is not to imply that the "God's eye view" necessarily denied to us is singular however.

and eye-opening study of how scientific understanding about the nature of the referent of a scientific term can change over time.[28] For the historical survey of theological references to Bell 1964 since the first references in 1977 to the present day, the theologians' writings themselves will be the primary sources. This will be the first survey of theological writing about Bell 1964. This thesis is a case study in the area of theology and science but the majority of what is written within it concerns the work of physicists, both theoretical and experimental and of philosophers of science. It is only after a full survey of Bell 1964 in its context and after an account of the work both theoretical and experimental to which it has led that I turn to the work of theologians. As Pope John Paul II enjoins, understanding must precede any theological application and only with a degree of understanding of Bell's work can the work of the theologians to which I shall refer be fairly assessed.

The Entangled God: Divine Relationality and Quantum Physics[29]

This most significant and sustained theological reflections on Bell 1964 and one to which I am indebted is *The Entangled God*[30] by Kirk Wegter-McNelly [KW-M], the most thorough theological exploration of Bell 1964 to date. It is a detailed, interesting and important book on the subject of divine relationality in which Wegter-McNelly has brought insights from modern science to bear on this vibrant topic. The scientific angle he chose to explore was entanglement, a term

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[28] Theodore Arabatzis. *Representing Electrons: A Biographical Approach to Theoretical Entities.* Chicago and London: University of Chicago Press. (2006).
[29] Kirk Wegter-McNelly, *The Entangled God: Divine Relationality and Quantum Physics*, Routledge Studies in Religion, New York, London: Routledge, (2011).
[30] KW-M

coined by Erwin Schrödinger in 1935.[31] However, it is John Bell, the author of Bell 1964, the subject of this thesis and not Schrödinger, who is the major figure in KW-M. Wegter-McNelly devoted two chapters of this book to Bell's work and even derived his own mathematical inequality on the basis of Bell's. As we explore Wegter-McNelly's treatment of Bell 1964 in Chapter Seven we shall see that, as careful, detailed, nuanced and interesting as Wegter-McNelly's treatment is, Bell's work has been mined for its theological potential before it has been fully explored in its own right. Wegter-McNelly's account of Bell 1964 serves his own wider theological purpose rather than exploring Bell's paper and its effects in its own terms. KW-M is about divine relationality and Bell's work is used to explore and illuminate this theme through the lens of entanglement. This is not to say that what Wegter-McNelly writes about Bell 1964 is inaccurate or untrue. Many physicists, mathematicians and philosophers of science agree with Wegter-McNelly's understanding of it but importantly, there are those who don't. Wegter-McNelly does not ignore those who would take issue with the way he interprets Bell's work but he fails to do them justice.[32] Wegter-McNelly is not telling a false story, but he isn't telling the whole story. What I have first learned from Wegter-McNelly is the importance of telling the whole story.

What Pope John Paul II asked for was responsible, serious interdisciplinary work. Wegter-McNelly stresses the importance of this. He positions his book as an interdisciplinary experience. It is a theological book but one which models "an interdisciplinary way of doing metaphorical theology, one that takes the time to understand but also to explain the disciplines it engages."[33] Wegter-McNelly stresses that "an interdisciplinary metaphorical theology ….. must be

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[31] Erwin Schrödinger. "Discussion of Probability Relations Between Separated Systems." *Mathematical Proceedings of the Cambridge Philosophical Society* 31, no. 4 (1935):555-63.p.555, see KW-M p.20
[32] E.g., KW-M pp.105-6
[33] KW-M. p.8

an eminently responsible theology ……….[with] a keen sense of responsibility to engage and represent those disciplines as faithfully as possible within its own realm of discourse."[34] Therefore, Wegter-McNelly, in a book of constructive metaphorical theology, gives a detailed, sustained and careful attention to a particular area of science. After KW-M there is no longer any need for a theologian working in the area of theology and science to justify or apologize for paying detailed attention to a specific area of scientific discourse because Wegter-McNelly has set a new benchmark. This is interdisciplinary work at its most serious and lays a path I follow.

However, while Wegter-McNelly understands correctly what is at stake in interdisciplinary theology, it is at this task that I think his book, as fine as it is, ultimately fails, not because he misunderstands or misrepresents those scientists whose work on Bell he chooses to explore but because the slice of the vast interpretative field with which he engages is so small. Wegter-McNelly faithfully represents those thinkers with whom he deals, but those with whom he deals are limited to those with whom he agreed. While what Wegter-McNelly does say about Bell 1964 is accurate, he is not, despite his own strictures, representing it "as faithfully as possible" because he does not encompass the whole breadth of the debate. Wegter-McNelly indicates the debate but does not explore it. If Bell 1964 is to be represented "as faithfully as possible," there is a much larger story to be told. This thesis will tell that larger story. I will concentrate on Bell 1964, what it said and what it did, the context out of which it sprang, the experimental work it inspired and still inspires. I will survey the vast array of meanings that scientists, both experimental and theoretical, and philosophers of science have imputed to it. As Wegter-McNelly pointed out interdisciplinary work, if carried out faithfully, has to pay more than lip service to the discipline of the other or others with which it engages. Thus it is vital to realise that reflecting on

34 KW-M p.9

scientific findings from a theological perspective is not simply to grapple with some disembodied "meaning." That would be to mispresent science, where meaning is always wrapped in the specifics of its making. I will pay attention to those theologians and theistic philosophers who have written on Bell 1964 and outline the implications theologians have drawn from how it has been interpreted scientifically, mathematically and philosophically and I will indicate where Wegter-McNelly's understanding of Bell lies within the spectrum of the whole debate.

In comparing the ways in which physicists, whether experimental or theoretical, philosophers of science and mathematicians interpret Bell 1964 with the way in which theologians have understood its meaning, one thing stands out clearly. While theologians largely understand the experimental violations of Bell's inequalities to indicate something about the world, namely its nonlocality, i.e. that at the quantum level there are certain connections, that while they cannot be used to send signals, operate faster than the speed of light, amongst scientists and philosophers of science there is little unanimity. Tracing a line from any of these understandings and interpretations, in Philip Clayton's terms,[35] as Wegter-McNelly has done so expertly, is both necessary and vital. Indeed, only in this way will our understanding of the fruits for theology of Bell 1964 grow. However, alongside any productive and interesting tracing of lines, I shall counsel a standing back and a surveying the whole with a humble recognition that finding *the* correct answer, as opposed to fruitful answers, is not merely a Sisyphean but an impossible task. Tracing lines is the inescapable route of testing out the worth for theology of findings in this field of study, but deciding between these lines is not. I will suggest that the first datum for

[35] Philip Clayton. "Tracing the Lines: Constraint and Freedom in the Movement From Quantum Physics to Theology." in *Quantum Mechanics: Scientific Perspectives on Divine Action (Volume 5)*. ed. Robert J Russell, Philip Clayton, Kirk Wegter-McNelly, and John Polkinghorne. Vatican City: Vatican Observatory Publications, (2001).

theological reflection is that there is no rational scientific means by which one choice from amongst the vast plurality of interpretations of Bell's work is scientifically mandated. Scientists and philosophers working in the field have no rational scientific means to decide incontravertably and once and for all between these varied and contradictory interpretations. Deciding how to interpret Bell's work remains a choice.

As we shall see, there are those who think that Bell's mathematical assumptions or assumptions about probability were wrong, others who think that the way the experimentalists handle statistics invalidate the results they claim and still others whose interpretation of quantum theory preclude them giving any ultimate meaning to the results of specific experiments and therefore conclude that the experimental violations, if such they are, are meaningless. However, the rest of the field, who think that Bell-type inequalities have been violated and are meaningful, are completely divided as to what that meaning is. This I conclude is highly theologically significant: it is an example of what it means for us to be creatures for whom a God's eye view is not accessible.

The question must then be asked, what theological resources have we to deal with this irreducible plurality of meaning and interpretation? What resources do we have to conceptualise a scientific field in which technological and experimental research continues fruitfully from entirely opposed conceptual bases. I will suggest the importance of taking cognizance of this "embarrassing"[36] and, as I contend irreducible multiplicity of views, and instead of trying to evade it, find conceptual resources that enable us to explore this rational irreducible multiplicity of explanation hopefully and not grudgingly. After all, as

[36] Sean Carroll, "The Most Embarassing Graph in Modern Physics," http://www.preposterousuniverse.com/blog/2013/01/17/the-most-embarrassing-graph-in-modern-physics/ (accessed 23rd November 2013.)

Shapin and Shaffer[37] remind us, it was when metaphysical certainty proved elusive that the scientific method as we know it was born. Admitting our limitations can be productive as well as honest.

As a conclusion to this case study, I will therefore suggest three trajectories that might enable us to bring out of the irreducible plurality of interpretations of Bell's work some possibilities from the Christian faith we have not yet fully faced or explored. I will suggest that there is more work to be done exploring rather than evading the reality of what it means to be a creature. There are three possible avenues that offer resources for developing our understanding of creaturehood. One avenue is the unlikely coupling of Deleuze and Deleuze and Guattari from the twentieth century and St Gregory of Nyssa from the fourth. Deleuze and Guattari demonstrated what thinking looks like when the possibility of a God's eye view or vantage point is no longer on offer. Their writings are virtuoso performances of thinking in the midst with no guarantees: the irreducible plurality of interpretations of Bell's work suggests they have something to offer. Deleuze and Deleuze and Guattari help us to accept, rejoice in and explore our situatedness. Their account of what science is offers a template of what we shall see happening in the wake of Bell 1964. As an unlikely partner to these two twentieth century thinkers, I suggest St Gregory of Nyssa, who from an entirely different world and from a perspective entirely antithetical to theirs arrives at the same point. We can never, even in our resurrected state, transcend the limitations of our humanity, which is always to be this one and not that one, to see from here and not from there. We have no possibility of occupying the transcendent, the God's eye view. Deleuze and Guattari talk of thinking from the plane of immanence that is immanent only to itself. St Gregory talks of the διαστημα/diastema that forever binds us within

[37] Shapin S, and Schaffer S. *Leviathan and the Air Pump: Hobbes, Boyle and the Experimental Life.* Princeton: Princeton University Press, (1985).

our creaturely limitedness. Neither St Gregory nor Deleuze and Guattari find this irksome but redolent with opportunity. The opportunities of immanence or creaturely limitedness that this coupling suggests is borne out by the richness that has sprung and continues to spring from one six page paper written by John Bell. In the conclusion to this case study, I shall suggest tentatively, how, having begun to understand Bell 1964 in a way Pope John Paul might have approved, Deleuze and Guattari and St Gregory of Nyssa can enable us to see it as an example of the possibilities of our creaturehood. The richness of applications derived from Bell 1964 exists in reality despite the lack of one true story we are able to tell ourselves about it. The limitation on our knowledge imposed by our creatureliness does not prevent us from acting and from bringing forth something new and thus expressing the reality of a creaturehood made in the image of God the creator.

A final avenue by which, having understood Bell, we might bring out from our Christian faith some unforeseen possibilities of the limitedness that is that the heart of what it means to be created[38] lies in the work of James K. Smith who draws on a variety of twentieth century philosophers to explore what being created means for our knowledge and understanding of the world. While Smith does not draw on Deleuze or Deleuze and Guattari nor mention St Gregory, Smith's work on the hubris of espousing philosophical realism and the correspondence theory of truth coheres well with Deleuze and Guattari's immanence and St Gregory's διαστημα of which the continuing fruitfulness of Bell 1964 despite our inability to pin it's meaning down can be said to be an expression. Deleuze and Deleuze and Guattari's celebration of human situatedness and St Gregory and James K. Smith's explorations of the possibilities of creaturehood offer

[38] James K.A. Smith, *Who's Afraid of Relativism: Community, Contingency and Creaturehood* Grand Rapids, Michigan: Baker Academic, (2014).

ways to explore what we see happening in the continuing demonstration of the rich possibilities for human action offered by Bell 1964 regardless of our inability to decide unequivocally what it means. Eschewing a God's eye viewing and being content with tracing lines offers a way of drawing out the theological potential of Bell 1964. As one traced line among many, Wegter-McNelly's *The Entangled God* is an educative and insightful piece of work. If taken as the final word on what Bell 1964 means, it is misleading. In this thesis, I shall pay attention to the "paradoxical book of Bell" and suggest ways in which this area of work exemplifies what it is to be created.

Chapter One: EPR - The Context of Bell 1964

This thesis is about a text, Bell 1964, by the late John Stewart Bell and how it has been interpreted by theologians of science and theologians. To pay attention to this text I shall borrow the tools and practices of other theological disciplines. I shall first write a commentary on Bell 1964. A good commentary attends to the specific of the text and places it within its historical context. It explores when and why a text was written and to whom. It outlines the debates into which the author stepped, the world-view and assumptions of the writer and of those to whom the paper is, albeit sometimes notionally, addressed. A good commentary sheds light on the specifics of what is at stake for the author, what he was choosing to defend, how he approaches the task and what had spurred him into writing. What was the author, or authors defending, what was he hoping to achieve and why?

1 "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" [EPR]

Bell sets out his paper's context in its title and first 13 lines. To understand it, we must first consider the seminal paper that preceded it and provided its context. As the title demonstrates, by writing "On the Einstein Podolsky Rosen Paradox,"[1] Bell was stepping into the discussions between Bohr and Einstein that had provoked Albert Einstein, with two colleagues Boris Podolsky and Nathen Rosen to publish EPR. Bell wrote his paper in response to EPR and to continue the discussions of which it was a part. Understanding Bell 1964, means understanding the context and text of EPR. This entails beginning with the debates leading to the "quantum-mechanical description of physical reality"[2] which EPR questioned.

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[1] Bell 1964
[2] EPR p.777

1.2.1 The Context of EPR: The Quantum Revolution

Quantum theory began in 1900, when Max Planck, while working on the problem of blackbody radiation,[3] proposed that energy was not emitted continuously but in discrete units. Einstein applied Planck's constant to light in 1905,[4] developing the idea of what became known as photons. In 1913, Niels Bohr applied Planck's idea to Rutherford's model of the hydrogen atom giving a coherent account of the hydrogen atom's emitted line spectra.[5] In 1917, Einstein applied the idea of the quantum to the admission, absorption and momenum of energy within an ideal gas[6] and, after reading Satyendra Bosé's paper,[7] developed with Bosé, the Bosé-Einstein statistics. Einstein was at the forefront of developments in theoretical physics. His problems with quantum theory began with Heisenberg's revolutionary 1925 paper.[8] Heisenberg made a breakthrough by working with observable quantities, namely the radiation emitted from an atom, rather than trying to conceive of what was going on inside. Heisenberg sent a copy

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[3] A concept introduced by Gustav Kirchoff in 1860 to explore a phenomenon unexplained by the then current theory: the wave length of emitted electromagnetic radiation depended only on the temperature of the body and not its material. Kirchoff postulated an ideal body that emitted all of its electromagnetic radiation as a tool to produce a theory that accounted for experimental results.
[4] Albert Einstein. "Über Einen Die Erzeugung Und Verwandlung Des Lichtes Betreffenden Heuristichen Gesichtspunkt" *Annalen de Physik* 17 (1905):132-48.
[5] The electrons within an atom can go down energy levels by emitting a photon of a particular energy or wavelength. When many electrons emit the same wavelengths of photons, a spike in the spectrum at this wavelength results, hence the banding pattern seen when the emitted light is diffracted.
[6] Albert Einstein. "Zur Quantentheorie Der Strahlung." *Physikalische Zeitschrift* 18 (1917):121-28.
[7] Satyendranath Bose. "Planck's Law and Light Quantum Hypothesis." *Zeitschrift für Physik* 26 (1924):178.
[8] Werner Heisenberg. "Über Quantentheoretishe Umdeutung Kinematisher Und Mechanischer Beziehungen." *Zeitschrift für Physik* 33 (1925):879-93.

of the paper to Max Born on July 11th who made the connection between Heisenberg's work and the matrix methodology of mathematics. On the 28th July, the day before his paper was received by Zeitschrift für Physik, Heisenberg was in Cambridge lecturing and mentioned the article in his lecture. R H Fowler obtained the proof sheets from him and sent them to Dirac in September.[9] In the same month, Born and Jordan's paper, which "developed [Heisenberg's approach] into a systematic theory of quantum mechanics,"[10] matrix mechanics, was published. Dirac published a paper[11] in which he "re-discovered independently" the main ideas of Born and Jordan's,[12] an approach he generalised in a paper the following year.[13] Dirac's formulation became known as Transformation theory and was mathematically equivalent to Heisenberg's. Meanwhile Heisenberg had collaborated with Born and Jordan and produced their "three man paper"[14] developing matrix mechanics and demonstrating its usefulness in specific problems.[15] Crucially, Pauli[16] had shown that the

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[9]Jagdish Mehra and Helmut Rechenberg. *The Historical Development of Quantum Theory Volume 2: The Discovery of Quantum Mechanics 1925.* New York: Springer-Verlag. (1982).p.322; Graham Farmelo, *The Strangest Man. The Hidden Life of Paul Dirac Quantum Genius.* London: Faber and Faber (2009)p.82

[10] Max Born, and Pascual Jordan "On Quantum Mechanics." in *Sources of Quantum Mechanics*. ed. B L van der Waerden. New York: Dover, (1968)p.277 .; German original: Max Born, and Pascual Jordan, "Zur Quantenmechanik," *Zeitschrift für Physik* 34 (1925)p.858.

[11] P.A.M. Dirac."The Fundamental Equations of Quantum Mechanics." *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 109 (1925)pp.642-53.

[12] B L van der Waerden, "Introduction," *Sources of Quantum Mechanics* New York: Dover, (1967).p.41

[13] P.A.M. Dirac. "Quantum Mechanics and a Preliminary Investigation of the Hydrogen Atom," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science* 110 (1926):561-79.

[14] Max Born, Werner Heisenberg and Pascual Jordan. "Zur Quantenmechanik II," *Zeitschrift für Physik* 35 (1925)p.557.

[15] E.g. the Zeeman effect where spectral lines split into components in the presence of a magnetic field. Kent A. Peacock. *The Quantum Revolution: A Historical Perspective* Greenwood. (2008).p.52

[16] Wolfgang Pauli. "Über Das Wasserstoffspektrum Vom Standpunkt Der Neuen Quantenmechanik." *Zeitschrift für Physik* 36 (1926)p.336.

hydrogen spectrum could be derived from the new theory.[17] However, as early as September 1925, Einstein had written to Ehrenfest disparagingly about Heisenberg's paper "In Göttingen they believe in it (I don't)."[18] In the spring of 1926, Heisenberg was invited to explain his new theory to the Colloquium at the University of Berlin. Einstein was present and invited Heisenberg home after the meeting. As Heisenberg remembered the conversation afterwards, Einstein questioned him about retaining the concept of an electron within the atom while dispensing with the concept of their orbits. Heisenberg explained his strategy of sticking to only what is directly observable and recounts what he remembers of Einstein's response. " 'But you don't seriously believe,' Einstein protested, 'that none but observable magnitudes must go into a physical theory?'

'Isn't that precisely what you have done with relativity?' I asked in some surprise. …………..

'Possibly I did use this kind of reasoning,' Einstein admitted, 'but it is nonsense all the same. ………it might be heuristically useful to keep in mind what one has actually observed. But on principle, it is quite wrong to try founding a theory on observable magnitudes alone. In reality the very opposite happens. It is the theory which decides what we can observe. You must appreciate that observation is a very complicated process. The phenomenon under observation produces certain events in our measuring apparatus. As a result, further processes take place in the apparatus, which eventually and by complicated paths produce sense impressions and help us to fix the effects in our consciousness - we must be able to tell how nature functions, must know the natural laws at least in practical terms, before we can claim to have observed anything at all. Only theory, ….. knowledge of natural laws enables us to deduce the underlying

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[17] van der Waerden, "Introduction."p.57

[18] Abraham Pais, "Max Born and the Statistical Interpretation of Quantum Mechanics," *Address to the Annual Meeting of the Optical Society of America, Tucson, Arizona, October 21, 1982 on the occasion of the centenary of Born's birth* (1982):1-22.p.6

phenomena from our sense impressions. When we claim that we can observe something new, we ought really to be saying that, although we are about to formulate new natural laws that do not agree with the old ones, we nevertheless assume that the existing laws - covering the whole path from the phenomenon to our consciousness function in such a way we can rely on them and hence speak of observations.

'....And in your theory, you quite obviously assume that the whole mechanism of light transmission from the vibrating atom to the spectroscope or to the eye works just as one has always supposed it does, that is essentially according to Maxwell's laws. If that were no longer the case, you could not possibly observe any of the magnitudes you call observable. Your claim that you are introducing none but observable magnitudes is therefore an assumption about a property of the theory you are trying to formulate. You are in fact, assuming that your theory does not clash with the old description of radiation phenomena in the essential points. You may be right of course, but you cannot be certain.'"[19]

Einstein was never reconciled to quantum mechanics. In 1926, Schrödinger developed wave mechanics[20] and received approving responses[21] from Planck and Einstein, who wrote back, "I am convinced that the Heisenberg-Born method is misleading."[22] However, the strangeness of Heisenberg's "quantum-theoretical" reinterpretation was not tamed by Schrödinger's wave mechanics since the mathematics of the two theories proved equivalent. [23] The

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[19] Werner Heisenberg. *Physics and Beyond Encounters and Conversations*. New York: Harper and Row, (1972).pp.63-4
[20] Felix Bloch. "Heisenberg and the Early Days of Quantum Mechanics," *Physics Today* 29, no. 12 (1976):23-27.pp.23-4
[21] Manjit Kumar. *Quantum: Einstein, Bohr and the Great Debate About the Nature of Reality*. Cambridge, UK: Icon Books, (2008).p.209
[22] Kumar, *Quantum: Einstein, Bohr and the Great Debate About the Nature of Reality*.p.209
[23] Discovered by Cornelius Lanczos: Cornel Lanczos. "Über Eine Feldmäßige Darstellung Der Neuen Quantenmechanik," *Zeitschrift für Physik* 35 (1926)p.112. and independently by Schrödinger Erwin

strangeness intensified with the publications of Born's papers[24] in July 1926, establishing beyond doubt that Schrödinger's wave equation did not refer to a physical wave. Rather, the wave equation gave the probability of a particle being found were an experiment to be carried out. Born acknowledged the necessity of giving up determinism. "One obtains the answer to the question, not 'what is the state after the collision' but 'how probable is a given effect of the collision.' Here the whole problem of determinism arises. From the point of view of our quantum mechanics there exists no quantity which in an individual case causally determines the effect of a collision."[25] It was the price for the success of new theory, with its three distinct but equivalent representations, matrix mechanics, wave mechanics and what would become Dirac's transformation theory. Einstein was less sanguine. As Einstein wrote to Born in December 1926, "Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing."[26] By January 1927 he is reported as saying to Ehrenfest, "My heart does not warm towards Schrödingerei — it is uncausal and altogether too primitive."[27] Despite being one of the pioneers of

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Schrödinger, "Über Das Verhältnis Der Heisenberg-Born-Jordanschen Quantenmechanik Zuder Meinen," *Annalen de Physik* 79, no. 4 (1926):734-56. See Mendel Sachs. "Cornelious Lanczos —Discoveries in the Quantum and General Relativity Theories," *Annales Fondation L. De Broglie* 27, no. 01 (2002)pp.85-91. https://arxiv.org/pdf/quant-ph/0206054.pdf. p.3

[24] Max Born. "Zur Quantenmechanik Der Stossvorgänge." *Zeitschrift für Physik* 37 (1926):863-67.; Max Born. "Zur Quantenmechanik Der Strossvorgänge." *Zeitschrift für Physik* 38 (1926):803-27.

[25] Kumar. *Quantum: Einstein, Bohr and the Great Debate About the Nature of Reality*.p.220 citing A. Pais. *Inward Bound: Of Matter and Forces in the Physical World.* Oxford: Clarendon Press, (1986).p.257. Pais quotes from Born. "Zur Quantenmechanik Der Stossvorgänge." p.866

[26] Kumar, *Quantum: Einstein, Bohr and the Great Debate About the Nature of Reality*.p.224 quoting from Max Born. *The Born-Einstein Letters 1916-55, Friendship, Politics and Physics in Uncertain Times.* Basingstoke: Macmillan, (2005).p.88

[27] "Mein Herz wird nicht warm bei der Schrödingerei — sie ist unkausal und überhaupt zu primitiv." See Arthur Fine. *The Shaky*

quantum theory, Einstein's antipathy to what became the Copenhagen interpretation[28] continued throughout his life.[29] This debate between Einstein and those who favoured the Copenhagen interpretation is the context of Bell 1964. EPR grew directly from these debates in the late 1920s and early 1930s. Bell's paper, named after EPR, was written as the next stage in that same debate.

1.2.2 The Context of EPR: Heated Discussions

Early in 1927 Einstein, still hoping to salvage a realist interpretation of Schrödinger's wave function, put together a realist theory of a wave fuction for a single system. However, when Bothe pointed out an inevitable consequence of the theory with which Einstein was unhappy, Einstein withdrew the paper and it was never published. Failing to develop an interpretation of quantum theory for single systems, Einstein began to espouse the ensemble interpretation,[30] a view he put forward at a discussion session in the 1927 Solvay conference.[31]

Game: Einstein, Realism and the Quantum Theory (2nd Edition). Chicago: Universty of Chicago Press, (1986).p.27

[28] Heisenberg coined the term "Copenhagen Interpretation" in 1955 once Bohm developed a different way of interpreting the formalism. See Don Howard. "Who Invented the Copenhagen Interpretation: A Study in Mythology." *Philosophy of Science* 71, no. 5 (2004):669-82. p.675.

[29] see Don Howard. "Re-Visiting the Einstein-Bohr Dialogue," *Iyyun* 56 (2007)pp.57-90. & Dipanker Home and Andrew Whitaker. *Einstein's Trouble With Quantum Theory: A Re-Appraisal* Springer, (2007).

[30] Fine, *The Shaky Game: Einstein, Realism and the Quantum Theory (2nd Edition)*.pp.28-9. This is borne out by Einstein's later paper in Max Born's festschrift, Albert Einstein. "Elementare Überlegungen Zur Interpretation Der Grundlagen Der Quanten-Mechanik," in *Scientific Papers Presented to Max Born on His Retirement From the Tait Chair of Natural Philosophy in the University of Edinburgh*. Edinburgh: Oliver and Boyd, (1953).

[31] Guido Bacciagaluppi and A Valentini. *Quantum Theory At the Crossroads. Reconsidering the 1927 Solvay Conference*. Cambridge: Cambridge University Press (2009).pp. 440-442 see Home and

According to Bohr's account[32] of the conference, Einstein's main aim was to demonstrate that the state of quantum particles can be specified further than the wave function allowed.[33] Accounts of the conference, both by participants and historians,[34] centre around this dispute between Bohr and Einstein. Through a thought experiment Einstein explained the core of the problem as he saw it. Drawing a picture on the board, Einstein said "Let S be a screen provided with a small opening O and P a hemispherical photographic film of large radius. Electrons impinge on S in the direction of the arrows. Some of these go through O, and because of the smallness of O and the speed of the particles, are dispersed uniformly over the directions of the hemisphere, and act on the film."[35] Einstein said the only way to interpret this in a way that does not conflict with the Geiger and Bothe[36] experimental results nor the almost continuous lines

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Whitaker, *Einstein's Trouble With Quantum Theory: A Re-Appraisal*. pp.92-3

32 Niels Bohr. "Discussion With Einstein on Epistemological Problems in Atomic Physics," in *Albert Einstein Philosopher-Scientist. Library of Living Philosophers Vol VII*. ed. Paul Arthur Schilpp. Library of Living Philosophers, New York: MJF Books, (1949). pp.211-213

33Niels Bohr. "Discussion With Einstein on Epistemological Problems in Atomic Physics," pp.214-5

34 e.g. Bohr. "Discussion With Einstein on Epistemological Problems in Atomic Physics."; Werner Heisenberg. "Quantum Theory and Its Interpretation," in *Niels Bohr: His Lfe and Work as Seen By His Colleagues and Friends*. ed. S. Rozental, New York: John Wiley and Sons, (1967).; Max Jammer, *The Philosophy of Quantum Mechanics*, London: Wiley, (1974).:109-120.

35 Bacciagaluppi, and Valentini, *Quantum Theory At the Crossroads. Reconsidering the 1927 Solvay Conference*.p.440.

36 "In a well-known experiment with 70kV. X-rays, Bothe and Geiger (W. Bothe and H. Geiger. "Über Das Wesen Des Comptoneffektsö Ein Experimenteller Beitrag Zur Theorie Der Strahlung," *Zeitschrift für Physik* 32, no. 1 (1925): 639-63.) showed that recoil electrons and scattered quanta actually appeared simultaneously, and this experiment has been taken as furnishing a general verification of the Compton theory [ie Compton scattering see Arthur H. Compton, "A Quantum Theory of the Scattering of X Rays By Light Elements," *Physical Review* 21, no. 5 (1923): 483-502.]. It has also been tacitly assumed as a result of the Bothe-Geiger experiment that the principles

stemming from an α particle observed in a cloud chamber is that the wave function "$|\psi|^2$ expresses the probability that *this* particle is found at a given point, which assumes an entirely peculiar mechanism of action at a distance, which prevents the wave, continuously distributed in space, from producing an action in two places on the screen."[37]

Bacciagaluppi and Valenti comment "for Einstein, action at a distance can be avoided only by admitting that the wave function is incomplete. According to Einstein's argument, quantum theory is either non-local or incomplete. For the rest of his life, Einstein continued to believe that locality[38] was a fundamental principle of physics, and so adhered to the view that quantum theory must be incomplete."[39] This problem continued to trouble Einstein during the 1930s.[40] Einstein's conversations and correspondence during the period shows him continuing to refine thought experiments so as to encapsulate his concerns about quantum theory accurately.[41]

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of conservation of energy and momentum can be applied to describe individual processes involving the scattering of radiation." W.E. Burcham, and W.B Lewis. "A Repetition of the Bothe-Geiger Experiment." *Mathematical Proceedings of the Cambridge Philosophical Society* 32, no. 4 (1936):637-42.p.637

[37] Bacciagaluppi, and Valentini. *Quantum Theory At the Crossroads. Reconsidering the 1927 Solvay Conference*.p.441

[38]Don Howard. "Einstein on Locality and Separability," *Studies in History and Philosophy of Science Part A* 16 (1985):171-201.; Don Howard. ""Nicht Sein Kann Was Nicht Esin Darf" or the Prehistory of EPR, 1909-1935: Einstein's Early Worries About the Quantum Mechanics of Composite Systems," in *Sixty-Two Years of Uncertainty: Historical, Philosophical and Physical Inquiries Into the Foundations of Quantum Mechanics of Composite Systems.* ed. Arthur I Miller. New York: Plenum Press,(1990).:61-111; Howard, "Re-Visiting the Einstein-Bohr Dialogue."

[39] Bacciagaluppi and Valentini. *Quantum Theory At the Crossroads. Reconsidering the 1927 Solvay Conference*.pp.177-8

[40] Howard, ""Nicht Sein Kann Was Nicht Esin Darf" or the Prehistory of Epr, 1909-1935: Einstein's Early Worries About the Quantum Mechanics of Composite Systems."p.100; pp.104-5.

[41] from Einstein to Ehrenfest in April 1932 and Leon Rosenfeld's later account of a conversation with Einstein in 1933 in Howard, ""Nicht Sein Kann Was Nicht Esin Darf" or the Prehistory of EPR, 1909-1935:

All this culminated in the famous 1935 EPR paper. Einstein's problem was not that he was troubled by what quantum theory may or may not posit about the nature of reality. Einstein's quarrel with quantum theory is that it doesn't measure up to what should be expected of a scientific theory, namely that the account any theory gives of what in the theory counts as reality should be coherent.

1.2.3 Context of EPR: Einstein's Epistemology

Einstein's scientific epistemology sheds light on his misgivings. By 1923, his regard for Mach had become more nuanced but he retained Mach's contention that the concepts with which a scientific theory is framed are free inventions.[42] Einstein had spoken of "postulating physical reality"[43] as early as 1921, well before his long running debate with Bohr and the title of his essay to honour Maxwell's centenary in 1931 is telling: "Maxwell's influence on the evolution of the *idea of physical reality.*"[44] Einstein's epistemology is detailed in numerous works over his career.[45] In 1933, he outlined it in "The Herbert Smith

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Einstein's Early Worries About the Quantum Mechanics of Composite Systems."p.104.

[42] F Laudisa. "A "Free Play With Concepts": Philosophy and Epistemology in Albert Einstein's Scientific Thought," *Lettera Matematica* 5, no. 1 (2017):55-63.p.57 citing Nature Editors Nature Editorial Team. "Einstein and the Philosophies of Kant and Mach," *Nature* 112, no. 2807 (1923)p.253.

[43] Albert Einstein. "Geometry and Experience: Lecture Before the Prussian Academy of Sciences, January 27 1921," in *Ideas and Opinions* New York: Souvenir Press, (1954).p.238

[44] Albert Einstein. "Maxwell's Influence on the Evolution of the Idea of Physical Reality 1931," in *Ideas and Opinions* New York: Souvenir Press, (1954).:266-70. (Italics mine).

[45] e.g. Einstein. "Geometry and Experience: Lecture Before the Prussian Academy of Sciences, January 27 1921."; Albert Einstein. "On the Method of Theoretical Physics: The Herbert Spencer Lecture, Oxford June 10 1933," in *Ideas and Opinions*. New York: Bonanza Books, (1954).; Albert Einstein. "Physics and Reality," *Journal of the Franklin Institute* 221, no. 3 (1936):349-82.; Albert Einstein."Quantenmechanik Und Wirklichkeit," *Dialectica* 2 (1948):320-24. translated in Born, *The*

Lecture"[46] and on May 7th 1952 he explained this same conception in a letter to Maurice Solvine. In his 1933 lecture, Einstein sets out his methodology as a theoretical physicist. It explains something of the doggedness with which he pursued the difficulties he saw in quantum theory. He writes, "A complete system of theoretical physics is made up of concepts, fundamental laws which are supposed to be valid for these concepts and conclusions to be reached by logical deduction. It is these conclusions which must correspond with our separate experiences; in any theoretical treatise their logical deduction occupies almost the whole book."[47] These concepts, he explains, cannot be deduced from experience as can be seen from the fact that different theories can be used to explain the same data. As Glenn notes, Einstein uses the example of his own theory of relativity and Newton's theory of gravity, which are entirely different but, "both he and Newton, for example, can predict the position of a planet at any given time in spite of the fact that relativity and Newton's theory of gravitation employ concepts of time that are inconsistent with one another. If concepts were derived from experience, Einstein believes, two systems with such a great difference could not both explain one experience."[48] If the concepts are not deduced from experience, how does the theoretical physicist arrive at them? They "are free inventions of the human intellect, "[49] "purely fictitious."[50]

Born-Einstein Letters 1916-55 Friendship, Politics and Physics in Uncertain Times.pp.166-170; Albert Einstein. "Autobiographical Notes," in *A Stubbornly Persistent Illusion.* Philadelphia, London: Running Press, (1949).; Einstein, "Reply to Criticisms."; Einstein, "Maxwell's Influence on the Evolution of the Idea of Physical Reality 1931."; Albert Einstein, "Relativity and the Problem of Space," in *Ideas and Opinions*, London: Souvenir Press, (2005).:360-77

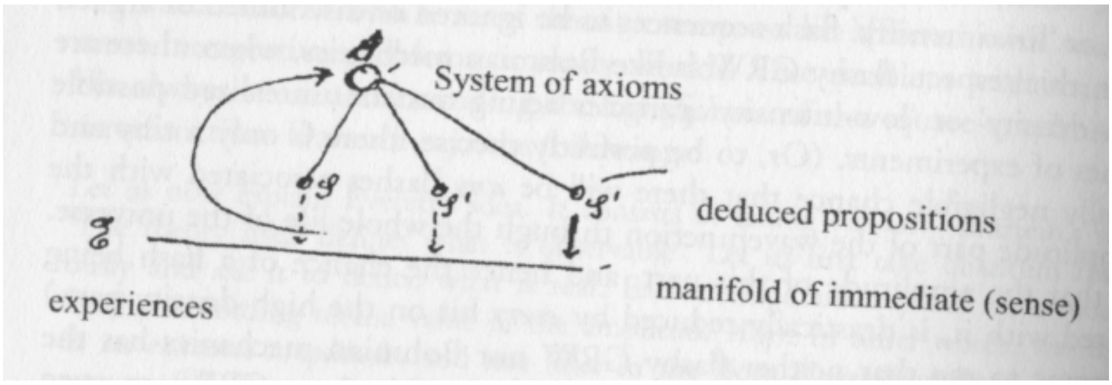
[46] Einstein. "On the Method of Theoretical Physics: The Herbert Spencer Lecture, Oxford June 10 1933."

[47] Einstein. "On the Method of Theoretical Physics: The Herbert Spencer Lecture, Oxford June 10 1933."p.272

[48] S Glenn. "Experience and Reason in Einstein's Epistemology," *Metaphilosophy* 43, no. 5 (2012):679-97.p.683

[49] Einstein. "On the Method of Theoretical Physics: The Herbert Spencer Lecture, Oxford June 10 1933."p.272

In the year following EPR he wrote: “On the other hand, these concepts and relations, and indeed the postulation of real objects and, generally speaking, of the existence of "the real world," have justification only in so far as they are connected with sense impressions between which they form a mental connection.”[51] In other words, if there is indeed an objective reality, it is, by definition, independent of our theories but our only hold upon it can be with those concepts, “meant to correspond with the objective reality” which we use “to picture this reality to ourselves.”[52] In 1952, Einstein explained this in a letter to Maurice Solvine of May 7th 1952, quoted by Tim Maudlin, complete with diagram. “As regards the epistemological problem, you have fundamentally misunderstood me, probably because I expressed myself poorly. I see the situation schematically thus:



(1) The E (experiences) are given to us
(2) The A are the axioms from which we deduce consequences. From a psychological point of view, the A rest on the E. But there is no logical path from the E to the A, instead only an intuitive (psychological) connection that is always 'subject to cancellation.'
(3) From the A are deduced in a logical way individual assertions S, which derivations can assert a claim to correctness.

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[50] Einstein, “On the Method of Theoretical Physics: The Herbert Spencer Lecture, Oxford June 10 1933.”p.272
[51] Einstein, “Physics and Reality.”p.291
[52] EPR p.777

(4) The S are brought into relation with the E (Testing in experience.) A careful examination shows that this procedure also belongs to the extra-logical (intuitive) sphere because the relation between the concepts appearing in S and the experiences E is not of a logical nature.

But this relation of the S to the E is (pragmatically) much less uncertain than the relationship of the A to the E. (Example of the concept dog and the corresponding experiences.) If such a correspondence were not achievable with great security (even though not logically comprehensible), then the logical machinery for the 'understanding of reality' would be completely worthless (example theology). - Ultimately it comes down to the eternally problematic connection of everything conceptual with that which can be experienced (sense experiences)."[53]

This brief overview of Einstein's epistemology provides further evidence as to what concerned Einstein. EPR was motivated by Einstein's desire not so much to see the world properly represented in quantum mechanical theory as to ensure that quantum mechanical theory was a theory fit to represent the world. Hence his later dismissal of Bohm's theory as "too cheap."[54]

1.3.1 EPR: Authorship, date and place of writing.

Einstein did not write EPR, "For reasons of language this [paper] was written by Boris Podolsky after much discussion."[55] Asher Peres,

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[53] Tim Maudlin. "Can the World be Only Wave Function?" in *Many Worlds? Everett, Quantum Theory and Reality*. ed. Simon Saunders, Jonathan Barrett, Adrian Kent, and David Wallace. Oxford: Oxford University Press, (2010).p.140

[54] letter to Born, Letter 99, 12th May 1952 Born, *The Born-Einstein Letters 1916-55 Friendship, Politics and Physics in Uncertain Times*. p.188

[55] Fine, *The Shaky Game: Einstein, Realism and the Quantum Theory (2nd Edition)*.p.35 from a letter to Schrödinger on June 19th 1935

whose PhD thesis advisor was Nathen Rosen, said later, "One day at the [Institute's] traditional 3 o'clock tea, Rosen mentioned to Einstein a fundamental issue of interpretation related to entangled wave functions. Einstein immediately saw the implications for his long-standing disagreement with Bohr. As they discussed the problem, Boris Podolsky joined the conversation, and later proposed to write an article. Einstein acquiesced."[56] The article was written while the three were at the Institute for Advanced Study at Princeton, New Jersey where Einstein had a permanent position. EPR was received by The Physical Review on March 25th 1935 and published on May 15th.

Later scholarship has stressed Einstein's misgivings with the way EPR was written.[57] Whatever Einstein's misgivings with the published paper, knowledge of this only came to light after Bell 1964 was written and hence, it was the argument of EPR as it was published with which Bell engaged.

1.3.2 The EPR Argument: Demonstrating the Contradiction[58]

The paper's title expresses the problem as Einstein saw it, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" a rhetorical question, which the paper sets out to answer in the negative. Firstly the authors stress there is a clear distinction between a theory and the objective reality it is designed to encapsulate. Objective reality is independent of any theory and of any concepts by which the theory is expressed. The point of the concepts is that they correspond with physical reality and enable us to picture objective reality in our thinking. Secondly, the authors give criterion

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[56] Kelly Devine Thomas. "The Advent and Fallout of EPR," *Institute from Advanced Study Publication* Fall Issue (2013)p.13.p.13
[57] Fine, *The Shaky Game: Einstein, Realism and the Quantum Theory (2nd Edition)*.pp.35-9.
[58] While Bell uses the term "paradox," the word does not occur in EPR. The authors use the word "contradiction,'' EPR p.779

for judging whether a theory is successful. They suggest two questions should be posed to the theory, "' (1) Is the theory correct?' and (2) 'Is the description given by the theory complete?'"[59] They explain how both these questions can be answered. With regard to the first, a theory is judged to be correct on the basis of the agreement between the theory's conclusion and human experience; it is " this experience, which alone enables us to make inferences about reality."[60] However, it is the second question with which the authors are concerned: "Is the description given by the theory complete?"[61]

They do not attempt to give an exhaustive account of the criteria needed to judge whether or not a theory can be considered complete. They point to one criterion they consider sufficient: "every element of the physical reality must have a counterpart in the physical theory. We call this the condition of completeness."[62] EPR focuses on this. Does every element of physical reality have a counterpart in the physical theory? In Einstein's view, "physical reality" was one of the concepts with which a theory operates, the justification for which lies with the sense it makes of the totality of our sense impressions: "On the other hand, these concepts and relations, and indeed the postulation of real objects and, generally speaking, of the existence of "the real world" have justification only in so far as they are connected with sense impressions between which they form a mental connection."[63] If there is indeed a physical reality, it is, by definition, independent of our theories, as EPR states, but our only hold upon it can be by using the idea of it as one of those concepts, "meant to correspond with the objective reality" so that we might "picture this reality to ourselves."[64] "Physical reality" is a concept that we make use of in constructing a

[59] EPR p.777
[60] EPR p.777
[61] EPR p.777
[62] EPR p.777
[63] Einstein, "Physics and Reality." p.291
[64] EPR p.777

theory that gives coherence to our understanding of our sense impressions. Having made the assumption and thereby formed a concept that our sense impressions give us access to a physical reality that is independent of us and of them, the next question is how are we to judge what is or is not an element of physical reality? Given that the writers have said that sense impressions in physics consist of experiment and measurement, it is no surprise that, as far as EPR is concerned, something will be considered an element of physical reality " If, without in any way disturbing a system, we can predict with certainty (i.e. with a probability equal to 1) the value of a physical quantity, then there exists an objective element of physical reality corresponding to this physical quantity."[65] The authors add "this criterion, while far from exhausting all possible ways of recognizing a physical reality, at least provides us with one such way, whenever the conditions set down in it occur." EPR's abstract says, " in a complete theory there is an element corresponding to each element of reality," EPR calls it the "criterion of reality."[66]

With this in place, EPR notes the first point at issue, "the quantum mechanical description," as it applies to a particle with a single degree of freedom. This section starts with the "fundamental concept" of quantum theory, namely "the state" " which is supposed to be completely characterized by the wave function ψ."

Using commonplaces of quantum theory they write,

"If ψ is an eigenfunction of the operator A, that is, if

$$\psi' \equiv A\psi = a\psi \qquad (1)$$

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[65] Giancarlo Ghirardi. *Sneaking a Look At God's Cards: Unveiling the Mysteries of Quantum Mechanics.* trans. Gerald Malsbary (rev ed.) Princeton N J: Princeton University Press, (2005).p.167
[66] EPR p.779

where *a* is a number, then the physical quantity A has with certainty the value *a* whenever the particle is in the state given by ψ."[67]

Drawing on their own criterion of reality, they conclude, " for a particle in the state given by ψ for which Equation (1) holds, there is an element of physical reality corresponding to the physical quantity A."[68] They then use this statement to demonstrate that therefore the momentum of a particle, in a state described by Equation (2)

$$\psi = e^{(2\pi i/h)p_0 x} \qquad (2)$$

a specific example of an equation in the form of Equation (1), the momentum of the particle has the value p_0 and by their definition of reality "is real."

They then turn to the case where Equation (1) doesn't hold and where therefore "we can no longer speak of the physical quantity A having a particular value. This is the case, for example, with the coordinate of the particle."[69] There are only relative probabilities that, if measured, the coordinate will be found to be somewhere between a and b. It therefore cannot fulfill their criterion of reality given that the outcome of any putative measurement cannot be accurately predicted, only "obtained" by a direct measurement.

Having demonstrated, the non-existence of a particle's co-ordinate, they point to the disturbance of the particle which would ensue from a direct measurement of the co-ordinate, meaning that the Equation (2) predicting momentum would no longer apply: once the co-ordinate had been obtained by a direct measurement, the particle would no

[67] EPR p.778
[68] EPR p.778
[69] EPR p.778

longer be in the state corresponding to its original wave function. They then generalize this to all cases of non-commuting[70] operators and conclude the first section of the paper with two mutually exclusive corollaries: "either (1) the quantum mechanical description of reality given by the wave function is not complete or (2) when the operators corresponding to two physical quantities do not commute the two qualities cannot have simultaneous reality." This is stressed again: "For if both of them had simultaneous reality—and thus definite values—these values would enter into the complete description, according to the criterion of completeness. If then the wave function provided such a complete description of reality, it would contain these values; these would then be predictable. This not being the case, we are left with the alternatives stated." They move on to the stage of the paper, "We shall show, however, that his assumption [the completeness of the quantum description of reality], together with the criterion of reality given above leads to a contradiction."[71]

EPR's second section demonstrates that a contradiction occurs when the assumption that the quantum mechanical description is complete is combined with their definition of reality. They build upon what has

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[70] In mathematics, operations, like addition, multiplication etc, are said to be commuting if the order in which they are carried out has no bearing upon the result and non-commuting otherwise. In quantum mechanics, the means by which values for specific parameters in a system, (e.g. momentum or position) are obtained, namely, operators, are likewise said to be commuting if the order in which they are carried out does not alter the value obtained and non-commuting otherwise. L.R.Kasday was the first to show the relevance of the fact that the values of parameters obtained from non-commuting operators cannot be modeled as a joint probability distribution for experiments testing Bell's inequality, "The reason a similar model cannot reproduce quantum predictions for the ideal measurements is that setting the ideal analyzers to several different angles corresponds to measuring several noncommuting observables. Quantum theory does not supply a joint probability distribution function for noncommuting observables, so the model cannot be constructed as above." L.R.Kasday." Experimental test of quantum predictions for widely separated photons."p.200

[71] EPR p.779

already been established in section 1, namely that for a system the state of which can be characterized by a wave function that is an eigenfunction of an operator corresponding to a physical observable, the value of which can be predicted with a probability equal to 1, those physical observables, the value of which can only be obtained by direct measurement, have no physical reality. The paper then posits two systems which have interacted for a specified amount of time, with the further assumption "after which time we suppose that there is no longer any interaction between the two parts." The initial states of both systems before their interaction was known and the combined state of the two systems can be calculated with Schrödinger's equation for any subsequent time. The state of either one of the two systems, after the interaction, according to quantum mechanics, can only be known by measurements, which the paper designates as "*reduction of the wave packet*" (italics original). The authors proceed to outline what they term "the essentials of this process," demonstrating both that "the wave packet given by the infinite series in Equation (7)

$$\Psi\left(x_{1,}x_{2}\right)=\sum_{n=1}^{-}\psi_{n}\left(x_{2}\right)u_{n}\left(x_{1}\right)$$

is reduced by measurement on system 1 to a single term e.g. $\psi_{k}\left(x_{2}\right)u_{k}\left(x_{1}\right)$ and that the set of functions $u_{n}\left(x_{1}\right)$ is determined by the choice of which physical quantity to measure such that if a choice had been made to measure a different physical quantity of system 1 the wave function for the infinite series and the wave function for the two systems after measurement would be different. They therefore conclude, "as a consequence of two different measurements performed on the first system, the second system may be left in states with two different wave functions."[72] This they find problematic given that " at the time of measurement the two systems no longer interact" so " no real change can take place in the second system in consequence of

[72] EPR p.779

anything that is done to the first system."[73] The as yet unspoken conclusion the reader is being steered to is that both these measured outcomes must derive from something that was there all along, although this does not fit with the paper's own criterion of reality, given that these outcomes cannot be predicted only measured. Hence the only spoken conclusion from this demonstration is that, " *it is possible to assign two different wave functions…. to the same reality*." They flesh out the demonstration with a specific example to show that the two chosen operators can be non-commuting and, as in the earlier example, they use momentum and the particles' coordinates. Using the formalism, they show that once a measurement has been performed on one of the two systems, the wave function of the other system is collapsed into a specific eigenvalue allowing the value of the physical quantity that corresponds to the operator to be predicted with certainty. But the wave function describing the second system will differ, and hence different values for different quantities, even non-commuting quantities, will be predicted depending upon which measurement was performed on the first system. The authors point out that according to their criterion of reality, being able to predict the value of a quantity with a certain equal to 1 means that that quantity is part of the physical reality. Thus both quantities, being predictable in this way, are therefore a part of the physical reality but only one can be described at a time; hence the quantum mechanical description must be incomplete.

1.4. EPR: What happened next?

Despite the attention the paper received from those at the forefront of the development of quantum physics,[74] EPR did not create great

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[73] EPR p.779

[74] Dirac initially thought that Einstein was correct, "Now we have to start all over again" he said, "because Einstein proved that it does not work. Kumar, *Quantum: Einstein, Bohr and the Great Debate About the Nature of Reality*. p.313

icontroversy at the time. Between its publication in 1935 and 1964, it was cited 72 times, between 1964 and 2000, 2900 times, while between 2016-2018, it has been cited 2550 times.[75]

Those with whom Einstein had been debating since Heisenberg's 1925 paper[76] took EPR very seriously. Bohr immediately wrote a paper published with the same title to answer it.[77] While Bohr's paper was felt to be obscure, it was generally held that he had answered EPR's point by stressing that in quantum theory the classical means by which measurements in the quantum domain are taken cannot be separated conceptually from the measurement results. It satisfied those who were already satisfied but did not answer Einstein, although he later remarked that of all those who had argued the point, Bohr came closest to understanding.[78] Bohr was held to have won the argument. While those who sympathized with Einstein were still dissatisfied, it was Bell who reenergized the debate.

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75 From Google Scholar, August 5th 2018. The total number of citations to that date was 16995.

76 Heisenberg. "Über Quantentheoretishe Umdeutung Kinematisher Und Mechanischer Beziehungen."

77 Niels Bohr. "Can Quantum-Mechanical Desciption of Physical Reality be Considered Complete?" *Physical Review* 48 (1935):696-702.

78 Einstein, "Reply to Criticisms."p.681

Chapter Two: "On the Einstein Rosen Podolsky Paradox"[1]

In this chapter, I pay attention to Bell 1964, explain its contents and describe why Bell wrote it. I shall highlight what Bell was defending and why.

2.1 Authorship and Date and Place of Writing

John Bell, a theoretical physicist working at CERN, wrote Bell 1964 while on sabbatical. The first draft was written at Brandeis University in Waltham near Boston, MA. The final version of the paper was completed during Bell's stay at the University of Wisconsin. [2] At both Universities, Bell gave lectures on the paper.[3] The paper was received on the 4th November 1964.

2.2 Background to Bell 1964: Assumptions and Footnotes

Bell 1964 was written to explore the crux of EPR: the completeness or otherwise of quantum theory. I start by exploring some of the conscious and unconscious assumptions made by Bell and the commitments held by him that frame his work.

2.2.1 Bell's Implicit Assumptions

Bell's own understanding of his assumptions will be noted here. The debate as to which assumptions others think underpin his inequality become important when we discuss how mathematicians, physicists both theoretical and experimental and philosophers of science understand the experimental violations of Bell's inequality, the

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[1] Bell 1964
[2] Andrew Whitaker. *The New Quantum Age* Oxford: OUP. (2012).p.122
[3] Whitaker. *The New Quantum Age*.p.122

centrepiece of his paper. As a mathematical expression, it relies implicitly on mathematical assumptions: Euclidean geometry and on a Kolmorogovian type probability theory. Bell does not explain or justify these choices. As we shall see, for the majority of those who comment upon Bell's work, these implicit assumptions are unproblematic but for a small minority they either invalidate or change the implications of his proof. A further implicit assumption about the nature of the wave function that Bell makes, without explaining or defending it, is that the wave function encodes information about the world beyond the brain of the physicist. Again it is an assumption that a majority of those in the field would also make, however there are an increasing number of theoretical physicists who do not share this assumption.[4]

2.2.2 Bell's Metaphysics of Science

Understanding Bell 1964 requires a sense of what Bell expected of a scientific theory. Disquiet with the significant role assigned to measurement drove much of his thinking about quantum foundations. Bell's position was spelt out in a 1966 paper, "The moral aspect of quantum mechanics,"[5] co-written with Michael Nauenberg. Bell and Nauenberg conclude: "the theory [i.e. quantum measurement theory]can at best be described as a phenomenological makeshift."[6] This troubles Bell throughout his career. He links it directly to the derivation of his inequality in a talk he gave in 1970. In Bell's talk,

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[4] I.e., those who espouse Qbism: "QBism specifically takes wave functions to specify degrees of belief about direct experiences (i.e., not agent-independent states of reality)." Personal email from Christopher Fuchs, December 8th 2014.

[5] Reprinted as John S. Bell and Michael Nauenberg. "The moral aspect of quantum mechanics" in *Speakable and Unspeakable in Quantum Mechanics*. ed John S. Bell Cambridge: Cambridge University Press (2004):22-28

[6] John S Bell, and M Nauenberg, "The Moral Aspect of Quantum Mechanics.".p.283

"Introduction to the Hidden Variable Question,"[7] he expresses his disquiet with a physical theory, quantum theory, that can only be expressed in terms of measurements in the classical domain and in which there is no possibility of fixing the boundary between the classical and the quantum domains. Bell states that rather than find out where this boundary lies, it is more probable that "we will find that there is no boundary."[8] In which case, he says, "the wave functions would prove to be a provisional or incomplete description of the quantum-mechanical part, of which an objective part would become possible."[9] The problem he raised in 1970 with measurement being a primitive of the theory he raised also in his last paper on the subject of quantum foundations, "La nouvelle cuisine."[10] It lies behind his 1966 paper showing that 3 impossibility proofs[11] do not hold and it lies behind Bell 1964 which set out to prove that no locally realistic theory could match the predictions of quantum mechanics for the same correlation experiments.

That a physical theory should enable physicists to speak about quantum reality rather than quantum measurements is part of the

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[7] John S Bell. "Introduction to the Hidden Variable Question" (Paper presented at the Foundations of Quantum Mechanics: Proceedings of the International School of Physics "Enrico Fermi" course IL, New York and London, 1971)., reprinted in John S Bell. "Introduction to the Hidden-Variable Question," in *Speakable and Unspeakable in Quantum Mechanics.* Cambridge: Cambridge University Press, (2004).:29-39.
[8] Bell, "Introduction to the Hidden-Variable Question."p.30
[9] Bell, "Introduction to the Hidden-Variable Question."p.30
[10] John S Bell. "La Nouvelle Cuisine." in *Speakable and Unspeakable in Quantum Mechanics.* Cambridge: Cambridge University Press, (2004).:232-248.
[11] i.e. that it is impossible to derive a theory that add "hidden variables" to specify the quantum state more fully than the existing formulations. Bell deals with von Neumann's proof (John von Neumann. *Mathematical Foundations of Quantum Mechanics.* trans. Robert T Beyer. Princeton: Princeton University Press, (1955).:305-328); JM Jauch, and C Piron. "Can Hidden Variables be Excluded in Quantum Mechanics?" *Helvetica Physica Acta* 36 (1963):827-37. and Andrew Gleason. "Measures on the Closed Subspaces of a Hilbert Space." *Journal of Mathematics and Mechanics* 6 (1957):885-93.

background to Bell 1964. Further considerations are clearly revealed in the seven footnotes to the paper, five of which are placed in the paper's abstract.[12]

2.2.3 Background to Bell 1964: Footnotes

In the first footnote, Bell cites EPR and three papers responding to it; Bohr's article, "Can Quantum-Mechanical Description of Physical Reality be considered complete?";[13] the two contributions by W.H Furry;[14] and a paper by David R. Inglis.[15] These citations indicate how Bell sums up the debate about EPR and where he situates his paper. In his response to EPR, Bohr took issue with its unspoken assumption that the particles and the measuring apparatus are separate such that a measurement being performed could be denoted as a "disturbance of the system."[16] Furry responds both to EPR and Bohr's reply. Furry's second paper includes a reflection on the papers in which Schrödinger[17] introduces the word entanglement denoting the phenomenon to which the second[18] of the EPR thought experiments pointed. Given that, as noted later by Bohm and Aharonov in their 1957 paper,[19] [BA], there was then no experimental evidence that the

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[12] Bell 1964 p.195
[13] Bohr. "Can Quantum-Mechanical Desciption of Physical Reality be Considered Complete?"
[14] W H Furry. "Note on the Quantum-Mechanical Theory of Measurement," *Physical Review* 49 (1936):393-99.; W H Furry. "Remarks on Measurements in Quantum Theory," *Physical Review* 49 (1936):476.
[15] David R Inglis. "Completeness of Quantum Mechanics and Charge-Conjugation Correlations of Theta Particles," *Reviews of Modern Physics* 33, no. 1 (1961):1-7.
[16] Bohr, "Can Quantum-Mechanical Desciption of Physical Reality be Considered Complete?"p.700
[17] Schrödinger. "Discussion of Probability Relations Between Separated Systems."; Erwin Schrödinger. "Die Gegenwärtige Situation in Der Quantenmechanik," *Naturwissenschaften* 23 (1935):807-12; 823-828; 844-849.
[18] EPR p.779
[19] Bohm and Aharonov. "Discussion of Experimental Proof for the Paradox of Einstein, Rosen and Podolsky."

second thought experiment in EPR would occur in practice, Furry explored the idea that "the difficulty comes from the yet experimentally unverified extrapolation of the many-body Schrödinger and Dirac equations to the case where the particle's [sic] wave functions do not overlap and where the particles do not interact."[20] That it might not occur in practice is known as Furry's Assumption A.[21] However, as Furry demonstrated, assuming that it would not happen did not dissolve the problem implied by the entanglement of the wavefunction noted by EPR. Inglis [22] comments on BA's suggested experiment to test Furry's Assumption A using spin-half particles and suggests an alternative experimental design using theta particles. By citing these papers alongside EPR, Bell is positioning his paper within the context of these discussions.

In his second footnote, Bell quotes Einstein's locality assumption, "But on one supposition we should, in my opinion, absolutely hold fast: the real factual situation of the system S2 is independent of what is done with the system S1, which is spatially separated from the former."[23] Bell's third footnote highlights the book by von Neumann[24] and the paper by Jauch and Piron containing proofs, put forward to rule out hidden variables, proofs which, in Bell's earlier but then still unpublished paper,[25] he had shown to be false, and to which he refers

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[20] BA p.1071

[21] Furry. "Note on the Quantum-Mechanical Theory of Measurement."p.395

[22] Inglis. "Completeness of Quantum Mechanics and Charge-Conjugation Correlations of Theta Particles."

[23] Albert Einstein. "Autobiographical Notes," in *Albert Einstein Philosopher-Scientist*, ed. Stephen Hawkings, New York: MJF Books, (1970).p.85 quoted in Bell 1964 p.200

[24] John von Neumann, *Mathematische Grundlagen Der Quantenmechanik*, Berlin: Springer, (1932).; English translation, von Neumann. *Mathematical Foundations of Quantum Mechanics*. Jauch, and Piron. "Can Hidden Variables be Excluded in Quantum Mechanics?"

[25] John S Bell. "On the Problem of Hidden Variables in Quantum Mechanics," *Reviews of Modern Physics* 38, no. 3 (1966):447-52. This

in his fourth footnote. The fifth refers to the two papers in which David Bohm[26] outlines a hidden variable interpretation of quantum mechanics. The next footnote refers to BA in which an EPR type experiment is outlined so as to see whether the predictions of quantum theory would occur in practice. However, this proposed experiment Bell will use for a different purpose, namely to formulate a means of testing whether or not the experimental results confirm the nonlocality of Bohm's theory. The final footnote is to p.37 of the Third Edition of Paul Dirac's *The Principles of Quantum Mechanics*[27] in which Dirac defines an observable as a "real dynamic variable whose eigenstates form a complete set"[28] and says that in theory every observable can be measured, however difficult any particular observable might be to measure in practice. Thus, in the title and first 13 lines of his paper, within which all but the final footnote occurs, Bell indicates very precisely the entire conceptual background to his paper.

The steps from EPR to Bell 1964 are as follows. EPR claims to demonstrate that quantum theory is incomplete. They describe a thought experiment in which a measurement on one system will immediately provide information about what the result of a measurement on another system with which it had once interacted would be. This is a step in EPR's argument demonstrating the incompleteness of quantum theory. Furry suggests this might not occur in practice. BA suggest an experiment to test Furry's conjecture. Bell suggests that experiment be used to test an inequality he has derived to reveal whether the experimental results would conform to a

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was written before Bell 1964, see Andrew Whitaker. *John Stewart Bell and Twentieth Century Physics. Vision and Integrity* Oxford: Oxford University Press. (2016).p.201

[26] Bohm,."A Suggested Interpretation of Quantum Theory in Terms of "Hidden Variables" I."; Bohm. "A Suggested Interpretation of Quantum Theory in Terms of "Hidden" Variables II."

[27] P.A.M. Dirac. *The Principles of Quantum Mechanics (3rd Edition)* Oxford: Clarendon Press, (1947).

[28] Dirac. *The Principles of Quantum Mechanics (3rd Edition)*.p.37

locality condition or not. Bell is not attempting to test Furry's Assumption A or the EPR contradiction. Bell assumes that Furry's Assumption A is incorrect and that quantum mechanics is incomplete and uses the suggested experiment for a significantly different purpose, namely to test whether or not the nonlocality of Bohm's completion of quantum mechanics has to be a feature of any theory proposed as a completion of quantum theory. This change between BA's own use of their thought experiment and the different use to which Bell puts it is not only significant in its own right, it is an example of something we shall see happens often as theory or experiments that are designed for one purpose are put to use for another.

2.3 The Text

Bell's prose is spare and concise. There are no wasted words and no unnecessary steps in the argument but its seeming simplicity is misleading. Each sentence is packed with meaning and is often not as straightforward as it might seem. The article comprises a title and six sections: I Introduction; II Formulation; III Illustration; IV Contradiction; V Generalization & VI Conclusion.

2.3.1 The Title: "On the Einstein Podolsky Rosen Paradox"[29]

Bell's paper references EPR but the word "paradox" was not used in the original paper. For the crux to which the authors of EPR point they use the word "contradiction."[30] Bell's use of the word paradox flags up his intention right at the start. Bohr, in his reply[31] to EPR, refers to the

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[29] Bell 1964 p.195

[30] EPR p.780. Bell also uses the word "Contradiction" as the heading for the fourth section of his paper where he demonstrates the proof of his result.

[31] Bohr. "Can Quantum-Mechanical Desciption of Physical Reality be Considered Complete?" Bohr does use the word "paradox" to describe what happens when "a more accurate time description of quantum

EPR contradiction as a "special problem" while W.H. Furry in his comments[32] the following year follows the original usage, "contradiction." By 1937, in his further discussion of EPR, Bohr used the word "paradoxical"[33] but insists that these "paradoxical circumstances" are "clarified" when it is recognized that it is impossible to separate physical objects in the quantum domain from the objects by which they are measured in the classical.[34] Schrödinger uses the word 'paradox' in "Disussion of Probability Relations between Separated Systems,"[35] a paper in which he shows that the phenomenon to which EPR had drawn attention, namely that "the representation [i.e., state function] arrived at for one system depends on the programme of observations to be taken with the other" is "quite a general one."[36] In a letter of August 19th 1935[37] Schrödinger disagrees with Einstein's suggestion that the problem of what the "psi-function" refers to is solved if it is is taken to refer to an ensemble rather than to a single quantum system.[38] Schrödinger replies that he doesn't think the "antimony or paradox"[39] can be resolved in this way. The use of these two words are indicative. In orthodox quantum theory, the ψ function represents all that can be said of a quantum system, and as

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phenomena" is attempted Bohr. "Can Quantum-Mechanical Desciption of Physical Reality be Considered Complete?"p.700

32 Furry. "Note on the Quantum-Mechanical Theory of Measurement."

33 Niels Bohr. "Causality and Complementarity," *Philosophy of Science* 4, no. 3 (1937):289-98.p.290.

34 Bohr. "Causality and Complementarity."p.290

35 Schrödinger. "Discussion of Probability Relations Between Separated Systems."p.556

36 Fine. *The Shaky Game: Einstein, Realism and the Quantum Theory (2nd Edition)*.p.68 quoting from Schrödinger. "Discussion of Probability Relations Between Separated Systems."p.556

37 Fine. *The Shaky Game: Einstein, Realism and the Quantum Theory (2nd Edition)*.pp.77-79

38 Schrödinger to Einstein August 19th 1935; for a comprehensive discussion of Einstein and Schrödinger's exchanges after EPR see Fine. *The Shaky Game: Einstein, Realism and the Quantum Theory (2nd Edition)*.pp.34-8; pp.64-85.

39 Fine. *The Shaky Game: Einstein, Realism and the Quantum Theory (2nd Edition)*.p.79 quoting from Schrödinger's letter of August 19th 1935 to Einstein.

Schrödinger notes in a letter to Einstein of July 13th in "our Johnny's"[40] formulation, that comes down to what can be measured.[41] In this case, the EPR situation represents a paradox, if a measurement is taken to be a measurement of something that pre-exists the measurement, given that a measurement on one system immediately changes what can be said about another system with which it has once interacted. However Schrödinger says he doesn't think the psi-function should be seen as denoting the physical state of the quantum system at all. "I am long past the stage where I thought that one can consider the ψ-function as somehow a direct description of reality."[42]
Schrödinger's use of the word paradox denotes what the "contradiction" would be should the psi-function equate to the physical state of the quantum system, and it is to this conception that Einstein suggested resolution points, namely viewing the ψ-function as representing an ensemble rather than a single quantum system.
Schrödinger's use of the Kantian word "antimony" immediately prior, points, in this context, to Schrödinger's own view that the psi-function is an "imaginary entity,"[43] "a catalogue of expectations."[44] Antimony is a word Kant used to refer to apparent paradoxes that arise because the necessary conditions of human experience are wrongly assumed to inhere in the things in themselves.[45] By using it, Schrödinger is saying that the apparent paradox arises because what is a part of the apparatus of human description of quantum experiments has been

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[40] John von Neumann
[41] Fine. *The Shaky Game: Einstein, Realism and the Quantum Theory (2nd Edition)*.p.76 i.e. von Neumann
[42] Fine. *The Shaky Game: Einstein, Realism and the Quantum Theory (2nd Edition)*.p.82 quoting from the 19th August 1935 letter from Schrödinger to Einstein.
[43] Schrödinger. "Die Gegenwärtige Situation in Der Quantenmechanik." p.8 of the online English translation at http://www.stp.dias.ie/~dorlas/Papers/QMSTATUS.pdf
[44] Schrödinger."Die Gegenwärtige Situation in Der Quantenmechanik." Online English translation p.11
[45] Re Kant's antimonies see Michelle Grier, "Kant's Critique of Metaphysics," *Stanford Encyclopedia of Philosophy* (2012). §4.1 and §4.2.

falsely assumed to be a description of the quantum world. Bell's use of the word "paradox" points to his position on Einstein's side of this particular argument, namely that the psi-function tell us about the physical state of the quantum system rather than merely representing our knowledge of it.

2.3.2 I.Introduction

Bell begins by setting out exactly what the paper is going to achieve. "The paradox of Einstein, Podolsky and Rosen was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore to the theory causality and locality. In this note that idea will be formulated mathematically and shown to be incompatible with the statistical predictions of quantum mechanics. It is the requirement of locality .... that creates the essential difficulty."[46] The Introduction sets out the scope and direction of the paper. While the first half of Bell's first sentence is accurate, the second half is not. EPR did set out to prove that quantum theory is incomplete and while they hope for a completion of it, they did not specify how. The second half of Bell's first sentence does not represent either what the paper did or set out to do. Einstein's preferred way out of the contradiction is to view the wave function as referring to an ensemble of systems and he regarded Bohm's theory as "too cheap."[47]

Having channelled the EPR hope in one direction, Bell footnotes a quotation from a later work of Einstein to provide an explanation for what these hidden variables should provide: "But on one supposition we should, in my opinion, absolutely hold fast: the real factual situation of the system S2 is independent of what is done with the

[46] Bell 1964 p.195
[47] Born. *The Born-Einstein Letters 1916-55 Friendship, Politics and Physics in Uncertain Times*.p.188

system S1, which is spatially separated from the former."[48] Einstein's epistemology remained remarkably stable over his career and so to use a later quotation as support for an imputed earlier position is legitimate. Here Einstein is clearly defending "locality" in the words "spatially separated" but the casuality that Bell also wishes to find here is not explicitly stated although can be seen as being implied by the phrase "what is done with." With Bell's third sentence, he is on firmer ground, simply stating what his paper will achieve. He will formulate mathematically the causality and locality with which he has said the writers of EPR wished to supplement quantum theory and demonstrate an incompatibility with the predictions of quantum mechanics. Bell next homes in on the requirement of locality to which he attaches a specific definition "that the result of a measurement on one system be unaffected by operations on a distant system with which it has interacted in the past,"[49] and, by doing so, ties it into the EPR thought experiment.

Bell makes reference to two "no hidden variables" proofs, von Neumann's,[50] and Jauch and Piron's.[51] He does not discuss them but refers instead to his earlier paper[52] in which he had examined them and "found [them] wanting."[53] Bell notes that a hidden variable interpretation has been constructed and points out that this theory has a "grossly nonlocal structure." Bell believes the mathematical inequality he has formulated in this paper is one with which any local causal theory would necessarily comply. That the statistical predictions of quantum mechanics do not comply with it demonstrates theoretically that one of the named assumptions of causality and

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48 Einstein. "Autobiographical Notes."p.85 quoted in Bell 1964 p.200
49 Bell 1964 p.195
50 von Neumann. *Mathematical Foundations of Quantum Mechanics*. pp.305 -323
51 Jauch, and Piron. "Can Hidden Variables be Excluded in Quantum Mechanics?"
52 Bell."On the Problem of Hidden Variables in Quantum Mechanics."
53 Bell 1964 p.195

locality cannot hold. That Bohm has already produced a non-local quantum theory demonstrates to Bell that it is locality that can no longer be assumed. Thus the final sentence in his introduction: " this is characteristic, according to the result to be proved here, of any such theory which reproduces exactly the quantum mechanical predictions."[54] Whatever the differing understandings of what Bell 1964 does or does not prove, it is important to remember that this is what, at the time of writing, Bell himself thought he had proved.

Bell is a precise and nuanced thinker. He chooses his words carefully. In his use of the words, "proved"[55] and "proof"[56] he underlines that the aim of this paper is to explore his insight that non-locality is not a characteristic peculiar to Bohm's hidden variable theory but necessary for any theory seeking to provide a more complete description of the state of a quantum system than the wave or psi function of orthodox quantum mechanics provides, while still matching all the predictions of quantum theory. Despite the experimentalists' rush to develop experiments capable of deciding between the predictions of quantum theory and Bell's inequality, the significance of the derivation lies first in the attention it draws to the fact that the mathematical predictions of quantum mechanics cannot be derived from the seemingly common sense notions of locality and causality, specifically in Bell's mind, locality. What Bell thinks he has proved, by his mathematical inequality, is that the predictions of quantum theory are incompatible with these foundational notions of locality and causality. Whether experimental results respect the limits of the inequality is a further matter. Like Einstein, Bell is not making any claims about what the world is like, or what reality is like. What Bell claims to have proved in this paper is something about any theory that is formulated to give account of how we picture the physical reality of the quantum world to

[54] Bell 1964 p.195
[55] Bell 1964 p.195
[56] Bell 1964 p.196

ourselves. Two things follow from this. Firstly, the discussions in the literature as to whether or not Bell's algebraic and geometrical[57] and probability assumptions[58] hold are therefore absolutely central. Experiments done on the basis of a proof that is flawed are neither here nor there. Secondly, it behoves those who wish to extrapolate from Bell's work to remember the arena of relevance that Bell claimed for his own result. Bell's purpose was to clarify the nature of the parameters that any theories about the quantum domain seeking to replicate the predictions of orthodox quantum theory must fulfill. Bell's introduction is masterly: in 9 short and pithy sentences, he sums up the history of the problem he is addressing, notes why and what he will be doing in the paper and notes how obstacles to the validity of his result have already been dealt with. The stage is set.

2.3.3 II Formulation

Bell begins his second section by distilling the BA thought experiment[59] to one succinct paragraph. Bell describes the experiment more specifically than they do and outlines the assumptions he himself makes. Bell outlines a theoretical experimental procedure. He writes: "Consider a pair of spin one-half particles formed somehow in the

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[57] Joy Christian. *Disproof of Bell's Theorem. Illuminating the Illusion of Entanglement Second Edition*. Boca Raton, Florida: BrownWalker Press, (2014).

[58] These were first questioned in Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons."p.200 & L de la Peňa, A.M. Cetto and T.A. Broday."On Hidden Variable Theories and Bell's Inequality," *Lettere Nuovo Cimento* 5, no. 2 (1972)p.177. Bell responded to de la Peňa, et al. "On Hidden Variable Theories and Bell's Inequality." in John S Bell. "Locality in Quantum Mechanics: Reply to Critics," *Epistemological Letters* 7 (1975):2-6. (John S Bell, "Locality in Quantum Mechanics: Reply to Critics," in *Speakable and Unspeakable in Quantum Mechanics,* Cambridge: Cambridge University Press, (2004).) but the debate has continued to the present. For a précis of these arguments, see Arthur Fine in Maximillian Schlosshauer, *Elegance and Enigma. The Quantum Interviews*, Berlin: Spinger-Verlag, (2011).pp.169-170

[59] BA p.1070

singlet spin state and moving freely in opposite directions. Measurements can be made, ………. , on selected components of the spins σ_1 and σ_2 . If measurement of the component where $\sigma_1 \cdot \vec{\alpha}$ where $\vec{\alpha}$ is some unit vector, yields the value +1 then, according to quantum mechanics, measurement of $\sigma_2 \cdot \vec{\alpha}$ must yield the value -1 and vice versa."[60] By specifying that the pair of spin one-half particles are in "the singlet state"[61] all Bell's readers would know what was implied, namely all spins are paired and the total spin of the system is zero. Thus, as Bell goes on to state, if the spin component of the first particle was "measured, " for example, along the z direction, measurement A, and found to be, once normalized, - 1, then, if taken, measurement B along the z direction on the spin component of the second particle must be +1. Alternatively if the measurement A was taken in the y direction and found to be +1, measurement B along the y direction, if measured must be -1. What Bell's readers would also know and which is what makes this so emblematic is that, just like the position and momentum of the EPR paper, spin directions in the singlet state are mutually exclusive. In quantum theory, this is not merely a question of one measurement disturbing or destroying the original state of the particle and rendering a second measurement impossible in practice. It inheres in the theory. Once spin is registered in one direction, there is no possibility of registering spin in any other direction on that particle that doesn't render random[62] the result of any subsequent measurement in the original direction. But, as in the case with the predicted momentum or position of the unmeasured particle in the

[60] Bell 1964 p.195. Many discussions of Bell's inequalities use modern notation and/or later versions of his result. In order to be clear about what Bell himself argued, I am reproducing his original result in its original notation throughout.

[61] For an explanation of the singlet state, see Roger Penrose, *The Road to Reality: A Complete Guide to the Laws of the Universe*, London: Jonathan Cape, (2004).pp.555-7

[62] But random in the special way of quantum experiments, in that while the result of any single measurement can be either +1 or -1, the statistical average will be 50:50 ie 0.

EPR thought experiment, in BA's example, taken up by Bell, the value, +1 or -1 for the second particle can be predicted with probability equal to one once the first measurement has been taken, regardless of the direction along which the analyzer at the first particle is aligned. As with the original EPR experiment, how can the second particle give the expected answer, regardless of which question it is asked, unless it comes with an existing instruction set or the setting of the first analyzer is somehow able to affect the second?

Thought experiments are always accompanied by assumptions, both implicit and explicit. In Bell's outlining of Bohm and Aharonov's thought experiment in the context of his paper, Bell has made two implicit assumptions neither stated or justified: that the discourse will be made in the particle half of the wave/particle duality; and that experiments are assumed to be the result of free choices made by scientists as to what questions to ask of which systems.[63] Describing his explicit assumptions, Bell writes "Now we make the hypothesis and it seems one at least worth considering, that if the two measurements are made at places remote from one another the orientation of one magnet does not influence the result obtained with the other"[64] meaning that once the particles are spatially separated, the situation of one cannot be affected by what is done to the other. Paying attention to Bell's wording here is very important. Bell references a comment made by Einstein in which Einstein talks about "the real factual situation"[65] of system S_1 and system S_2: "But on one supposition we should, in my opinion, absolutely hold fast: the real factual situation of the system S_2 is independent of what is done with the system S_1 ,

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[63] Even this seemingly unobjectionable assumption has to be stated and discussed, see Schlosshauer, *Elegance and Enigma. The Quantum Interviews*.p.166.
[64] Bell 1964 p.195
[65] see above n.61

which is spatially separated from the former."[66] Bell's own wording is more specific and more nuanced, "if the two measurements are made at places remote from one another the orientation of one magnet does not influence the result obtained with the other." Bell's wording is congruent with Bohrian conditions that quantum mechanical experiments must be talked about only in classical terms. Bell eschews talk of "the real factual situation" and speaks rather of the orientation of a magnet at one station and the read out of the magnet at the other. Thus, however relevant Jarret's distinction between what Bub later termed "outcome" and "parameter" independence may be for later Bell type inequalities,[67] Bell's own original "hypothesis" or assumption cannot be broken down into two i.e., on the one hand, consideration of the parameter of magnet one and the parameter of magnet two and then the consideration of the outcome of magnet one and the outcome of magnet two. Bell consciously holds together the orientation, i.e. the parameter of one magnet with the readout, i.e. the outcome of the other. He is keeping his assumption as an assumption about what is the case in the classical world of experiments. The orientation to which magnet one is set is assumed to bear no relation to the read out given by magnet two and mirrors the thought, although with more nuanced language, of the EPR paper's conclusion that "no reasonable definition of reality would permit" the reality of the second system to "depend…. upon the process of measurement carried out on the first system, which does not disturb the second in any way."[68]

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[66] Einstein, "Autobiographical Notes."p.85
[67] see Jon P Jarret. "On the Phyiscal Significance of the Locality Conditions in the Bell Arguments." *Noûs* 18, no. 4 (1984):569-89. & Jeffrey Bub. "The Philosophy of Quantum Mechanics." *British Journal of the Philosophy of Science* 40 (1989):191-210.p.199. Jarret notes that it is only more general version's of Bell's inequality to which his distinction applies, Jarret. "On the Phyiscal Significance of the Locality Conditions in the Bell Arguments."p.569
[68] EPR p.780

These assumptions, taken with the observed facts about the spin of singlet states, that any component of the spin of the unmeasured particle can be predicted[69] in advance of it being measured itself by the result of the measurement of that spin component on the other particle, imply "the result of any such measurement must actually be predetermined." This leads on to the conclusion that Bell will proceed in the rest of the paper to "formulate mathematically" namely that "since the initial quantum mechanical wave function does not determine the result of an individual measurement, this predetermination implies the possibility of a more complete specification of the state." It is important to note that this is the inverse of the EPR argument "We see therefore that, as a consequence of two different measurement performed upon the first system, the second system may be left in states with different wave functions"[70] but leads to the same conclusion, that the quantum mechanical description as given by the wave function represents an incomplete specification of the state of the system and paves the way for the rest of the paper; which begins "Let this more complete specification be effected by means of parameters λ."[71]

Some questions about Bell's theorem focus on these "parameters λ," thinking that his result can be side stepped by finding things that should have been included here and weren't.[72] In his original paper, Bell is quite clear what is included amongst the parameters designated by λ: "It is a matter of indifference in the following whether λ denotes a

[69] Although he doesn't specify it, Bell means predict in the EPR sense "with certainty," EPR p.777.
[70] EPR p.779
[71] Bell 1964 p.195
[72] e.g. Georges Lochak. "Paramètres Cachés Et Probabilités Cachées, Contribution Au Colloque: "Un Demi-Siècle De Mécanique Quantique" Université Louis Pasteur, Strasbourg 1975," *Fundamenta Scientiae* 38 (1975). This Bell answers in Bell, "Locality in Quantum Mechanics: Reply to Critics."

single variable or a set, or even a set of functions, and whether the variables are discrete or continuous." Anything that could count as the parameters supplying what has been omitted from the wave function and provide a "complete specification" of the state[73] is included in λ. In his 1975 article in "Epistemological Letters," Bell states that λ includes any parameters within the measuring device but, obeying the locality assumption, only the parameters of the measuring device with which the particle interacted.[74] Then Bell spells out this locality assumption in mathematical terms:[75]

"The result A of measuring $\vec{\sigma}_1 \cdot \vec{a}$ is then determined by $\vec{a}$ and λ, and the result B of measuring $\vec{\sigma}_2 \cdot \vec{b}$ in the same instance is determined by $\vec{b}$ and λ and

$$A(\vec{a},\lambda) = \pm 1, \quad B(\vec{b},\lambda) = \pm 1. \qquad (1)$$ "[76]

This seemingly straightforward assumption is more problematic than it might appear. It is the nub of Bell's argument. In the quantum mechanical understanding of the experimental set up Bell has outlined, the correlation of the expectation values of the readings at both ends of the experiment is taken to be dependent on the angle between the

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[73] Rębilas makes this point in his discussion of C.S Unnikrishnan's claim made in a series of papers (e.g. see Unnikrishnan C S. "Proof of Absence of Spooky Action At a Distance in Quantum Correlations," *Pranama Journal of Physics* 59, no. 2 (2002):295-301.) that Bell omitted to take account of the phase information. Rębilas counters Unnikrishnan, "The hidden variable λ is conceived in the local realistic theories quite generally and may be directly identified with the relative phase φ1—φ2." Krzysztof Rébilas. "On the Unnikrishnan Resolution of the EPR Puzzle," *Foundations of Physics Letters* 17, no. 3 (2004):277-86.p.281
[74] Bell, "Locality in Quantum Mechanics: Reply to Critics."pp.64-5
[75] F.S. Levin. *An Introduction to Quantum Theory*. Cambridge: Cambridge University Press, (2002).pp548-9
[76] Bell 1964 pp.195-6.

detectors. To that extent, nonseparability is in the theory. For a separable or local hidden variable theory, this has to be framed as two independent dependences, between the angle of deviation of the unit vector from the positive/negative polarization pole and whatever hidden parameters give each particle its polarization. This is all contained in what looks like a straightforward mathematical statement. Speaking only in terms of the classical experimental set up by which any results are produced, Bell next reiterates this "vital assumption"[77] of locality, that the orientation of one magnet cannot influence the measurement at the other. Bell then goes on to state "the main result" which he says is "quite simple."[78]

Before going on to outline this result, it is important to understand both the notation that Bell uses and the theoretical background upon which he relies. A is the result of a measurement of the spin of particle 1 in a particular direction and B is the result of a measurement of the spin of particle 2 in particular direction and $\vec{a}$, $\vec{b}$ and later $\vec{c}$ are unit vectors which denote the direction. Where applicable, the subscript on σ denotes upon which of the two particles in the singlet state, the measurement has been made. In his proof, Bell also uses expectation values, written as $P(\vec{a},\vec{b})$ or $P(\vec{a},\vec{c})$ for example. These are the correlation functions for measurements on the first and second particles with the unit vectors $\vec{a}$ and $\vec{b}$ in the first case and $\vec{a}$ and $\vec{c}$ in the second case.

[77] Bell 1964 p.196
[78] Bell 1964 p.196

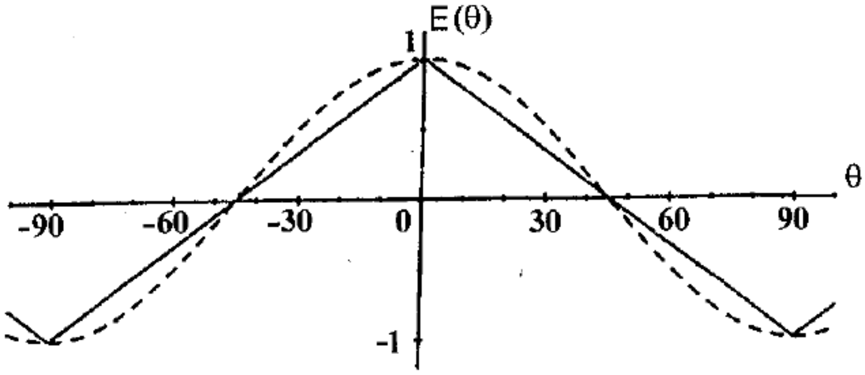

Fig 1: Polarisation correlation coefficient as a function of the relative orientation of the polarisers: (i) Dotted line: Quantum mechanical prediction; (ii) solid line: the naïve model.[79]

In quantum mechanics, the correlation of two binary variables is defined as the average value of the product of the two outcomes of runs of measurements. These do not register the average values of the measurement results but the averages of the correlation between them (confusingly +1, -1 or 0[80]). In the case of measurements such as these on the spin components of particles in the singlet state, the correlations between the two results depends on the difference between the two measurement angles,[81] a simple dependence in the case of quantum theory and, in the case of a local hidden variable theory, a dependence upon the difference between the angle of deviation of the unit vector from the positive/negative polarization pole and whatever hidden parameters give each particle its polarization.

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[79] Aspect's Figure 3 in Alain Aspect. "Bell's Theorem: The Naive View of an Experimentalist," in *Quantum [Un]Speakables - From Bell to Quantum Information*, ed. R A Bertlmann, and Anton Zeilinger Dodrecht: Springer,(2002).p.127

[80] Confusing because the measurement results, when normalized, are also +1 or -1

[81] For this account, see Kevin Brown, *Reflections on Relativity* (Math Pages, 2011). § 9.5 at http://mathpages.com/rr/s9-05/9-05.htm

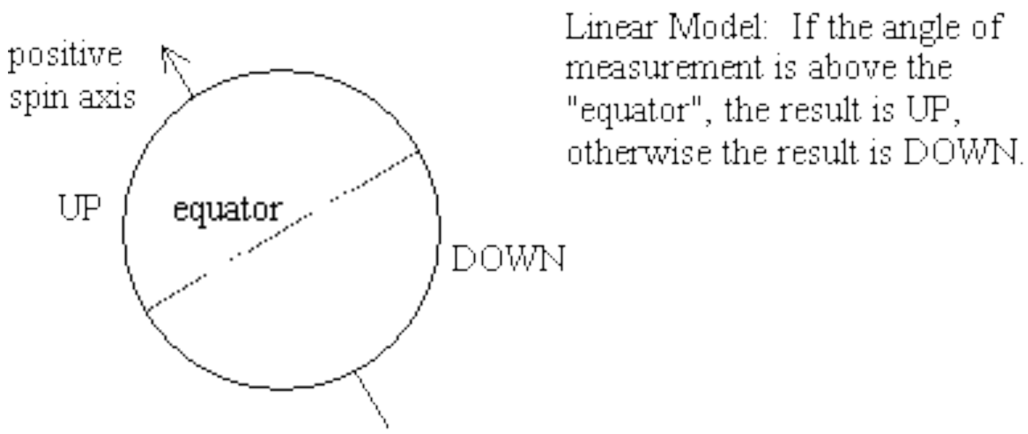

Figure 2: Linear Model[82]

Although not clearly stated by Bell in this paper, as Figure 1 shows, the expectation values for a hidden variables theory (the straight line) can be assumed to have a linear dependence on the angle of deviation of the unit vector as explained in Figure 2. "If the correlation varied linearly as q ranged from 0 to p [sic], it would be easy to explain in classical terms. We could simply imagine that the decay of the original spin-0 particle produced a pair of particles with spin vectors pointing oppositely along some randomly chosen axis. Then we could imagine that a measurement taken at any particular angle gives the result UP if the angle is within π/2 of the positive spin axis, and gives the result DOWN otherwise."[83] On the other hand, the quantum mechanical prediction (the curved line in Figure 1) is that that expectation value, $P(\vec{a},\vec{b})$, for example, will equal minus cos θ, where θ is the angle between $\vec{a}$ and $\vec{b}$.[84] This is where the problem for classicality comes in because the settings of both analyzers are, by definition, incorporated in the means by which the expectation value of the correlation of the readings at each separate analyzer is worked out.

[82] Model taken from Brown, *Reflections on Relativity*.p.651
[83] Brown, *Reflections on Relativity*.p.651
[84] This is because the dot product of two unit vectors equals the cosine of the angle between them.

Bell's assumption of "separability or locality"[85] cannot permit this in the derivation of his statistics, which, are derived from the measurement results themselves.

In both theories, when the angles between the directions in which the measurements are taken are 0° or 360° (or 2π in radians), there will be a perfect anticorrelation (i.e. the spin will be registered either -1,+1 or +1,-1) and this translates into a correlation score of -1. At 180° (or π in radians), there will be a perfect correlation (i.e. the spin will be registered as either +1,+1 or -1,-1) and this translates into a correlation score of +1. At 90° $\left(\frac{\pi}{2}\right)$ or 270° $\left(\frac{3\pi}{2}\right)$ there is a 50:50 chance of a either a perfect correlation or anticorrelation between the pairs of registered spins which translates as a correlation score of 0. So for any of the pair of measurement results, $\left(\vec{a},\vec{b}\right)$, $\left(\vec{a},\vec{c}\right)$ or $\left(\vec{b},\vec{c}\right)$, the expectation value, for example $P\left(\vec{a},\vec{b}\right)$, is worked out by allotting +1 every time the measurement value is the same and -1 everytime it is opposed and then dividing by the number of pairs registered. At angles other than these the expectation value changes in proportion with the angle[86] and will always be expressed as a number between -1 and +1.

Bell writes:

" If $\rho\left(\lambda\right)$ is the probability distribution of λ then the expectation value of the product of the two components $\vec{\sigma}\cdot\vec{a}$ and $\vec{\sigma}\cdot\vec{b}$ is

$$P\left(\vec{a},\vec{b}\right)=\int d\lambda\rho(\lambda)A\left(\vec{a},\lambda\right)B\left(\vec{b},\lambda\right) \qquad (2)$$

[85] Bell 1964 p.195

[86] In the quantum mechanical prediction, the angle between the analyzers and in the local realistic theory, that between the angle of each analyzers from the angle of the relevant zero polarization.

This should equal the quantum mechanical expectation value, which for the singlet state is

$$\langle \vec{\sigma}_1 \cdot \vec{a} \;\; \vec{\sigma}_2 \cdot \vec{b} \rangle = -\vec{a} \cdot \vec{b} \qquad (3)$$

But it will be shown that this is not possible."[87]

This section ends with an explanation of what λ includes. Bell notes that some think his derivation would better encode a locality assumption were there to be a set of λ for A and a set of λ for B. Bell says it is perfectly possible to conceptualize it in this way but he is clear that λ stands for any number of variables upon which A and B depend. Bell suggests that as a complete physical theory of the type invisaged by Einstein, "the hidden variables would have dynamical significance and laws of motion; our λ can then be thought of as initial values of these variables at some suitable instant."[88]

2.3.4 III Illustration

In this section, before giving the proof of his result, Bell first outlines its scope. He notes three occasions where the outcomes of measuring spin components can be accounted for in terms of a hidden variable explanation, and "the statistical features of quantum mechanics arise because the value of the variable is unknown in individual circumstances"[89] i.e. where his equations (2) and (3) would produce the same answer. Firstly: " there is no difficulty in giving a hidden variable account of spin measurements on a single particle,"[90] something he demonstrates mathematically. Secondly, the cases in which (i) the same component of spin of the correlated particles are measured and the results give +1 for one particle and -1 and also

[87] Bell 1964 p.196
[88] Bell 1964 p.196
[89] Bell 1964 p.196
[90] Bell 1964 p.196.

where (ii) different spin components are measured with an equal chance for +1 and -1, which, again, Bell demonstrates mathematically. The final case in which the experimental results can be equally well explained by an hidden variable explanation and again which Bell demonstrated mathematically, is the one "Einstein would have liked least[91]" whereby the setting of each polarizer affect the measurement results at both.

2.3.5 IV Contradiction

Having cleared the ground, it is in this section, Bell proceeds to prove "the main result,"[92] which he has already stated: that the expectation values in his equations (2) and (3) cannot equal each other in every case. Equation (3) is the standard quantum mechanical expectation value for measurements of different spin components of the two particles in the singlet state described in Bell's version of Bohm and Aharonov's thought experiment and (2) is that derived by Bell based on the assumption that the results of each individual measurement are predetermined by local variables not specified by the quantum mechanical wave function. Bell proceeds to outline his proof step by step:[93]

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[91] Bell, "On the Problem of Hidden Variables in Quantum Mechanics." p.452

[92] Bell 1964 p.197

[93] In this outline of Bell's thinking, I am indebted to the discussion of his inequality by Gérard Gouesbet. *Hidden Worlds in Quantum Physics.* Mineola, New York: Dover Publications Inc. (2013).pp.285-286; David J Griffiths. *Introduction to Quantum Mechanics*. New Jersey: Prentice Hall. (1995).pp.377-378; Susanne Groothuis, "The Bell Inequalities" Bachelor Project, Universiteit van Amsterdam, (2012).pp.5-6; Niclas Hoglund and Olof Jacobson. "Bell's Theorem and Inequalities, With Experimental Considerations."Degree Project in Engineering Physics, First Level, Royal Institute of Technology (KTH). (2013).pp.7-10; Levin, *An Introduction to Quantum Theory*.pp. 548-550; Travis Norsen. "Counter-Factual Meaningfulness and the Bell and Chsh Inequalities." (2006).pp.2-4 . Throughout, except where stated, I use the notation of Bell's original 1964 paper.

Step 1:

"ρ is a normalized probability distribution

$$\int d\lambda \rho(\lambda)=1\,, \qquad (12)"$$

Step 2:

"because of the properties (1), P in (2) cannot be less than -1."[94] (This the case with a perfect anticorrelation, when A and B devices are orientated parallel along the same direction. Neither can it be more than +1, a perfect correlation, when the A and B devices are orientated anti parallel along the same direction.) Bell explains thus:

"It can reach -1 at $\vec{a}=\vec{b}$ only if $A(\vec{a},\lambda)=-B(\vec{a},\lambda)$ (13)",

discounting " a set of points λ of zero probability."

Step 3:

Since $A(\vec{a},\lambda)=-B(\vec{a},\lambda)$, (and therefore also $-A(\vec{a},\lambda)=B(\vec{b},\lambda)$), in equation (2), the equation for the expectation value of the product of $A(\vec{a},\lambda)$ and $B(\vec{b},\lambda)$, -A can be substituted for B,

$$P(\vec{a},\vec{b})=-\int d\lambda\rho(\lambda)A(\vec{a},\lambda)A(\vec{b},\lambda) \qquad (14)$$

As Levin says "[This] Equation ..... is completely general. The question is whether it leads to results in agreement with those of quantum mechanics. Bell showed, using a third unit vector c, that it did not."[95]

Step 4:

Bell introduces another bivalent unit vector, c and makes the same assumptions as with unit vector b above[96], so, although not stated, $P(\vec{a},\vec{c})=\int d\lambda\rho A(\vec{a},\lambda)C(\vec{c},\lambda)$ supplies $P(\vec{a},\vec{c})=-\int d\lambda\rho(\lambda)A(\vec{a},\lambda)A(\vec{c},\lambda)$

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94 This proof can be found at Bell 1964 pp.197-198

95 Levin. *An Introduction to Quantum Theory*.p.549

96 Hoglund, and Jacobson. "Bell's Theorem and Inequalities, With Experimental Considerations."p.9

in $P(\vec{a},\vec{b})-P(\vec{a},\vec{c})=-\int d\lambda\rho\left[A(\vec{a},\lambda)A(\vec{b},\lambda)-A(\vec{a},\lambda)(\vec{c},\lambda)\right]$

$A(a,\lambda)A(b,\lambda)$ which gives the difference between the expectation values of $(\vec{a},\vec{b})$ and $(\vec{a},\vec{c})$.

Step 5:
Bell then re-arranges the right side of the expression. Norsen explains how: Bell "inserts unity into the [second] term in the square brackets in the form $1=A(\vec{b},\lambda)A(b,\lambda)$ (justified by the idea that $A(\vec{b},\lambda)=\pm 1$ so that, either way, its square is one." [97]

In an intermediate step that Bell does not show, but Norsen does, this gives

$$P(\vec{a},\vec{b})-P(\vec{a},\vec{c})=-\int d\lambda\rho(\lambda)\left[A(\vec{a},\lambda)A(\vec{b},\lambda)-A(\vec{a},\lambda)A(\vec{b},\lambda)A(\vec{b},\lambda)A(\vec{c},\lambda)\right]$$

then by taking $A(\vec{a},\lambda)A(\vec{b},\lambda)$ outside the brackets and reversing the signs, thereby reducing to

$$P(\vec{a},\vec{b})-P(\vec{a},\vec{c})=\int d\lambda\rho(\lambda)A(\vec{a},\lambda)A(\vec{b},\lambda)\left[A(\vec{b},\lambda)A(\vec{c},\lambda)-1\right]$$

Step 6:
Referring back to his (1), and thus informed by the absolute values but without any further explanation, Bell derives his next expression:

$$\left|P(\vec{a},\vec{b})-P(\vec{a},\vec{c})\right|\leq\int d\lambda\rho(\lambda)\left[1-A(\vec{b},\lambda)A(\vec{c},\lambda)\right].$$

On the left side of this expression is the modulus of the difference between the expectation values of the products of $P(\vec{a},\vec{b})$ and $P(\vec{a},\vec{c})$. Griffiths, clarifying how Bell has arrived at his values for the right hand side, explains: "it follows from equation ... [(1)] that

97 Norsen. "Counter-Factual Meaningfulness and the Bell and CHSH Inequalities."p.3

$-1 \leq \left[A(\vec{a},\lambda) A(\vec{b},\lambda) \right] \leq +1$ ”[98] meaning that “its absolute value is +1”[99] and thereby allowing its removal from the expression. Given that, as Hoglund and Jacobson note, also following from (1) is

$$\text{“}\left| A(\vec{b},\lambda) A(\vec{c},\lambda) - 1 \right| = 1 - A(\vec{b},\lambda) A(\vec{c},\lambda) \text{”}$$ [100]

thereby allowing the right hand side to read.

$$\int d\lambda \rho(\lambda) \left[1 - A(\vec{b},\lambda) A(\vec{c},\lambda) \right]$$

It is the substitution of the absolute values that allows Bell to frame this expression as inequality: the value of the right hand side is bound to exceed that of the left.

Step 7: Bell’s original inequality:

Bell remarks that $A(\vec{b},\lambda) A(\vec{c},\lambda)$ is $P(\vec{b},\vec{c})$ and so substitutes it in the reversed expression

$$1 + P(\vec{b},\vec{c}) \geq \left| P(\vec{a},\vec{b}) - P(\vec{a},\vec{c}) \right| \qquad (15)$$

This is the original Bell’s inequality. But this is not where Bell’s argument stops. He expresses succinctly what this expression achieves,

“Unless P is constant, the right hand side is in general of order $\left| \vec{b} - \vec{c} \right|$ for small $\left| \vec{b} - \vec{c} \right|$. Thus $P(\vec{b},\vec{c})$ cannot be stationary at the minimum value (-1 at $\vec{b} = \vec{c}$) and cannot equal the quantum mechanical value (3) ”[101] (see Fig. 1).

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[98] Griffiths. *Introduction to Quantum Mechanics*.p.378
[99] Gouesbet. *Hidden Worlds in Quantum Physics*.p.286
[100] Hoglund, and Jacobson. “Bell’s Theorem and Inequalities, With Experimental Considerations.”p.9
[101] Bell 1964 p.198

Bell is drawing attention to an implication of his inequality. Apart from the case he mentions where the probabilities are constant, in cases where the modulus of $\vec{b}-\vec{c}$ (ie the difference between the angles b and c) is small, the value of the right hand side of the inequality generally equals this modulus meaning that $P(\vec{b},\vec{c})$ cannot be stationary at the minimum value of -1 (as the quantum mechanical value predicts it is). Bell explains this point more fully in a talk he gave at Pisa in 1976, published as "Einstein-Podolsky-Rosen experiments"[102] where he uses it to demonstrate the validity of his theorem. Here, Bell assuming[103] that $P_q(\vec{a},\vec{b})$ equals $P_h(\vec{a},\vec{b})$ points out that where $\vec{a}=\vec{b}$ (ie the angle θ between them is 0), $P(\vec{a},\vec{b})=-1$. Using the assumption behind P_h, this means that " A and B must have opposite signs everywhere in the λ,μ,ν,.... space[104]. Consider now what happens when $\vec{a}$ is varied to some new value $\vec{a'}$. B (which is independent of $\vec{a}$ by hypothesis) does not change for given λ,μ,ν,..... But A will change sign at certain points, and these points will contribute $AB+1$ instead of $AB=-1$ in the average.. so

$$P(\vec{a'},\vec{a})-P(\vec{a},\vec{a})=2\rho$$

where ρ is the total probability of the set of points λ,μ,ν,... at which A changes sign. Now this set of points, at which A changes sign when $\vec{a}$ is varied to $\vec{a'}$ in no way depends on $\vec{b}$. It follows ....

$$\left|P(\vec{a'},\vec{b})-P(\vec{a},\vec{b})\right|\leq 2\rho$$

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102 John S Bell. "Einstein-Podolsky-Rosen Experiments." in *Speakable and Unspeakable in Quantum Mechanics*. Cambridge: Cambridge University Press. (2004).:89-91
103 I am using Levin's terminology. The subscript q = quantum and h= hidden variable.
104 i.e. all the hidden parameters which complete the description given by the quantum mechanical wave function and account for the values registered by the analyzers that are averaged over to produce the correlation function.

So for all values $\vec{b}$, $\vec{b} = \vec{a}$ is that for which P varies most rapidly with $\vec{a}$."

Bell concludes, "Unlike the quantum correlation ... which is stationary in θ at θ=0, at the hidden variable correlation ... must have a kink there." (see Fig 3).

The inability of the expression, derived on the assumption of "a more complete specification of the state," to be "stationary at the minimum value" is a point Bell made earlier in the paper about the expression he derived to show how a hidden variable explanation can reproduce the quantum mechanical statistics when both particles were measured in the same direction always resulting in an anticorrelation. He noted then, "it will be seen that this is characteristic of functions of type (2)" (i.e. expressions that are derived on the basis of "a more complete specification of that state" than that provided by the wave function), unlike the quantum mechanical predictions, something he then goes on to demonstrate by the derivation of his inequality.

Bell's point that at θ=0, $-\cos\theta_{ab}$ the expectation values for correlations, derived on the basis of "a more complete specification of the state," do not match those predicted by quantum mechanics, is demonstrated for other angles also by later commentators. For the thought experiment Bell has considered, two spin half particles emitted by a common source and propagating in opposite directions, where θ is the angle between the analyzers, the quantum mechanical prediction for the expectation value is $-\cos\theta_{ab}$.[105] While Bell has already noted the occasions when the quantum mechanical predictions fulfil the inequality demanded by local hidden variable theories, for

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[105] Franck Laloë. *Do We Really Understand Quantum Mechanics?* Cambridge: Cambridge University Press, (2012).p.61. For an explanation of the singlet state, see Roger Penrose, *The Road to Reality: A Complete Guide to the Laws of the Universe*, London: Jonathan Cape, (2004).pp.555-7

many angles they do not[106] and Griffiths gives an example of where the value predicted by quantum mechanics violates Bell's original inequality:[107] in Levin's notation, where $P_q(a,b) \neq P_h(a,b)$ Griffiths takes three coplanar vectors, with **a**[108] and **b** at 90° to each other, with **c** in between them at 45° to each. In this case[109], $P_q(a,b)=0$; $P_q(a,c)$ and $P_q(b,c)$ = -0.7071 which violates Bell's inequality

1+ (-0.7071) $\not\geq$ 0 – (-0.7071).

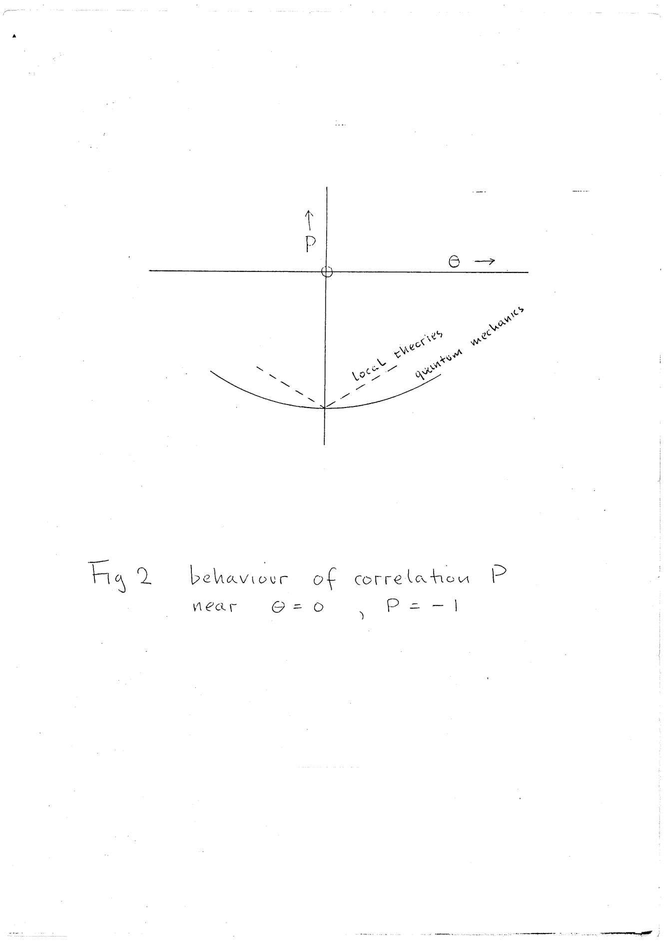

Fig 3: Bell's diagram of the behaviour of correlation P near θ = 0, $P=-1$

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106 It is important to note that at some angles they do, as Bell pointed out earlier in the paper.
107 Griffiths, *Introduction to Quantum Mechanics*.p.379
108 Using Griffith's notation to denote vectors rather than that of Bell's original paper.
109 For clarity, I am using Levin's notation.

However, it is important to note that the point Bell makes is not that the values for P_h are not the same as the values of P_q : as he himself points out, there are "infinitely many ways"[110] of conjecturing what the values of P_h might be. Bell's point is that the values for P_q predicted by quantum mechanics do not lie within the bounds predicted by an inequality he has shown must necessarily restrict the values of P_h however they are calculated.

Finally, Bell completes the argument in a manner Gouesbet say is "worth reporting,"[111] "Nor can the quantum mechanical correlation (3) be arbitrarily closely approximated by the form (2)"[112] and finishes the paper with the formal proof of this, producing, what Gouesbet calls, "a second Bell inequality."[113]

$$4(\varepsilon+\delta)\geq\left|\vec{a}\cdot\vec{c}-\vec{a}\cdot\vec{b}\right|+\vec{b}\cdot\vec{c}-1 \qquad (22)$$

This inequality, Bell also derives step by step.[114]

Step One:

Instead of equations (2) and (3),[115] Bell posits

"the functions $\bar{P}(\vec{a},\vec{b})$ and $\overline{-\vec{a}\cdot\vec{b}}$ where the bar denotes independent averaging of $P(\vec{a}',\vec{b}')$ and $-\vec{a}'\cdot\vec{b}'$ over vectors $\vec{a}'$ and $\vec{b}'$ within specified small angles of $\vec{a}$ and $\vec{b}$."[116]

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110 Bell 1964 p.84

111 Gouesbet, *Hidden Worlds in Quantum Physics*.p.287

112 Bell 1964 p.199

113 Gouesbet, *Hidden Worlds in Quantum Physics*.p.288

114 For this explanation, I use Gouesbet, *Hidden Worlds in Quantum Physics*.pp.287-9

115 See above p.24

116 Bell 1964 p.198

Step Two:

The difference between the modulus of average of $P(a,b)$ and of $-a \cdot b$ Bell denotes as being bounded by ε

$$\left|\overline{P}(a,b)+a \cdot b\right| \leq \varepsilon \qquad (16)$$

In deriving the second inequality, he demonstrates that this difference cannot be made arbitrarily small, showing that the difference between P_q and P_h, however the latter is calculated, is statistically significant at small angles either side of θ=0, ie $a=b$, which, as Bell has just demonstrated is one of the places where P_q, being stationary as predicted by quantum mechanics, violates inequality (15).[117]

Step 3:

Bell introduces another quantity δ which denotes the modulus of the difference between the averaged over difference of the small differences between a and b and the modulus of the small angle between a and b itself ie

$$\left|\overline{a \cdot b}-a \cdot b\right| \leq \delta \qquad (17)$$

Step 4:

Adding (16) and (17) produces:

$$\left|\overline{P}(a,b)+a \cdot b\right| \leq \varepsilon+\delta \qquad (18)$$

Step 5:

Because of (2), Bell notes that

[117] See above p.28

$$\overline{P}(a,b) = \int d\lambda \rho(\lambda) \overline{A}(a,\lambda) \overline{B}(b,\lambda) \quad (19)$$

expressing the fact that average of expectation values around a and b only stem from the local hidden parameters that affect measurement A at *a* and measurement B at *b* and the probability distribution of λ. Since the modulus of both $\overline{A}(a,\lambda)$ and $B(b,\lambda)$ is equal to or less than 1, using (18) and (19), for the case when $a = b$ where $-a \cdot b = -1$

$$d\lambda \rho(\lambda) \left[\overline{A}(b,\lambda) \overline{B}(b,\lambda) + 1 \right] \leq \varepsilon + \delta \quad (21)$$

Step 6:

Just as in the reasoning by which he derived his original inequality, Bell introduces a third angle c, assuming that all the reasoning that was applicable to $\overline{P}(a,b)$ and $\overline{-a \cdot b}$ is applicable to $\overline{P}(a,c)$ and $\overline{-a \cdot c}$.

Thus, using (19), Bell notes

$$\overline{P}(a,b) - \overline{P}(a,c) = \int d\lambda \rho(\lambda) \left[\overline{A}(a,\lambda) \overline{B}(b,\lambda) - \overline{A}(a,\lambda) \overline{B}(c,\lambda) \right]$$

and expands

$$= \int d\lambda \rho(\lambda) \overline{A}(a,\lambda) \overline{B}(\lambda) \left[1 + \overline{A}(b,\lambda) \overline{B}(c,\lambda) \right] - \int d\lambda \rho(\lambda) \overline{A}(a,\lambda) \overline{B}(c,\lambda) \left[1 + \overline{A}(b,\lambda) \overline{B}(b,\lambda) \right]$$

Step 7:

Using (20), Bell notes that the modulus, the absolute value of

$\overline{P}(a,b) - \overline{P}(a,c)$ is

$$\leq \int d\lambda \rho(\lambda) \left[1 + \overline{A}(b,\lambda) \overline{B}(c,\lambda) \right] + \int d\lambda \rho(\lambda) \left[1 + \overline{A}(b,\lambda) \overline{B}(b,\lambda) \right]$$

Step 8:

Whence using (19) and (21):

$$\left|\overline{P}(a,b)-\overline{P}(a,c)\right|\leq 1+\overline{P}(b,c)+\varepsilon+\delta$$

then “finally”

Step 9:
Using (18), Bell writes

$$|a\cdot c-a\cdot b|-2(\varepsilon+\delta)\leq 1-b\cdot c+2(\varepsilon+\delta) \text{ or } 4(\varepsilon+\delta)\geq|a\cdot c-a\cdot b|+b\cdot c-1$$

thus demonstrating that there is a lower limit on the difference between the quantum mechanical and local hidden variable correlation function for measurements taken with analyzers set off at small angles. Then, with a certainty that the first experimental physicists who attempted to test Bell’s inequality did not share,[118] Bell puts forward this example as a case “that requires little imagination to envisage the measurements involved actually being made” and goes on to outline systems that could provide opportunities for experimental work where “the statistical predictions of quantum mechanics are incompatible with separable predetermination.”[119]

Bell concludes his paper by summing up what his two inequalities have proved: “the quantum mechanical expectation value cannot be represented, either accurately or arbitrarily closely, in the form (2)”[120] (ie by a local hidden variable model) and, in his final paragraph, underlines the implications for any hidden variable model that aims to replicate the predictions of quantum mechanics, “there must be a mechanism whereby the setting of one measuring device can influence the reading of another instrument, however remote.” Thus, his paper

[118] John F Clauser. “Early History of Bell’s Theorem,” in *Quantum [Un]Speakables. From Bell to Quantum Information*, ed. R A Bertlmann, and Anton Zeilinger. Berlin-Heidleberg-New York: Springer-Verlag, (2002).p.7
[119] Bell 1964 p.199
[120] Bell 1964 p.199

acheived what he had designated as an "interesting"[121] next step at the end of his 1966 paper: to prove that the "extraordinary"[122] nonlocality of the Bohmian scheme was a necessary rather than idiosyncratic feature of any hidden variable theory designed to complete quantum mechanics while agreeing with all of its statistical predictions. This recognition that the setting of one instrument must be able instantaneously to affect the reading of the other, however remote, comes with a sting in the tail: "Moreover the signal involved must propogate instantaeously, so that such a theory could not be Lorentz invariant."[123] However, Bell notes "the situation changes if the quantum mechanical predictions are of limited validity" by which he means not that the predictions break down at certain angles but that "the settings of the instruments are made sufficiently in advance to allow them to reach some mutual rapport by exchange of signals with velocity less than or equal to the speed of light"[124] and, referring to the experiments already proposed by Bohm and Aharonov to prove the EPR paradox,[125] underlines the importance of the instrument settings being changed while the particles are in flight. This he calls "crucial" and it was something that Aspect and his team finally achieved in 1982 in experiments which showed strong violation of the version of the CHSH inequalities that Freedman and Clauser derived in 1972.[126]

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[121] Bell. "On the Problem of Hidden Variables in Quantum Mechanics." p.452

[122] Bell. "On the Problem of Hidden Variables in Quantum Mechanics." p.452

[123] Bell 1964 p.199. Whether this is the case or not has been a matter of discussion in the literature e.g. see Lucien Hardy. "Quantum Mechanics, Local Realistic Theories, and Lorentz-Invariant Realistic Theories," *Physical Review Letters* 68, no. 20 (1992):2981-2984. & Won Tae Kim, and Edwin J. Son. "Lorentz-Invariant Bell's Inequality," *Physical Review A* 71 (2005):014102:1-014102:3.

[124] Bell 1964 p.199

[125] BA

[126] Alain Aspect, et al., "Experimental Test of Bell Inequalities Using Time-Varying Analyzers," *Physical Review Letters* 49, no. 25 (1982):1804-1807.

2.4 The Transmission History of Bell 1964

While it is obvious, it is important to remember that Bell 1964 was written before the internet enabled anyone to post their research, thoughts, opinions and finding on line and before there were search engines to find and bring the most seemingly arcane writings to light. Bell 1964 was published in the third issue of the first volume of an obscure journal, "*Physics*." Within four years, the journal had ceased publishing[127] making his paper hard to access. It was not until 1983 that Bell 1964 was reprinted in John Wheeler and Wojciech Zurek's book, "Quantum Theory and Measurement"[128] and then again in 1987 in John Bell's own collection of papers, "Speakable and Unspeakable."[129]

[127] All the issues are now online under the auspices of the American Physical Society https://journals.aps.org/ppf/browse

[128] John Archibald Wheeler and W H Zurek. *Quantum Theory and Measurement*. Princeton, NJ: Princeton University Press, (1983).:403-408.

[129] Bell, John S. 'On the Einstein-Podolsky-Rosen Paradox.'*Speakable and Unspeakable in Quantum Mechanics,* Cambridge: Cambridge University Press, (2004):14-21.

Chapter Three: Preparing to Experiment

I have presented a commentary on Bell 1964, outlining its context and exploring the text and argument. In this chapter I survey the journey from Bell 1964 to the possibility of realizable experiments. We shall pay attention to the theory streams available to and motivating those who were excited by Bell 1964 and its possibilities. The experimental testing of Bell-type inequalities, Bell-type because Bell's own inequality was not itself suitable for testing, has been going on since the first experiment conducted in 1970[1] until now. To understand these experiments and the theory that generated and flowed from them, we shall follow labyrinthine routes through differing experimental and conceptual streams. We shall outline the theory base of the paper in which a testable version of Bell's inequality was published[2] [CHSH] in detail as an example of how experiments in this area are no less theoretically conceived than the theories they are designed to test. This demonstrates the complexity of how experiments are constructed and scientific meaning generated. We shall see for ourselves the truth of Einstein's observation as related by Heisenberg, "theory …. decides what we can observe."[3] This is not to undermine the theoretical and experimental work that has gone on in this area nor the conclusions that have been deduced from it. This is how meaning is constructed. It is rather an opportunity to demonstrate the intricate ways by which, in this field, things that come to be seen as facts have been so designated.[4] We shall see how what is

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[1] L. R. Kasday, J. Ullman & C.S. Wu. "The Einstein-Podolsky-Rosen Argument: Positron Annhilation Experiment," *Bulletin of the American Physical Society* 15, no. 4 (1970):586.; Kasday, "Experimental Test of Quantum Predictions for Widely Separated Photons."
[2] John F Clauser, et al. "Proposed Experiment to Test Local Hidden-Variable Theories," *Physical Review Letters* 23 no. 15, (1969):880-84
[3] Heisenberg. *Physics and Beyond Encounters and Conversations*.p.63
[4] Shapin and Schaffer. *Leviathan and the Air Pump: Hobbes, Boyle and the Experimental Life*.

envisaged as the final capstone in one conceptual construction becomes a stepping stone in another, how the mechanisms by which something has become a fact or a principle become irrelevant as it is put to use for a different purpose and in a different way. If theologians working in the area of science are going to draw conclusions or construct meaning from scientific discourse, it is important that they have paid attention to how what they are discussing as scientific fact has become so.

3.1 From publication to testable inequality.

Tracking citations is one of the ways by which the influence of a scientific paper is determined. In 1987, Leslie Ballentine published a graph[5] of Bell 1964 citations from 1966 to 1986 noted in the Science Citation index. However, Bell 1964[6] was first cited in 1965 in Bernard

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[5] Leslie Ballentine. "Resource Letter Iqm-2: Foundations of Quantum Mechanics Since the Bell Inequalities," *American Journal of Physics* 55 (1987):785-92.p786

[6] Between 1964 and 1974 Bell 1964 was cited by

1. d'Espagnat. *Conceptions De La Physique Contemporaine*.p149
2. Max Jammer. *The Conceptual Development of Quantum Physics*. New York: McGraw-Hill Book Company, (1966).
3. Bernard d'Espagnat. "Things, Structures and Phenomena in Quantum Physics," in *Logic, Methodology and Philosophy of Science III* Amsterdam: North-Holland Publishing Company, (1968).
4. Olivier Costa de Beauregard. "On Time Information and Life I," *Dialectica* 22, no. 3-4 (1968):187-205.
5. S Schlieder. "Einige Bemerkungen Zur Zustandsänderung Von Relativistichen Quantenmechanischen Systemen Durch Messungen Und Zur Lokalitätsforderung," *Communications in Mathematical Physics* 7 (1968):305-31.
6. Henry P Stapp. "Correlation Experiments and the Nonvalidity of Ordinary Ideas About the Physical World," *Lawrence Berkeley Laboratory Report* LBL-533 (1968):1-10.
7. P.M. Clarke and J.E. Turner. "Experimental Tests of Quantum Mechanics," *Physics Letters* 26A (1968):447.
8. CHSH
9. Leslie Ballentine. "The Statistical Interpretation of Quantum Mechanics," *Review of Modern Physics* 42, no. 4 (1970):358-81.
10. Wigner E P."On Hidden Variables and Quantum Mechanical Probabilities," *American Journal of Physics* 38 (1970):1005-09.

d'Espagnat's, *Conceptions de la physique contemporaine*[7] before Max Jammer's 1966 citation in an Appendix to *The Conceptual Development of Quantum Physics.* [8] Bell 1964 was referenced twice in 1967 in conference talks, firstly by Bernard d'Espagnat at the Proceedings of the Third International Congress for Logic, Methodology and Philosophy of Science held in Amsterdam from August 25th to September 2nd 1967, and secondly by Olivier Costa de Beauregard, who cited Bell 1964 in his bibliography.[9] D'Espagnat footnotes Bell's paper twice and, like de Beauregard, indicates acceptance of Bell's argument. The first time, d'Espagnat cites him as proof of the problems that quantum theory poses for realism and then that the price for any hidden variable programme is the acceptance of "strong and instantaneous interactions at large distances between any components of the universe."[10]

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11. Philip M Pearle. "Hidden-Variable Example Based Upon Data Rejection," *Physical Review D* 2 (1970):1418-25.
12. Henry P Stapp. "S-Matrix Interpretation of Quantum Theory," *Physical Review D* 3, no. 6 (1971):1303-20.
13. Bell. "Introduction to the Hidden Variable Question."
14. John S Bell. "On the Hypothesis That the Schroedinger Equation is Exact," *Ref: TH.1424-CERN* (1971):1-20.
15. Robert Colodny. *Paradigms and Paradoxes: The Philosophical Challenge of the Quantum Domain*. Pittsburgh: University of Pittsburgh Press, (1972).
16. Mioara Mugur-Schächter, Daniel Evrarad François Thieffine."Study of the Presence Probability Distribution in Autointerference States," *Physical Review D* 6, no. 12 (1972):3397-3418.
17. Crawford. J. A. "A Noncommutative Representation of Classical Dynamics. Connections With Field Quantization," *Il Nuovo Cimento* 9B, no. 1 (1972):1-39.

[7] d'Espagnat, *Conceptions De La Physique Contemporaine*.
[8] Jammer, *The Conceptual Development of Quantum Physics*.p.387.
[9] Costa de Beauregard, "On Time Information and Life I." p.195-6. Lecture given on the 24th October 1967.
[10] d'Espagnat, "Things, Structures and Phenomena in Quantum Physics."note p.381.

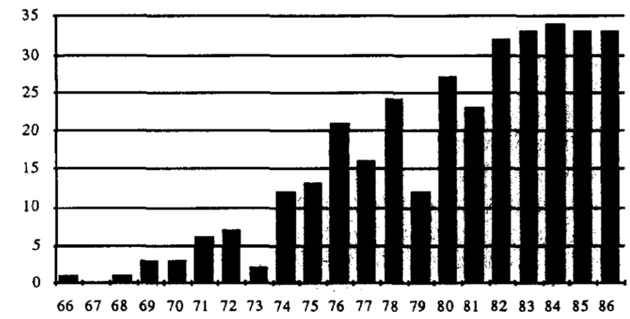

Fig. 1. Annual citations in *Science Citation Index* of Bell's paper (Ref. 53).

786 Am. J. Phys., Vol. 55, No. 9, September 1987

Although, only one citation is logged in Ballentine's graph for 1968, the year when both of these lectures were published, S Schlieder also cites Bell 1964 in a paper on relativistic quantum mechanics.[11] Clarke and Turner also cited Bell[12] in 1968. The final early citation of Bell 1964 was also in 1968, by Henry Stapp at a Cambridge conference.[13]

D'Espagnat, Costa de Beauregard, Schlieder and Stapp were all theoretical physicists but experimental physicists were also taking notice. The first written communication Bell himself had had from any one concerning Bell 1964 was a letter in February 1969 from experimental physicst John Clauser, keen to put Bell's theorem to the test or "to call Bell's bluff"[14] by which Clauser meant testing the tacit, but utterly experimentally unsupported assumption Bell makes in the 1964 paper that the quantum predictions for the relevant thought experiments are borne out in practice. Clauser had derived a version of

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[11] Schlieder. "Einige Bemerkungen Zur Zustandsänderung Von Relativistichen Quantenmechanischen Systemen Durch Messungen Und Zur Lokalitätsforderung."p.312 His description of relavitistic quantum mechanics in which the "states depend on the possible information of the observer"p. 305 looks prescient, given the current strength of the Qbist interpretation of quantum mechanics.
[12] Clarke, and Turner. "Experimental Tests of Quantum Mechanics."
[13] Stapp. "Correlation Experiments and the Nonvalidity of Ordinary Ideas About the Physical World."
[14] Clauser. "Early History of Bell's Theorem."p.79

Bell's inequality that did not required ideal systems[15] and found out that while Wu and Shaknov's experiment[16] [WS] that tested whether or not the two quanta emitted in the annihilation of a positron-electron pair are polarized at right angles to each other had not tested the question at the angles at which a Bell-type inequality might be violated, Wu's student Kasday was preparing to rerun the experiment. Clauser suggested Kasday test at the appropriate angles. This experiment was to be the first published, testing Bell's inequality. Realizing that WS would not be conclusive, Clauser discussed whether the crossed- beam scattering experiments with alkali metals being done at MIT might be suitable to test for a Bell inequality violation. It was suggested that a recent experiment carried out by Kocher might be but this had not tested at the appropriate angles either. "I next wrote letters to Bell Bohm and de Broglie, asking (a) did they know of any experiments testing the result, and (b) did they consider that a repeat of the Kocher Commins experiment with improved polarizers at intermediate angles would be convincing. All three courteously replied NO to (a) and YES to (b). Bell himself was particularly enthusiastic about the idea. Thus encouraged, I drafted an abstract for the Washinton DC APS Spring Meeting proposing the experiment."[17]

Abner Shimony was exploring ways to test Bell's inequality as early as 1966[18] but by 1967 had laid the project aside. Shimony moved to Boston University and became supervisor for Michael Horne, who was keen to work on developing an experimental test for Bell's inequality. They joined forces with Richard Holt to devise a practicable

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[15] John F Clauser. "Early History of Bell's Theorem and Experiment," in *Foundations of Quantum Mechanics*, ed. T.D. Black, M.M Nieto, Marlon O. Scully, R.M Sinclair, and H.S Piloff. World Scientific Co Ltd, (1992). p.169
[16] Wu and I. Shaknov, "The Angular Correlation of Scattered Annihilation Radiation."
[17] Clauser. "Early History of Bell's Theorem and Experiment."p.169
[18] Olival Freire Jnr. "Philosophy Enters the Optics Laboratory: Bell's Theorem and Its First Experimental Tests," *Studies in History and Philosophy of Modern Physics* 37 (2006):577-616.p.590

experiment, also using the Kocher-Commins' method of producing polarized photons in a calcium cascade.[19] John Bell, upon whose work the experiments were based, had chosen to explore ideal experiments done with spin-half particles. However in the late 1960s it was still impossible to design a feasible test with spin half particles. It remained so until Lamehi-Rachti and Mittig's experiment of 1976[20] after which a Bell-type inequality was not tested again using spin parameters until 2001.[21] But, before Shimony, Horne and Holt could put anything into print, John Clauser had submitted his abstract.[22] The four teamed up and published the outline of their proposed experiment in 1969.[23]

The first step was Clauser's "generalization of Bell's theorem which applies to realizable experiments."[24] Bell's equation[25] for the quantum mechanical expectation value of the singlet state "cannot hold exactly in an actual experiment. Any real detector will have an efficiency less than 100% and any real analyzer will have some attenuation as well as

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[19] Kocher, and Commins "Polarization Correlation of Photons Emitted in an Atomic Cascade." [KC]
[20] M Lamehi-Rachti, and W Mittig. "Quantum Mechanics and Hidden Variables: A Test of Bell's Inequality By the Measurement of the Spin Correlation in Low-Energy Proton-Proton Scattering," *Physical Review D* 14, no. 10 (1976):2543-2555.
[21] Edward S Fry and Thomas Walther. "Atom Based Tests of the Bell Inequalities — the Legacy of John Bell Continues.," in *Quantum [Un]Speakables. From Bell to Quantum Information*. Berlin-Heidleberg-New York: Springer-Verlag, (2002).p.110 and M.A. Rowe, D.Kielpinski, V Meyer, C.A.Sackett, W.M. Itano, C. Monroe & D. Wineland. "Experimental Violation of a Bell's Inequality With Efficient Detection," *Nature* 409 (2001):791-94.
[22] John F. Clauser. "Proposed Experiment to Test Local Hidden Variable Theories," *Bulletin of the American Physical Society* 14 (1969):578. See David I Kaiser. *How the Hippies Saved Physics. Science, Counterculture, and the Quantum Revival*. New York London: W.W Norton & Company, (2011).p.45
[23] CHSH
[24] CHSH p.881
[25] Equation 3 Bell 1964 p.196

some leakage into its orthogonal channel."[26] The limitations of the experimental equipment then available meant the first inequality in CHSH was not experimentally testable either. Consequently, in the second stage of their paper, Clauser, Horne, Shimony and Holt derived a version of their inequality that, with an added assumption, is testable in a feasible experiment.

3.1.1 The Original CHSH inequality

The original CHSH inequality was derived for a two channel[27] experiment: "Consider an ensemble of correlated pairs of particles moving so that one enters apparatus Ia and the other apparatus IIb, where a and b are adjustable apparatus parameters. In each apparatus a particle must select one of the two channels labeled +1 and -1. Let the results of these selections be represented by A(a) and B(b), each of which equals ±1 according as the first or second channel is selected." Then, they state their assumptions, " a statistical correlation of A (a) and B(b) is due to information carried by and localized within each particle"[28] i.e. which are locality and realism/determinism/or property definiteness. Whether or not Bell relied on an assumption of realism in his derivation of the inequality in Bell 1964,[29] it is clear that CHSH does.[30] They continue, "The information, which emphatically is not

[26] John F Clauser and Abner Shimony."Bell's Theorem:Experimental Tests and Implications," *Report on Progress in Physics* 41 (1978):1881-927.p.1889

[27] i.e. where each pair in the pair would be confronted by a choice of two channels rather than as would be the case in a one channel experiment, registered by one device. The symbol ≡ means equivalent to.

[28] CHSH p.88

[29] Most say that he did, some disagree, see Tim Maudlin. "Space-Time in the Quantum World," in *Bohmian Mechanics and Quantum Theory: An Appraisal*. ed. James T Cushing, Arthur Fine, and S Goldstein Dodrecht: Kluwer Academic Publishers, (1996).; Travis Norsen. "Against "Realism," *Foundations of Physics* 37, no. 3 (2007):311-40.

[30] for determinism, see CHSH p.881; for realism, see Clauser and Shimony. "Bell's Theorem:Experimental Tests and Implications." p.1881 These words are used interchangably in the later debate.

quantum mechanical, is part of the content of a set of hidden variables, denoted collectively by λ. The results of the two selections are then to be deterministic functions A (a,λ) and B(b,λ). Locality reasonably requires A(a,λ) to be independent of the parameter b and B(b,λ) to be likewise independent of a, since the two selections may occur at an arbitrarily great distance from each other."[31] Given that they do not specify that their hidden variables, λ, differ from the λ in Bell 1964, we can assume that they considered their assumptions also underlay Bell's 1964 derivation. They define the correlation function for the pairs of emitted particles as follows:

$$P(a,b) \equiv \int_{\Gamma} A(a,\lambda) B(b,\lambda) \rho(\lambda) d\lambda \qquad (1)$$

where Γ is the total space of λ; ρ(λ) the normalised probability distribution of λ; and d(λ) the probability of finding a specific value of λ. As, with Bell 1964, a third angle, c, is introduced and, without stating it, the analogous assumption made that

$$P(a,c) \equiv \int_{\Gamma} A(a,\lambda) B(c,\lambda) \rho(\lambda) d\lambda \qquad (2)$$

Thus, it follows that:

$$\left|P(a,b) - P(a,c)\right| \leq \int_{\Gamma} \left|A(a,\lambda)B(b,\lambda) - A(a,\lambda)B(c,\lambda)\right| \rho(\lambda) d\lambda \qquad (3)$$ [32]

Steps similar to Bell's in his original derivation are taken so as to rephrase the right hand side of the equation as follows. Norsen says Bell "inserts unity into the [second] term in the square brackets in the form

$$1 = A(b,\lambda)A(b,\lambda)$$

[31] CHSH p.881
[32] CHSH p.881

(justified by the idea that $A(b,\lambda)=\pm 1$ so that ...its square is one.)”[33]

Analogously, and also without showing the immediate steps, in CHSH unity is inserted in the form

$B(b,\lambda)B(b,\lambda)$

thus:

$$\int_{\Gamma}\left|A(a,\lambda)B(b,\lambda)-A(a,\lambda)B(b,\lambda)B(b,\lambda)B(c,\lambda)\right|\rho(\lambda)d\lambda$$

which they rephrase as :

$$\int_{\Gamma}\left|A(a,\lambda)B(b,\lambda)\right|\left[1-B(b,\lambda)B(c,\lambda)\right]\rho(\lambda)d\lambda \quad (4)$$ [34]

which in turn, because $\left|A(a,\lambda)B(b,\lambda)\right|$ is 1, can be rewritten as

$$\int_{\Gamma}\left[1-B(b,\lambda)B(c,\lambda)\right]\rho(\lambda)d\lambda \quad (5)$$ [35]

then as

$$1-\int_{\Gamma}B(b,\lambda)B(c,\lambda)\rho(\lambda)d\lambda \quad (6)$$ [36]

To obtain an inequality that is testable in practice, CHSH then note that in practice the correlated photons’ polarizations will not be exactly opposite:

“Suppose that for some b'[37] and b we have P(b', b)=1-δ, where 0≤δ≤1. Experimentally interesting cases will have δ close to but not equal to

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33 Norsen.“Counter-Factual Meaningfulness and the Bell and CHSH Inequalities.”p.3

34 CHSH p.881

35 CHSH p.881

36 CHSH p.881

zero. Here we avoid Bell's experimentally unrealistic restriction that for some pair of parameters b' and b there is a perfect correlation (i.e., δ = 0)."[38]

Then, "Dividing Γ into two regions $\Gamma_+ \Gamma_-$ such that

$\Gamma_{\pm} = \left\{ \lambda \middle| A(b',\lambda) = \pm B(b,\lambda) \right\}$ we have $\int_{\Gamma\_} \rho(\lambda) d\lambda = \tfrac{1}{2}\delta$ $\int_{\Gamma\_} \rho(\lambda) d\lambda = \tfrac{1}{2}\delta$ "[39]

they show that the rightside of the expression in equation (6),

i.e. $\int_{\Gamma} B(b,\lambda) B(c,\lambda) \rho(\lambda) d\lambda$ can now be written

$\int_{\Gamma} A(b',\lambda) B(c,\lambda) \rho(\lambda) d\lambda - 2\int_{\Gamma\_} A(b',\lambda) B(c,\lambda) \rho(\lambda) d\lambda$ [40] (7)

where Γ has been split into its two regions, Γ+ and Γ-,

$A(b',\lambda)$ substituted for $B(b,\lambda)$ as the equivalent measurement and

$\int_{\Gamma\_} \rho(\lambda) d(\lambda)$ doubled to give δ.

Given that $\int_{\Gamma} A(b',\lambda) B(c,\lambda) \rho(\lambda) d\lambda$ can be written as $P(b',c)$ and

the modulus of $A(b',\lambda) B(c,\lambda)$ is, by definition, its highest value,

CHSH's next step is to note that $\int_{\Gamma} B(b,\lambda) B(c,\lambda) \rho(\lambda) d\lambda$ is larger

than or equal to $P(b',c) - 2\int_{\Gamma} \left| A(b,\lambda) B(c,\lambda) \right| \rho(\lambda) d\lambda$ [41] (8)

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[37] This is a direction for measurement at the A side.
[38] CHSH p.881
[39] CHSH p.881
[40] CHSH p.881
[41] CHSH p.881

which, given that $\left|A(b',\lambda)B(c,\lambda)\right|$ is equal to 1 and $2\int_{\Gamma_-}\rho(\lambda)d\lambda$

$2\int_{\Gamma_-}\rho(\lambda)d\lambda$ is equal to δ, means the expression can be re-expressed as

$P(b',c)-\delta$. [42] (9)

Substituting this in (6) gives $1-P(b',c)+\delta$ (10)

As $P(b',b)=1-\delta$ therefore $\delta=1-P(b',b)$ $\delta=1-P(b',b)$ and substituting this for δ in equation (10) gives

$1-P(b',c)+1-P(b',b)$ (11)

Thus, CHSH go on to derive the inequality,

"$\left|P(a,b)-P(a,c)\right|\leq 2-P(b',b)-P(b',c)$" (12)

thus showing that δ, the deviation from the perfect correlation (or anti-correlation) can be discounted.[43]

This is not the inequality tested by the experiment they go on to outline, nor was it tested in the experiment FC later carried out . This inequality is for a two channel experiment not conducted until Alain Aspect's team did so in 1982.[44] Given that in the experiment they are proposing to conduct the expectation value P(a,b,) depends on the difference between the angles a and b, CHSH rewrite their inequality as

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[42] CHSH p.881

[43] "In CHSH, a small amount of departure from perfect correlation is allowed. This is called δ; the authors ..... are able to show that the main results is independent of the value of δ." Whitaker, *The New Quantum Age*.p.168. They do so by expressing the value of δ implied by their assumption of cases for which the correlation is less than perfect, i.e., P(b´,b)= 1-δ i.e., δ=1-P(b´,b) and insert this for δ in equation 10 which gives them an equation without δ.

[44] Alain Aspect. P. Grangier and Gérard Roger. "Experimental Realization of Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*: A New Violation of Bell's Inequalities," *Physical Review Letters* 49, no. 2 (1982):91-94.

$$\left|P(\alpha)-P(\alpha+\beta)\right| \leq 2-P(\gamma)-P(\beta+\gamma) \tag{13}$$

where $\alpha \equiv b-a$, $\beta \equiv c-b$ & $\gamma \equiv c-b$. While the authors could be seen here as putting into the inequality the nonlocality they are seeking to test, given all that has gone before, we must assume that they mean that P (a,b) depends on the angle of a affecting only the measurement at A and b the measurement at B etc.,.

3.1.2 Deriving an Inequality for Realizable Experiments

This inequality derived "for realizable experiments" was still a step too far for the technology of the time. It assumes that the number of detected particles is the same the total number of particles emerging from the analyzers, a condition that if the particles are optical photons was impossible to meet, given that the detectors had far less than 100% efficiency. Had detectors been 100% efficient, the inequality "would apply directly to experimental counting rates"[45] in a two channel test where ±1 would be defined as detection or non-detection of a photon in the relevant channels at each side of the experiment. As detectors did not have anywhere near that accuracy, Thus, the original CHSH inequality "is not an experimentally testable inequality."[46]

They then devised an experimental set up that they knew was acheivable and an inequality that could be tested by it. Their subsequent argument had four stages:
1) A(a)= ±1 and B(b) = ±1 now refer to the emergence or non emergence of a photon from a filter, one on each side of the experiment.

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[45] CHSH p.881
[46] Fry and Walther. "Atom Based Tests of the Bell Inequalities — the Legacy of John Bell Continues."p.105

2) The filters in question are now linear polarization filters with a and b referring to their orientations and the 'measurement' being the absorption or non-absorption of the photon.
3) An exceptional value of ∞ is introduced to represent the removal of a polarization filter. This necessarily means that A(∞) and B(∞) are equal to +1, as with the polarization filter removed, a photon will emerge.
4) Now that P(a,b) is an emergence correlation function, an extra assumption has to be made in order to derive an experimental prediction, namely that "if a pair of photons emerges from Ia and IIb the probability of their joint detection is independent of a or b. Then if the flux into Ia IIb is a constant independent of a and b, the rate of detection R(a,b) will be proportional to w[A(a)+, B(b)+], where w[A(a)±, B(b)±] is the probability that A(a) = ±1 and B(b) = ±1."[47] Fry and Walther, confusingly, call this the CHSH assumption:[48] confusingly named, because it is not needed where the original CHSH inequality is being used. This assumption about the emergence of a pair of photons from the detectors being independent of the detector settings is necessary only when using the inequality specifically adapted to the then currently realizable experimental conditions, where there are two sides of the experiment but the only choice in each side is emergence or non-emergence. Whitaker explains it, "The assumption in this case is that the probability of both of a pair of entangled photons being detected is entirely independent of whether polarizers are present in either wing, or, in cases where they are, the direction of either axis of polarization. In other words, the probability of a photon being detected can be treated as a constant, and since, in fact, we will be dealing with

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[47] CHSH p.881
[48] Fry, and Walther."Atom Based Tests of the Bell Inequalities — the Legacy of John Bell Continues."pp.104-5

the ratios of numbers of events in different cases,[49] this constant can be ignored."[50]

CHSH then derive a version of their original inequality on the basis of these preconditions for experiments using optical photons. They define the following terms:

$R_0 = R(\infty,\infty) \qquad R_1(a) = R(a,\infty) \qquad R_2(b) = R(\infty,b)$

and state the following "evident"[51] formulas:

$$P(a,b) = w\left[A(a)_{+,} B(b)_{+}\right] - w\left[A(a)_{+,} B(b)_{-}\right] - \left[A(a)_{-,} B(b)_{+}\right] + \left[A(a)_{-,} B(b)_{-}\right] \tag{14}$$

$$w\left[A(a)_{+,} B(\infty)\right] = w\left[A(a)_{+,} B(b)_{+}\right] + w\left[A(a)_{+} B(b)_{-}\right] \tag{15}$$

and similar formulas for $w\left[A(\infty)_{+,} B(b)_{+}\right]$ and $w\left[A(\infty)_{+,} B(\infty)_{+}\right]$

obtaining, by substitution and the cancelling out of redundant terms,

$$P(a,b) = \frac{4R(a,b)}{R_0} - \frac{2R_1(a)}{R_0} - \frac{2R_2(b)}{R_0} + 1 \tag{16}$$

They write "We can now express (1) [the original CHSH inequality] in terms of experimental quantities, namely coincidence rates with both polarizers in and with one and then the other removed. If R_1 (a) and R_2 (b) are found experimentally to be constants R_1 and R_2, the result is

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[49] i.e. four runs of the experiment at each polarizer angle, one with no polarizers, one with each polarizer alone in turn and one with both polarizer's present.

[50] Whitaker. *The New Quantum Age*. p168. This cannot be experimentally demonstrated, see Franco Selleri and G Tarozzi. "Quantum Mechanics Reality and Separability," *Rivista del Nuovo Cimento* 4, no. 2 (1981):1-53.p.380, while one hidden variable theory, semi-classical radiation theory explicitly denies it, see Clauser, and Shimony. "Bell's Theorem:Experimental Tests and Implications." pp1912-1913.

[51] CHSH p.882

$$\left|R(a,b)-R(a,c)\right|+R(b',b)+R(b',c)-R_1-R_2\leq 0 \text{ (2a)}$$ [52]. (17)

In the special case in which P (a,b) = P(a-b), (2a) becomes

$$\left|R(a)-R(\alpha+\beta)\right|+R(\gamma)+R(\beta+\gamma)-R_1-R_2\leq 0 \quad \text{(2b)"}$$ [53] (18)

where $\alpha \equiv$ b-a; $\beta \equiv$ c-b; and $\gamma \equiv$ b-b' and R_1 is the coincidence rate with the second polarizer removed and R_2 that with the first polarizer removed.

The authors then describe a "realizable apparatus" where "quantum mechanics predicts the violation of inequality (2b)."[54] Despite Bell refering to BA's thought experiment,[55] which BA say the experiment of WS instantiates, CHSH explain that WS's experiment is unsuitable for their purpose and explain why. The CHSH inequality requires the experimental results to be framed as a choice between two options. WS can be arranged to do that but, even so, could not discriminate between the predictions generated by a local hidden variable theory and the predictions of quantum mechanics, as Horne pointed out in his unpublished PhD thesis.[56] CHSH therefore noted Kocher and Commins

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[52] CHSH p.882, see Franco Selleri. *Quantum Paradoxes and Physical Reality*, vol. 35, Fundamental Theories of Physics, Dordrecht/Boston/London: Kluwer Academic Publishers, (1990).:216-220. The original inequality is re-arranged so that all the quantities are to the left of the inequality sign. Then expressions for each of the correlation functions of the form (16) are substituted in it, and bearing in mind that R_0 =1, and assuming that, as Clauser, Horne, Shimony and Holt say, R_1 and R_2 are constants, this then can be reduced and rearranged as above.

[53] CHSH p.882

[54] CHSH p.882

[55] Bell 1964 p.195

[56] Abner Shimony. "Experimental Test of Local Hidden Variables," in *Foundations of Quantum Mechanics. (Proceedings of the International School of Physics "Enrico Fermi" Vol IL)*, ed. Bernard d'Espagnat Varenna (1971).p185

recent experiment,[57] an equivalent experimental methodology using similarly dichotomitic parameters, in which, although the polarizers were not set at angles at which the predictions of quantum mechanics would violate the bounds set by the inequality (2b), they could be arranged to do so.[58]

CHSH indicate the quantum mechanical predictions for their proposed experiment[59] and note the relative angles of the polarizers for two versions of KC at which these predictions maximally violate the equality they have just derived. "The greatest violations always occur at α=22.5°, β=45 °, γ=157.5° for the 0-1-0 cascade and α=67.5°, β=135°, γ=112.5° for the 0-1-1 cascade. Note that in each case the four angles, α, $\alpha+\beta$, γ, and $\beta+\gamma$ which occur in Inequality (2b) characterize

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57 i.e.KC. Shimony notes "Snider and Pritchard brought to our attention the experiment of Kocher and Commins." Shimony, "Experimental Test of Local Hidden Variables."p.185.

58 KC, like WS before them, were attempting to record the correlations most clearly and therefore the relative angles they chose were different from those chosen by Clauser, Horne, Shimony and Holt who needed to choose those that showed the greatest distinction between the quantum mechanical predictions and the amended CHSH inequality.

59 Based on work done by Horne and Freedman, each in their unpublished PhD theses, Michael A Horne. "Experimental Consequences of Local Hidden Variable Theories (Unpublished)" Boston University, (1970).; Stuart J Freedman. "Lawrence Berkeley Laboratory Report No Lbl-391 (Unpublished)" University of California, (1972). See Stuart J. Freedman, et al. "Experimental Status of Hidden Variable Theories," in *Quantum Mechanics, Determinism, Causality and Particles. An International Collection of Contributions in Honor of Louis De Broglie on the Occasion of the Jubilee of His Celebrated Thesis*, ed. M. Flato, Z. Maric, D. Sternheiemer, and J.P. Vigier Dodrecht,Boston: D.Reidel Publishing Company, (1976).p.53 The calculated predictions include the efficiencies of the polarizers, as outlined by Snyder, Pasternack and Hornbostel in their 1948 paper (Hartland S Snyder, Simon Pasternack and J. Hornbostel. "Angular Correlation of Scattered Annihilation Radiation," *Physical Review* 73, no. 5 (1948)pp.440-48.) which, along with that of Pryce and Ward (M.H.L. Pryce, and J.C. Ward, "Angular Correlation Effects With Annihilation Radiation," *Nature* 160, no. 4065 (1947)pp.435.) were the original theorists in this area.

only two distinct relative orientations of the polarizers, namely 22.5° and 67.5°."[60]

However there are still limitations imposed by real equipment. The quantum mechanical predictions quoted by CHSH have to include a function which "represents a depolarization due to non-collinearity of the two photons, and approaches unity for infinitesmal detector solid angles."[61] As Shimony later explained "the total angular momentum 0 of the two-photon system is accomplished by the coupling of orbital and spin angular momentum, and increasing the orbital contribution (by increasing θ) has the effect of dampening the correlations of polarization."[62] But Shimony confirms that "even for large enough θ to permit a good counting rate, the range of P_{qm} (α) is sufficient to yield a discrepancy with Bell's inequality."[63] In any real experiment, it must be taken into account because θ is never equal to 0. Likewise, no polarizers are 100% efficient. So, for their proposed experiment, at the relative angles they have outlined, with calcite polarizers, there is a relationship between the specific angles they use and the efficiency of the parellel polarizer that must be fulfilled should the experiment be suitable to test the amended CHSH inequality. They plot out the requisite area demonstrating what angles can be used with what efficiency of polarizer and close the paper with the recommendation of which sort of polarizers to use for best effect. All that is now required is for an experiment to be carried out.

3:2 Conceptual Backgrounds to CHSH

In order to derive a testable form of Bell's inequality, CHSH has to have a specific experimental arrangement in mind, an arrangement capable of testing the inequality but also producing the existents the

60 CHSH p.883
61 FC
62 Shimony, "Experimental Test of Local Hidden Variables."p.188
63 Shimony, "Experimental Test of Local Hidden Variables."p.188

behaviour of which is to be tested. Paying attention to the conceptual streams upon which CHSH drew and to how streams of experimental apparatus designed on the basis of one theory are pressed into service to examine quite another reveals the complex interrelationship of theory and practice. How scientists construct meanings cannot be understood unless the details of the complex interrelationship between theory and experiment are examined.

CHSH begin by situating themselves within the context of EPR. They use BA's "paradox" rather then EPR's "contradiction"[64] without comment and wrongly attribute the word to Bohr.[65] CHSH note the "no hidden parameters"[66] proofs for which they cite Bell's 1966 paper[67] and link this to Bell 1964 by saying "Bell succeeded in replacing these postulates by a physically reasonable condition of locality."[68] This is an elision that Bell did not make. He simply alluded to his disposal of the proofs to validate the usefulness of what he was setting out to achieve. This tells us two things. Firstly, we should remember not to take on trust what authors of one scientific paper say about papers upon which they rely because they may be relying on what they take to be the underlying argument rather than upon the specific details of the papers in question. Secondly, it confirms that CHSH considered the assumption of locality to be the main underpinning of Bell's own inequality. CHSH continue, "[Bell] showed that in a gedankenexperiment of Bohm (a variant of that of EPR) no local hidden-variable theory can reproduce all of the statistical predictions of quantum mechanics."[69] This statement is almost accurate. Bell did show that no local hidden variable theory could replicate the statistical

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64 EPR p.779
65 n.b. Bohr uses the adjective "paradoxical" not the noun "paradox."
66 Von Neumann referred to them as "dispersion free" because adding variables to the quantum mechanical description would mean that the result of each measurement would always be specific.
67 Bell, "On the Problem of Hidden Variables in Quantum Mechanics."
68 CHSH p.880
69 CHSH p.880

predictions of quantum mechanics [70] and the thought experiment to which Bell refers was the one from Bohm. However, Bell refers to the version in BA.[71] While this misascription of the reference may not be significant, it is a reminder not to take statements on trust.

CHSH say they present "a generalization of Bell's theorem[72] applicable to realizable experiments."[73] They demonstrate how a slight alteration to one of the two experiments that has "realized" Bohm's thought experiment can provide "a decisive test."[74] This seamless shifting between Bohm's thought experiment, their reworking of Bell's inequality and a generalization of an experiment that had already been developed is not quite as straight forward as this sentence would have us believe. Bohm's thought experiment, BA's first thought experiment, the one which Bell references, was a thought experiment that was conceptualised using spin half particles and therefore not the experiment that BA say was instantiated in WS. Bell adopts this first thought experiment of BA's and so is careful in his paper only to refer to the spin half particle thought experiment and thus makes no reference to the specific experiments that had been conducted and which BA adduce as evidence that a more accurate experiment along the same lines could be conducted. CHSH show no such reticence.

In their section on "Existing experimental results," CHSH note that Bohm's thought experiment with spin half particles, which Bell references is not realizable and refer to two "related experiments ... on polarization correlation of photons:"[75] one the WS experiment, which was the one to which BA refer, the other the more recent experiment of KC. While CHSH conclude that the WS is not suitable, they included

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[70] Bell 1964 p.199
[71] Bell 1964 p.195
[72] It is clear that CHSH mean the inequality when they refer to Bell's theorem.
[73] CHSH p.881
[74] CHSH p.881
[75] CHSH p.882

it in their paper because BA adduce it as evidence that the predictions of quantum theory hold. Although they do not use WS' methodology, it is upon WS theory bases that KC and therefore CHSH depend and so its inclusion is doubly important. Neither WS nor KC "has produced evidence against local hidden-variable theories."[76] CHSH explain why the WS experimental methodology cannot be adapted to provide "a decisive test"[77] and then outline an experiment based on KC's methodology to test inequality.

3:2:1 The Paper of Kocher and Commins[78]

KC sets out to verify whether EPR's thought experiment occurs in practice rather than simply being a prediction of quantum theory.[79] What is noted tentatively only in Kocher's PhD thesis outlining the experiment, is that it may very well have been the first experiment to test the polarisation orientation of photons emitted in an atomic cascade experiment.[80] While Kocher notes Bell 1964, he does not consider of the relevance of their results for it. It is CHSH who enfold KC into their project of designing and conducting an experiment to test a Bell-type inequality. In his thesis, Kocher specifically eschews interest in testing whether or not a hidden variable theory is possible: ".. it may well be argued that a hidden variable model contributes little to our understanding of nature if the new theory cannot be distinguished experimentally from standard quantum theory."[81]

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76 CHSH p.881
77 CHSH p.881
78 KC
79 KC p.575
80 Berol L. Robinson and L. Mandansky. "Polarization Correlations of the Gamma-Rays of Cs^{134} and of Annhilation Radiation," *Physical Review* 88 (1952):1065.p.63
81 Carl Alvin Kocher, "Polarization Correlation of Photons Emitted in an Atomic Cascade" (University of California, 1967).p.72

We shall follow the stages of KC's discussion and note the theory bases they assume along the way. Experiments in the quantum domain rely on theory for every stage of their performance. They rely on theory to describe the nature of the things they are using to produce the existents to be tested. They need theory to outline what they take to be happening as they perform certain actions on these existents and they need theory to predict what results will occur should they submit these existents to a procedure. They rely also on the theory upon which the design of the experimental equipment is based and while consideration of this is beyond the scope of this thesis, it is nevertheless an important point to bear in mind. KC lay out what their experiment demonstrates in their succinct opening sentence: "We describe observations of the correlation in linear polarization of two successive photons emitted in the cascade $6^1S_0 \rightarrow 4^1P_1 \rightarrow 4^1S_0$."[82] However they turn immediately to a different experiment, an annihilation experiment, a methodology which they did not use, but an experiment in which the correlation in linear polarization of two photons that they use in their own experiment has already been both theoretically and experimentally established. Surprisingly the conceptual background of their own experiment is not explored at all. This raises two issues: why did KC choose to elide their experiment with the theory base of another another quite different experiment rather than their own and what were the conceptual bases of the experiment that they did conduct. While KC does not provide the answers for these questions, there is a fuller report of the KC experiment in Kocher's PhD thesis in which Kocher does indicate the theory behind the experiment's methodology.[83] Kocher writes, "Quantum theory predicts that a measurement of the linear polarization of one photon can determine precisely the linear

[82] KC p.575
[83] Kocher. "Polarization Correlation of Photons Emitted in an Atomic Cascade."pp6-11

polarization of the other photon."[84] It is clear in Kocher's thesis that they choose the cascade method not because of any conceptual differences with WS's methodology but, because the photons emitted in the atomic cascade, unlike those in WS, would be emitted in the part of spectrum that made their detection by "conventional photomultipliers and linear polarizers of the Polaroid type"[85] possible. However, if we are looking for a theoretical explanation of the correlation of photon polarization in a cascade as opposed to in an annihilation experiment, we will be disappointed. Despite using an entirely different methodology, the theory used to conceptualise the photon correlations with which Kocher begins his thesis is still the theory base behind the account of the correlations of photons emitted simultaneously by annihilation. There is a precedent for this elision in Robinson and Kandinsky's paper which he cites[86] although he does not mention this. He simply notes, in the first Appendix to his thesis, that Robinson and Kandinsky's is the only example in the literature he can find where the linear polarization has been directly measured rather than inferred.[87] Kocher's theory section opens with the words, "the theory of photon polarization is well known"[88] and states he will discuss two approaches to the problem. "The first consists of an explicit demonstration that the conservation laws of angular momentum and parity imply a definite correlation in the photon polarizations"[89] for which he references three works: "Feynman

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[84] Kocher. "Polarization Correlation of Photons Emitted in an Atomic Cascade."p1

[85] KC p.575

[86] Robinson and Mandansky. "Polarization Correlations of the Gamma-Rays of Cs^{134} and of Annihilation Radiation.". WS infer it from Compton scattering.

[87] Kocher. "Polarization Correlation of Photons Emitted in an Atomic Cascade."p.63

[88] Kocher. "Polarization Correlation of Photons Emitted in an Atomic Cascade."p.6

[89] Kocher."Polarization Correlation of Photons Emitted in an Atomic Cascade."p.6

Lectures on Physics 1965 Vol III";[90] John Wheeler's "Polyelectrons"[91] & Yang's "Selection Rules for the Dematerialization of a Particle into Two Photons."[92] However all of these are describing the emission of photons simultaneously by annihilation not successively by cascade.[93] Only with the second approach does Kocher discuss the polarization correlation of his method cascade method. For this, he cites Biedenharn and Rose's 1953 paper[94] and Frauenfelder and Steffen's chapter in "Alpha, Beta and Gamma Ray Spectroscopy Vol II"[95] both on angular correlations. Even though he gives no evidence or rationale, Kocher is clear that the first method, based on Wheeler and on Yang's discussion of photons emitted simultaneously in annhilation can be equally applied to the photons emitted successively in the calcium cascade. [96] Don Hamilton had proposed that the same directional correlation would be observed in the emission of successive photons as was observed in the emission of simultaneous photons in annihilation radiation[97] but Kocker does not mention this.

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[90] Richard Feynman, R.B. Leighton and M.Sands. *The Feynman Lectures on Physics Vol III* Addison-Wesley, (1965).
[91] John Archibald Wheeler. "Polyelectrons," *Annals of the New York Academy of Sciences* 48 (1946):219-38.
[92] C.N Yang. "Selection Rules for the Dematerialization of a Particle Into Two Photons," *Physical Review* 77, no. 2 (1950):242-45.
[93] Feynman, R.B. Leighton and M.Sands. *The Feynman Lectures on Physics Vol III*.p.18-5; Wheeler, "Polyelectrons." pp.226-228; Yang, "Selection Rules for the Dematerialization of a Particle Into Two Photons." p.242
[94] L.C. Biedenharn and Morris E. Rose. "Theory of Angular Correlation of Nuclear Radiations," *Review of Modern Physics* 25 (1953):729.
[95] H. Frauenfelder and R.M Steffen. "Chapter XIX, Section 9: Angular Correlations," in *Alpha, Beta and Gamma Ray Spectroscopy Vol II*, ed. K Siegbahn Amsterdam: North Holland Publishing Company, (1966).
[96] Kocher. "Polarization Correlation of Photons Emitted in an Atomic Cascade."p.7
[97] The title of the paper refers to the emission of quanta but in the abstract as well as the body of the paper the emission of gamma radiation is specifically dealt with.

When describing how the results will be assessed, Kocher refers to Bates and Damgaard's 1949 paper[98] and to Glennon and Wiese's 92 page bibliography of papers detailing specific cascades[99] both of which provide details of atomic transitions. Kocher lists 66 items in his bibliography so his experiment is clearly not short of theoretical and practical underpinnings but as Jensen and Markushin later note much of what passed for the theoretical underpinning of cascade experiments at that time were "phenomenological cascade models that [were fitted] to the data with some *ad hoc* parameters."[100] The three papers KC cite that make reference to atomic cascade rather than annihilation experiments, apart from Bates and Damgaard,[101] are those of Smith and Gallagher[102], Kaul[103] and Frauenfelder and Steffen.[104] All of these papers are cited to back up decisions made by KC in the way they took measurements rather than providing any theoretical underpining for KC's assumption that the theory that gives an account of the correlation in the linear polarization of photons simultaneously emitted in annihilation experiments can be assumed as accounting for the similar correlation in the linear polarization of photons successively emitted in cascade experiments. Frauenfelder and

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98 D.R. Bates and Agnete Damgaard. "The Calculation of the Absolute Strengths of Spectral Lines," *Philosophical Transactions of the Royal Society A* 242, no. 842 (1949):101-22.
99 B.M. Glennon and W.L. Wiese. *Bibliography on Atomic Transition Probabilities* Washington: National Bureau of Standards. Institute of Basic Standards, (1966).
100 T.S. Jensen and V.E. Markushin, "Atomic Cascade and Precision Physics," in *Precision Physics of Simple Atomic Systems*, ed. Saverley G. Karsenboim and Valery B. Kirschov Springer, (2003).pp.54-5
101 Bates, and Damgaard. "The Calculation of the Absolute Strengths of Spectral Lines."
102 Winthrop W. Smith and Alan Gallagher. "Radiative Lifetime of the First $2p^{3/2}$ State of Ionized Calcium and Magnesium By the Hanle Effect," *Physical Review* 145 (1966):26.
103 R.D. Kaul. "Observations of Optical Photons in Cascade," *Journal of the Optical Society of America* 56, no. 9 (1966):1262.
104 Frauenfelder and Steffen. "Chapter XIX, Section 9: Angular Correlations."

Steffen's paper[105] outline what happens when a magnetic field is applied perpendicular to the detector axis and is cited by KC to account for what happens in their experiment when the polarizers are removed.[106]

Despite the KC experiment being a cascade experiment, the theory upon which they rely for the conceptualisation of their experiment, what is happening and what they are testing, remains the theory base of the annihilation experiment of WS. KC cites Yang's 1950 paper[107] and the experiments of Bleuler and Bradt[108] and WS itself. This is not a minor point given that CHSH are not seeking to demonstrate that something happens but to extrapolate from what happens to make claims about the underlying physical reality. This requires a strong conceptual base. It is therefore to the complex and interconnecting conceptual and experimental threads that underlie the annihilation experiment of WS upon which KC rely that we must look next.

3.2.1.1 The WS Experiment

WS reported their experiment"[109] as the climax of a discussion. They performed an experiment originally suggested by John A. Wheeler,[110] to test "a prediction of pair theory that the two quanta emitted in the annhilation of a positron-electron pair, with zero relative angular

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[105] Frauenfelder and Steffen "Chapter XIX, Section 9: Angular Correlations."
[106] KC p.576
[107] Yang. "Selection Rules for the Dematerialization of a Particle Into Two Photons."
[108] E Bleuler and H.L. Bradt. "Correlation Between the States of Polarization of the Two Quanta of Annihilation Radiation," *Physical Review* 73 (1948):1398.
[109] WS p.136.
[110] developed further by Pryce and Ward. "Angular Correlation Effects With Annihilation Radiation." & Snyder, Pasternack & Hornbostel. "Angular Correlation of Scattered Annihilation Radiation."

momentum, are polarized at right angles to each other."[111] Since the earlier experiments testing Wheeler's prediction, the precision of the equipment available had increased and Wu and Shakov had hoped, by an increase in the coincidence counting rate, to be able to demonstrate more solidly the orthoganal polarization of the emitted photons. It is this increase their paper reports.

3.2.1.1.1. WS Theoretical Bases

The theoretical/experimental stream that Wu and Shaknov's experiment ended begins in several disparate places: Pauli[112] at Zurich, Dirac, Blackett and Occhalini in Cambridge, Anderson and Millikan at Caltech, Oppenheimer in California.[113] These distinct strands begin to coalesce with Blackett and Occhalini's interpretation of Carl Anderson's 1932 paper[114] in terms of Dirac's relativistic theory of the electron.[115] Anderson discussed three photographs taken of the charged particles produced by cosmic rays. Anderson's photographs, interpreted in terms of particles and tracks, and taken in a Wilson Cloud Chamber, rely on further tranches of theory which we are going to have to assume. Nevertheless, it is important to note this.

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[111] WS p.136

[112] To start with, Pauli hated Dirac's theory of holes, see a letter, 19th April 1933, to Blackett see Jagdish Mehra, and Helmut Rechenberg, *The Conceptual Completion and Extensions of Quantum Mechanics 1932-1941. Epilogue: Aspects of the Further Development of Quantum Theory 1942-1999* New York: Springer-Verlag, (2001).p.916 n1027 Dirac could not have framed the theory without Pauli's exclusion principle.

[113] Dirac noted in1984 that "people had been obtaining pictures of radioactive sources emitting positrons without realising what they were. Several had even been published." P.A.M. Dirac, "Blackett and the Positron," in *Cambridge Physics in the Thirties*, ed. John Hendry Bristol: Adam Hilger, (1984).p.62

[114] Carl D. Anderson. "The Apparent Existence of Easily Deflectable Positives," *Science* 76, no. 1967 (1932):238-39.

[115] For a history of the electron see Arabatzis, *Representing Electrons: A Biographical Approach to Theoretical Entities*..

Until Anderson's paper, "a positive electron has always been found with an associated mass 1,850 times that associated with the negative electron"[116] i.e. a proton, as Dirac had predicted. Weyl convinced Dirac that, while the overall theory is right, the positive particle cannot be a proton[117] and that the hole with positive energy identified in his 1930 paper, must have the same mass as an ordinary electron. Carl Anderson was later to find them, without creating them or looking for them. By Anderson's own admission,[118] although he had heard of Dirac's theory, the experiment in which the anti-electron was discovered was based on a completely different theory and looking to answer a completely different research question. The theory was that of Robert Millikan and the positive charges in the cloud chamber photographs, detected since late 1931, could be explained in Millikan's framework by suggesting the ejection of protons following the "disintegration of the nucleus."[119] It was this theory that Anderson was testing. The first examination of the data was aimed at looking for evidence that would decide between the photon hypothesis of Millikan (that cosmic rays were photons and were incident upon the nucleus of

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116 Anderson, "The Apparent Existence of Easily Deflectable Positives."
117 Dirac cites Hermann Weyl. *Gruppentheorie Und Quantenmechanik (2nd Edition)* Leipzig: Verlag von S. Hirzel, (1931).p.234. see pp.262-3 of the Dover paperback translation Hermann Weyl, *The Theory of Groups and Quantum Mechanics,* trans. H P Robertson. New York: Dover Publications, (1931). Dirac emends his book, "The Principles of Quantum Mechanics" accordingly see Helge Kragh. "Paul Dirac and the Principles of Quantum Mechanics," in *Reseach and Pedagogy. A History of Quantum Physics Through Its Textbooks* Edition Open Access: Max Planck Research Library for the History and Development of Knowledge, (2013).p.258
118 see Anderson, Carl D. "Early Work on the Positron and Muon," *American Journal of Physics* 29 (1961):825-30. and Anderson, Carl D."Oral History Transcript- Dr. Carl Anderson," *Niels Bohr Library and Archives, American institute of Physics, College Park, MD, USA* (1966).
119 Matteo Leoni. "Theory Vs. Experiment: The Case of the Positron," in *Frontiers of Fundamental Physics and Physics Education Research*, ed. Burra G. Sidharth, Marisa Michelini, and Lorenzo Santi. Springer Proceedings in Physics Vol 145 Springer, (2014).p.2, of the online version of his paper, first given as a talk at 12th Frontiers of Fundamental Physics symposium, November 21-23, 2011 at Udini.

elements causing their disintegration) and the neutron hypothesis of Chadwick (that neutrons were emitted when an atom was bombarded with α-particles[120]) to provide evidence to back Millikan's atom building theory.[121] In his first solo paper published three months later, Anderson says "It is concluded, therefore, that the positives can only be protons"[122] because his main concern is still to validate Millikan's atom building theory. It is only in the third paper on these photographs, and Anderson' second solo paper on the subject, that a different account emerges in the article's tantalising opening sentence, "Up to the present a positive electron has always been found with an associated mass 1,850 times that associated with the negative electron."[123] The title of the article, "The Apparent Existence of Easily Deflectable Positives" suggests Anderson is still hedging his bets but in this article he states for the first time, "the masses of these particles must be small compared to the mass of the proton"[124] and concludes quite categorically, "The interpretation of tracks as due to protons, or other heavier nuclei, is ruled out on the basis of range and curvature....... indicating a positively-charged particle comparable in mass and magnitude of charge with an electron."[125] While this positive particle is being discussed, its discovery is a spin off from Anderson's work on Millikan's theory of cosmic rays not on Dirac's electron theory. Anderson proposed that the existence of negative electrons,

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[120] Alpha particles are equivalent to helium atoms, consisting of two protons and two neutrons http://www.epa.gov/radiation/understand/alpha.html#discovered accessed 6th May 2015

[121] Robert A. Millikan and Anderson, Carl D. "Cosmic-Ray Energies and Their Bearing on the Photon and Neutron Hypotheses," *Physical Review* 40, no. 3 (1932):325-28.p.327

[122] Carl D. Anderson. "Energies of Cosmic Ray Particles," *Physical Review* 41, no. 4 (1932):405-21.p.418

[123] Anderson. "The Apparent Existence of Easily Deflectable Positives." p.238

[124] Anderson. "The Apparent Existence of Easily Deflectable Positives." p.238

[125] Anderson. "The Apparent Existence of Easily Deflectable Positives." p.239

positrons, as they became known, was the best interpretation of the photographed tracks although does not mention Dirac. Anderson notes that while preparing his paper, he had seen press reports of Blackett and Occhialini's evidence confirming the existence of a positive electron.[126] Blackett and Occhialini had made the link with Dirac's theory[127] noting that Dirac's account explains the rarity of these particles.[128] Their paper announces their improved method for taking cosmic ray photographs[129] and discusses the photographs.

Pair theory, encompassing pair creation/production and pair annihilation, was the name given to Dirac's prediction of a positively charged anti-electron, once Anderson's photograph's had been interpreted as depicting this.[130] Dirac repeated his suggestion that the idea could be tested experimentally by arranging for pairs of ultra-high energy photons to collide: if the theory were correct, in some of these collisions the photons would disappear and an electron would appear with an anti-electron,'[131] a "process subsequently called 'pair

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[126] P.M.S. Blackett, and G.P.S. Occhialini. "Some Photographs of the Tracks of Penetrating Radiation," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science* 139 (1933):699-719.p.703

[127] On p.714, they cite P.A.M. Dirac. "A Theory of Electrons and Protons," *Proceedings of the Royal Society of London Series A Containing Papers of a Mathematical or Physical Character* 126, no. 801 (1930):360-65.; P.A.M. Dirac. "Quantised Singularities in the Electromagnetic Field," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science* 133 (1931):60-72.

[128] On pp.362-3 of Dirac, "A Theory of Electrons and Protons," Dirac's account makes it clear that the word "particle" must be used circumspectly. Particles are not little bullets but that which can be represented "by a three dimensional wave-function."

[129] Blackett, and Occhialini. "Some Photographs of the Tracks of Penetrating Radiation."p.699-701

[130] For a clear explanation of both pair creation and annilation, see Victor F. Weisskopf. "Recent Developments in the Theory of the Electron," *Reviews of Modern Physics* 21, no. 2 (1949):305-315.pp.310-311

[131] Graham Farmelo. *The Strangest Man. The Hidden Life of Paul Dirac Quantum Genius* London: Faber and Faber, (2009).p.195, quoting from, P.A.M. Dirac. "Lectures on Quantum Mechanics Reported By B.

production.'"[132] By 1935, pair production[133] and annihilation are an acknowledged and researched phenomena[134] and by 1936, Heitler has written up the theory in the fourth chapter of the first edition of his text book, "The Quantum Theory of Radiation."[135] In 1946 however, Wheeler notes that "Pair theory is still in the course of development."[136] He makes two suggestions for experiments to test some predictions of pair theory. The experiment that Wu and Shaknov perform is the second and simpler of Wheeler's suggestions. Wheeler explains, "We have already remarked that by far the dominating type of annihilation is that in which the positron combines with an electron whose spin forms a singlet state with respect to the spin of the positron. Associated with this selection of pairs which have zero relative angular momentum before the annihilation process, is an analagous polarization phenomenon in the two quanta which are left at the end of the process."[137] The word analagous for Wheeler points to a commonality between the singlet state of the electron and positron pair with regard to their spin before the annihilation and the polarization of the photons emitted during it. The singlet state refers to the spin property of the electron while the polarization phenomenon of the photons means that "if one of these photons is linearly polarized in one plane, then the photon which goes off in the opposite direction with equal momentum is linearly polarized in the perpendicular

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Hoffman," *Mimeographed, Library, Institute of Advanced Study* (1931)pp.134. Farmelo references them as Dirac Papers 2/26/15 (FSU). A copy of the notes are kept at the Churchill Archive Centre Cambridge DRAC 2/9 Lectures on Quantum Mechanics given at Princeton October 1931

[132] Ray Monk. *Inside the Centre: The Work of J. Robert Oppenheimer* London: Jonathan Cape, (2012).p.192

[133] Pascual Jordan. "Quantum Electrodynamics. Regarding the Theory of Pair Production," *Zeitschrift für Physik* 96, no. 3-4 (1934):163-66.

[134] J.C. Jaegar. "Pair Production By Magnetic Multipole Radiation," *Mathematical Proceedings of the Cambridge Philosophical Society* 31, no. 4 (1935):609-11.

[135] W Heitler. *The Quantum Theory of Radiation*, International Series of Monographs on Physics Oxford: Oxford University Press, (1936).

[136] Wheeler. "Polyelectrons."pp.221-2

[137] Wheeler. "Polyelectrons."pp.234-5

plane."[138] Wheeler's suggested experiment would test whether or not this "analagous polarization phenomenon in the two quanta which are left at the end of the process" occurs. It is this point, originally pointed out by Heitler,[139] that Wu and Shaknov, set out to prove and which their experiment successfully demonstrated. The polarizations of photons emitted in the annihilation are orthogonally polarized. WS lies at the end of this particular stream because it draws from the work of others who had sought to prove the same point and because it is considered conclusive. However, because of Wheeler's use of the word "analagous," for Bohm and Aharonov, working in a completely different theoretical/experimental stream, and having a thought experiment with spin half particles in the singlet state in mind, Wu and Shaknov's experiment offers a means to test whether or not the the prediction of quantum theory that a measurement conducted on one system can be used to predict the outcome of a measurement of another system with which it has once interacted, a prediction that EPR used as a stepping stone in their argument demonstrating that quantum theory is incomplete, occurs in practice : and all because of the word "analagous."

Testing for the orthogonal polarization of the photons predicted by pair theory involves an experimental design based upon further theory. Just as Wu and Shaknov's experiment, once considered conclusive, can then be put to use in designing the means by which to test further and distinct theories, as Bohm and Aharonov go on to suggest, so Wu and Shaknov themselves, as Wheeler before them in his thought experiment, relied on experimental design, drawn from experiments considered conclusive in previous experimental/theoretical streams. They tested a prediction of pair theory using "coincidence measurements of the scattering of both the annihilation photons at various azimuths" using Compton Scattering

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138 Wheeler. "Polyelectrons."pp.235
139 Heitler. *The Quantum Theory of Radiation*.p.271

with its own theoretical/experimental stream which we will not follow up but is important to note. This also involves an anomaly:[140] the concept of photons is derived from the light quantum theory while polarization is a wave phenomenon. An anomaly is no less an anomaly because the community is entirely used to and comfortable with it. It reminds us that the stability of produced effects is not evidence for the ontological value of the pictorial language which acts as a convenient shorthand for communication and for model making or conceptualisation that facilitates the production of an overall and comprehensive account of what is. This is of particular importance for theologians because it is the production of meaning in science with which they most usually engage.

Until Einstein published in 1905 what he described as his "very revolutionary"[141] paper in which he "takes what looks like a dreary fragment of the thermodynamics of heat radiation....... [and] converts this expression into a simple, probabilistic formula whose unavoidable interpretation is that the energy of radiation is spatially localized in finitely many, independent points,"[142] the consensus in the scientific community for two hundred years had been that light was a wave phenomenon. This was still widely held in 1920 when, in his speech accepting his Noble Prize, Charles G. Barkla said "All this evidence seems to indicate that a quantum of radiation in the sense in which has frequently been used, i.e. as an indivisible bundle of radiation energy,

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[140] Compton discusses the wave-particle duality of light and suggests de Broglie's pilot wave theory as a means of resolving it Arthur H. Compton. "The Corpuscular Properties of Light," *Reviews of Modern Physics* 1, no. 1 (1929): 74-89.p.86; p.88. Bohr sees it rather as an example of an inescapable property of our descriptions in quantum physics, that a space-time and an energy/momentum picture are mutually exclusive.

[141] John D. Norton. "Atoms. Entropy, Quanta: Einstein's Miraculous Argument of 1905," *Studies in History and Philosophy of Modern Physics* 37 (2006):71-100.p.72 where Norton quotes from Einstein's letter of May 1905 to his friend Conrad Habicht.

[142] Norton. "Atoms. Entropy, Quanta: Einstein's Miraculous Argument of 1905."p.72

does not exist. The process of radiation may be, and is, continuous."[143] But the evidence was mounting against this position. In December 1922, Arthur H. Compton presented an abstract of a paper[144] to the American Physical Society which sketched what was to become known as the Compton effect[145] in which he carefully enunciates the quantum theory of light. As Compton later summarizes, "Experiments on the photoelectric effect and on scattered x-rays, taken together with these experiments on the individual interactions of radiation and electrons, show therefore that the radiation is emitted in units, is progated in definite directions, and is absorbed again in units of undiminished energy. Light thus has all the essential characteristics of particles."[146] Immediately, Compton adds, "it is well known however that light has the characteristics of waves. The phenomena of reflection, refraction, polarization and interference, which occur with light, can leave no reasonable doubt about its wave properties."[147] As Bohr notes twenty years later, the wave-particle duality of light is not simply a case of using the metaphor of wave or particle independently depending on the problem under discussion. The duality is intrinsic to the very definition of a photon. "Notwithstanding its fertility, the idea of the photon implied a quite unforeseen dilemma, since any simple corpuscular picture of radiation would obviously be irreconcilable with interference effects, which present so essential an aspect of radiative phenomena, and which can be described only in terms of a wave picture. The acuteness of the dilemma is stressed by the fact that the interference effects offer our only means of defining the concepts

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143 Charles G. Barkla. "Characteristic Röntgen Radiation," in *Nobel Lectures in Physics 1901-1920*, ed. Stig Lundqvist Singapore: World Scientific (1998).p.397

144 Compton. "A Quantum Theory of the Scattering of X Rays By Light Elements."

145 It is also known as the Compton-Debye effect because it was independently discovered in early 1923 by Peter Debye Peter Josseph Wilhelm Debye. "Zerstreuung Von Röntgenstrahlen Und Quantentheorie," *Physikalische Zeitschrift* 24 (1923):161-66..

146 Compton. "The Corpuscular Properties of Light."p.86

147 Compton."The Corpuscular Properties of Light."p.86

of frequency and wave-length entering into the very expression for the energy and momentum of the photon."[148] This complexity is important to remember when assessing what is going on in experiments proposed or carried out on photons to test Bell-type inequalities.

This discursus into the theoretical work and presuppositions that underlay the experimental design that is taken for granted by KC and by Kasday, Ullman and Wu,[149] Holt and Pipkin,[150] FC and all the many many photons based tests of Bell-type inequalities after them has not been given so as to undermine confidence in the results of the FC or any experiments that followed. It is simply to show how, whenever they are later used to support or undermine a particular experimental position, facts established by experiment have to be understood in the light of all the various theories that underlie both the theory and technical design of the experiments by which they have been established. This is not an underhand way of taking sides as to whether or not or which ontology underlies quantum experiments, simply a reminder that the word "measure" in the quantum context is a loaded word. D'Espagnat's concept of a "fabricated ontology" is useful in this regard:[151] continuing research in physics is possible because physicists use concepts to refer to experimental results in order to think about them coherently and to work with them, whether as theoreticians or experimentalists. D'Espagnat's stricture that the reification of these concepts should be clearly understood as a research strategy rather than a research conclusion is an important one to bear in mind, "We ascribe to such words as "particles" etc novel

148 Bohr. "Discussion With Einstein on Epistemological Problems in Atomic Physics."p.203

149 Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons."; L R Kasday, J.D. Ullman & C.S. Wu "Angular Correlation of Compton-Scattered Annihilation Photons and Hidden Variables," *Nuovo Cimento* 25, no. 2 (1975)pp.633-61.

150 Richard A. Holt and Francis M. Pipkin. "Harvard Preprint," (1974).

151 Bernard d'Espagnat. *On Physics and Philosophy* Princeton and Oxford: Princeton University Press, (2006).p.281

meanings because we are aware of a historical continuity between classical and contemporary physics and it is only by means of such an extension that we can, without logical inconsistency, consider the latter to be a continuation of the former……. And those ….. who feel unable to conceive that rationality can be exerted independently of a materialist world-view should be encouraged to keep to the latter. The only request that should be addressed to them is that they should refrain from converting their choice into an illegitimate doctrinal creed."[152] For the purposes of understanding WS and its importance for KC and therefore for CHSH and all the subsequent experimentation with photons on Bell-type inequalities which is still in progress it is important to be aware of the complexity of deriving the possibility of ontological reality from experimental results. As Einstein reminded the young Heisenberg, "It is the theory which decides what we can observe."[153] Thus, however tempting it is, when we use the word "photon," we cannot presume anything about the nature of light or posit the existence of a neat little bullet of light. By using the word "photon," we are stepping into a whole web of theory, interpretation and experiment from which we cannot extricate ourselves. After all as Bohr has reminded us, concepts that belong entirely to the thought world of waves are used in the very definition of what a photon as a particle is. [154]

Discussions about the nature of what, if anything, lies behind the experimental procedures by means of which photons are photons are still current in the literature.[155] When trying to attempt to interpret

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[152] d'Espagnat. *On Physics and Philosophy*.p.281
[153] Heisenberg. *Physics and Beyond Encounters and Conversations*.p.63
[154] Bohr. "Discussion With Einstein on Epistemological Problems in Atomic Physics."p.203
[155] E.g., Daniel Mirrell and Stuart Mirrell. "Macroscopic Violation of Duality Generaled on a Laser Beam," *Journal of Modern Physics* 4, no. 7 (2013):911-22.; Mario Rabinowitz. "Challenges to Bohr's Wave-Particle Complementarity Principle," *International Journal of Theoretical Physics* 52, no. 2 (2013):668-78.

the meaning of an experiment rather than eludicate a further use for the technology, we have to remember that the theory base for theoretical physics is a web of often divergent assumptions that enables us to act. This is not to preclude the possibility of understanding what lies behind experiment, that would be to take a side, but it behoves us to bear in mind the complexity of asking what seems like a simple question, "what does it mean?"

This is not to suggest that by using photons rather than electrons to enact the EPR thought experiment or by positioning themselves within the annihilation trajectory within which WS are anchored rather than their own atomic cascade world view KC are doing anything underhand or misleading. It is simply a reminder that experiments derive their existents, their apparatus, their methodologies and their justifications from the vast array of scientific thought that precedes them and that experiments are always conducted with a purpose.

CHSH are as keen as KC themselves to see the KC experiment within the same conceptual nexus as WS because it is WS that BA cite. They make the elision between WS and KC by introducing both of them together, "two related experiments have been performed."[156] Having done so, they point out why the WS methodology, even adapted to their dichotomitic inequality, can never produce a violation of it and so they are able to move over seamlessly to the related experiment, KC. It hasn't produced data that would violate CHSH's final inequality but, there are angles at which the polarizations could be measured which are capable of violating the inequality. They end the paper specifying which the crucial angles are and point out the difference between results with coated polarizers that reduce reflection and those which don't.

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[156] CHSH p.882

The next stage for Clauser and for Pipkin is putting this theory into practice. Clauser goes on to perform an experiment with a doctoral student, Stuart Freedman, while Holt carries on the experiment he had been working on with his supervisor, Pipkin

Chapter Four: Bell-type Experiments

CHSH marks the start of the journey to test Bell's inequality. To bring out some of the salient features as to how meaning is and has been constructed on the basis of Bell's work, relevant to any theological consideration, I pay attention to the experimental and theoretical work that has stemmed from Bell 1964. This chapter will be in three parts. In part one, I shall detail the first seven experiments conducted.[1] Part two will be a brief overview of the new fields of quantum theory that Bell 1964 has engendered and in part three, we shall look at five recent experiments, explaining why Bell-type inequalities are still being tested.

4.1: The First Seven Experiments

4.1.1: Kasday, Ullman and Wu.

The first experiment carried out to test a Bell-type inequality was reported on by Kasday in 1970.[2] "Using Compton scattering, we measured the relative linear polarizations of the photons emitted when a positron annihilates at rest in a metal. The results were in

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[1] Kasday, Ullman & Wu. "The Einstein-Podolsky-Rosen Argument: Positron Annhilation Experiment."; Kasday, "Experimental Test of Quantum Predictions for Widely Separated Photons."; Kasday, Ullman & Wu."Angular Correlation of Compton-Scattered Annihilation Photons and Hidden Variables."; Holt, and Pipkin. "Harvard Preprint."; John F Clauser. "Experimental Investigation of a Polarization Correlation Anomaly," *Physical Review Letters* 36, no. 21 (1976):1223-26.; Edward S Fry and Randell C Thompson. "Experimental Test of Local Hidden-Variable Theories," *Physical Review Letters* 37, no. 8 (1976):465-68.; G Faraci, D. Gutkowski, S. Nottarigo & A.R. Penisi. "An Experimental Test of the EPR Paradox," *Lettere al Nuovo Cimento* 9 (1974)pp.607-11.; FC; Lamehi-Rachti and Mittig "Quantum Mechanics and Hidden Variables: A Test of Bell's Inequality By the Measurement of the Spin Correlation in Low-Energy Proton-Proton Scattering."

[2] Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons."

agreement with the quantum predictions."[3] A report on the experiment was published in April 1970 in the Bulletin of the American Physical Society.[4]

Kasday, Ullman and Wu's strategy is interesting. They conduct the experiment and gather the data, but they then interrogate the data using different assumptions and through the varying conceptual lenses.[5] They tested against three theoretical scenarios: firstly, against the quantum mechanical predictions for the experiment, which, as Kasday notes, assumes the existence of ideal analyzers;[6] secondly, against the local hidden variable theory predictions, with the assumption of ideal analyzers common to quantum theory but with the additional assumption that the the quantum theoretical relationship between an experiment conducted directly on the annihilation radiation with ideal analyzers and with those obtained by Compton analyzers on scattered radiation holds and finally, again making the two assumptions outlined above, against the Bohm and Aharonov version of the Schrödinger-Furry conjecture that the relationship between the two systems that had previously interacted breaks down beyond a certain distance.[7]

Utilising the WS methodology, the experiment rests on WS's theory. More work had been done in the area since WS, and this is reflected in Kasday's bibliography.[8] After outlining the quantum mechanical

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[3] Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons."p.195
[4] Kasday, Ullman & Wu. "The Einstein-Podolsky-Rosen Argument: Positron Annhilation Experiment."
[5] Kasday, "Experimental Test of Quantum Predictions for Widely Separated Photons."pp.206-7
[6] Kasday, "Experimental Test of Quantum Predictions for Widely Separated Photons."p.198
[7] BA p.1074
[8] i.e G Bertolini, M. Bettoni & E. Luzzarini. "Angular Correlation of Scattered Annihilation Radiation," *Nuovo Cimento* 2 (1955)pp.661-62.; H Langhoff. "Die Linearpolarisation Der Vernichtungsstrahlung Von

predictions for the experiment, Kasday sums up Bell's motivation and then summarizes Bell's inequality and stresses again that the quantum mechanical prediction implies the use of ideal linear polarization analyzers. This is a condition that cannot be met in practice, and therefore the measurements on the polarization of the photons are made by Compton scattering for which the appropriate technology is available. However this requires extra assumptions if the data produced could, even in theory, violate the Bell inequality. [9]

In a private communication to Kasday, Bell showed that a local hidden variable model that assumes that "correlation between the scattering events at the two detectors arises from their joint dependence on a single hidden variable uniformly distributed between 0 and 2π reproduces the quantum predictions for all momentum measurements that could be made on the two scattered photons. Hence, unless additional assumptions were made, agreement of the experimental results with quantum predictions would be consistent with a local hidden variable theory."[10] However, as Kasday notes in the paper's first appendix, this model of Bell fails for photons of lower energies.[11]

When Kasday, Ullman and Wu's data is tested in the second scenario, with the two assumptions, against a Bell-type inequality, the inequality is violated. Clauser and Shimony later explain why they consider the second assumption, that the the quantum theoretical relationship between an experiment conducted directly on the annihilation radiation with ideal analyzers and with those obtained by

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Positron," *Zeitschrift für Physik* 160 (1960)pp.186-93. see Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons."p.209.

[9] Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons."pp.198-9

[10] Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons."p.199

[11] Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons."p.208

Compton analyzers on scattered radiation holds, is too strong: "in a quantum-mechanical treatment of the problem, the photons are acknowledged not to be in a state of definite polarisation. Quantum mechanically, neither photon's polarisation is in a definite state, but each is in what is known as an 'improper mixture' of such states ...... In quantum theory, the only correct procedure for handling such systems is to perform calculations for the composite two-photon state. Thus we see that the 'marriage' between quantum mechanics and a general local realistic theory required by assumption (ii) results in a fatally incorrect handling of both theories."[12] In his 1970 seminar, Kasday had not outlined the assumption fully but it was comprehensively explained in the 1975 paper where Kasday, Ullman and Wu conclude their experiment "proves what we set out to show that there exists a function relating.. the probability of a photon Compton scattering in the direction k and the average output of an ideal analyzer oriented along the x′-axis.''[13] They state that the credibility of this assumption derives from Synder, Pasternack and Hornbostel's analysis in 1948.[14] Nevertheless, despite defending the assumption, the authors do not claim that the results of this experiment rule out local hidden variable theories. However, they do not think their own experiment is alone in this regard: "no experiment done with currently available technology could lead to such a definite conclusion."[15] In Bell's 1976 assessment of the first seven experiments carried out, he agreed with them. Kasday,

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[12] Clauser, and Shimony,."Bell's Theorem:Experimental Tests and Implications."p.1917

[13] Kasday, Ullman & Wu. "Angular Correlation of Compton-Scattered Annihilation Photons and Hidden Variables."p.658. Kasday first outlined the proof in his PhD thesis. Clauser and Shimony were aware of it when they wrote their 1978 report and were not convinced.

[14] Snyder, Pasternak & Hornbostel. "Angular Correlation of Scattered Annihilation Radiation."p.447 outlined in Kasday, Ullman & Wu. "Angular Correlation of Compton-Scattered Annihilation Photons and Hidden Variables."p.652.

[15] Kasday, Ullman & Wu. "Angular Correlation of Compton-Scattered Annihilation Photons and Hidden Variables."p.654

Ullman and Wu's experiment[16] is spoken in the same terms as that of FC. Of Kasday, Ullman and Wu, Bell concludes, it is "(in the extrapolated sense) in significant disagreement with the inequality, "[17] while of FC, he says, it "(in the sense of some extrapolation) disagree[s] significantly with the locality inequality."[18]

It was Kasday who first pointed out in this seminar that a local model in which the photons can be imagined as "deciding in advance" how they will respond to any of the measurements that could be carried out can never reproduce quantum mechanical predictions for these ideal measurements because some of these measurements are noncommuting. "Quantum theory does not supply a joint probability function .... for noncommuting observables, so the model cannot be constructed as above."[19] This is a point that later becomes very significant in the discussions amongst mathematicians, physicists, and philosophers as to what the violations of Bell-type inequalities might mean.

4:1:2 Cascade Experiments with Mercury: To Publish or not to Publish

Before Clauser, Horne, Shimony and Holt had teamed up, Holt was working on an experiment to test Bell's inequality using methodology akin to KC's based on a recent experiment of Nussbaum and Pipkin.[20] Pipkin and Holt continued with this project and carried out the

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16 Kasday, Ullman & Wu. "Angular Correlation of Compton-Scattered Annihilation Photons and Hidden Variables."
17 Bell. "Einstein-Podolsky-Rosen Experiments."p.87
18 Bell. "Einstein-Podolsky-Rosen Experiments."p.88
19 Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons."
20 Clauser. "Early History of Bell's Theorem."p.80. Pipkin at Harvard had performed an experiment similar to KC and it was this that Holt was using as a model. Gilbert H Nussbaum, and Francis M. Pipkin. "Correlation of Photons in Cascade and the Coherence Time of the 6_3P_1," *Physical Review Letters* 19, no. 19 (1967):1089-1092.

experiment but did not publish because their data did not violate Bell's inequality and disagreed with quantum theory. They circulated a preprint.[21] As with KC, the correlated photons in their experiment were produced by transitions in an atomic casade, but like Nussbaum and Pipkin, with mercury not calcium. A full account of Pipkin and Holt's unpublished experiment is given in Clauser and Shimony's review paper.[22] Pipkin and Holt were not expecting a discrepancy with quantum mechanical predictions and, even though they could find nothing wrong, they did not trust the result. In 1974, Pipkin said they were still perplexed as to why their experiment had not violated Bell's inequality[23] and this perplexity was general at the time of Bell's conference address in 1976 in which he alluded to it,[24] especially since Clauser's 1976 repeat of the experiment had violated the inequality.[25] While Clauser had noted differences between his experiment and Pipkin and Holt's, he could not pinpoint why the two experiments had had different outcomes.[26] In 1978, Clauser and Shimony put the discrepancy down to a flaw in Pipkin and Holt's equipment[27] but in 2005 Holt was still unclear.[28] In 1976, Edward S. Fry and Randall C. Thompson conducted a cascade experiment with mercury which, like

[21] Clauser. "Early History of Bell's Theorem."p.81
[22] Clauser, and Shimony."Bell's Theorem: Experimental Tests and Implications."pp1909-1911
[23] Olival Freire Jnr,.*The Quantum Dissidents: Rebuilding the Foundations of Quantum Mechanics* Springer, (2014).p.259n50
[24] Bell. "Einstein-Podolsky-Rosen Experiments."p.88
[25] Clauser, and Shimony."Bell's Theorem:Experimental Tests and Implications."pp.1910-11
[26] Clauser. "Experimental Investigation of a Polarization Correlation Anomaly."p.1225
[27] Clauser and Shimony,."Bell's Theorem: Experimental Tests and Implications."p.1910
[28] Freire Jnr. *The Quantum Dissidents: Rebuilding the Foundations of Quantum Mechanics*. p.263n62. Friere references a personal communication from Holt on 21st March 2005 and states he believed, at the time of writing "The Quantum Dissidents," that this remained Holt's position.

Clauser's, violated the inequality.[29] Fry and Randall's experiment was ground-breaking, because they had used a "C.W. single line tunable [sic] laser (a quite rare instrument at that time). Their signal was several order of magnitude larger than in previous experiments, allowing them to collect the relevant data in a period of 80 minutes."[30] Clauser's experiment, conducted in the same year, had taken 412 hours.[31]

4.1.3 Back to Annihilation Photons

Pipkin and Holt's was not the only experiment conducted in the 1970s to respect Bell's inequality. In 1974, Faraci, Gutowski, Nottarigo and Pennisi conducted an experiment, like Kasday, Ullman and Wu, with annihilation photons. They were not attempting to test Bell's inequality but they included the curve predicted by it and found that their measurements followed Bell's predicted curve, contradicting the predictions of quantum theory. In a talk given in 1975, Bell said their experiment is "in dramatic disagreement with quantum mechanics!"[32] and, in 1976, notes there was still no agreement as to why the Kasday, Ullman and Wu[33] experiment and the Faraci, Gutowski, Nottarigo and Pennisi,[34] both annihilation experiments where the polarization correlation was measured by Compton scattering, should have

[29] Fry, and Thompson. "Experimental Test of Local Hidden-Variable Theories."
[30] Alain Aspect. "Experimental Tests of Bell's Inequalities With Correlated Photons," in *Waves, Inofrmation and Foundations of Physics Conference Proceedings of the Italian Physical Society Vol 60*, ed. R Pratesi, and L Ronchi Bologna: The Italian Physical Society, (1998).p.363
[31] Clauser. "Experimental Investigation of a Polarization Correlation Anomaly."p.1225
[32] John S Bell. "The Theory of Local Beables" (Paper presented at the Presented at the sixth GIFT Seminar, Jaca 2-7 June 1975, Geneva, 1975).p.10
[33] Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons."
[34] Faraci, Gutkowski, Nottarigo & Penisi. "An Experimental Test of the EPR Paradox."

produced such different results. In their 1975 paper Kasday, Ullman and Wu make suggestions as to why Faraci et al's [35] correlation rates may be overstated.[36] Other annihilation experiments were done in the mid 1970s and the results were found in agreement with quantum mechanics.[37]

4.1.4 Freedman and Clauser

Freedman and Clauser's experiment was the first of the experiments to violate a Bell-type inequality without resorting to assumptions that were considered unreasonable, so it is seen now as the iconic experiment that, once and for all, demonstrated what was to become clearer and clearer as the experimental results piled up, that the predictions of quantum mechanics would hold. In the 1970s, however, it was discussed alongside the other experiments conducted to test Bell-type inequalities.[38] Clauser and Freedman took two years to design, build and test their experimental apparatus and two months to run the experiment published in April 1972, the third experiment to test a Bell-type inequality and the first published experiment to report an experimental violation of a Bell-type inequality using photons emitted successively in an atomic cascade in calcium. The results depend on three assumptions, that "for any local hidden variable theory: (1) The two photons propagate as separated localized particles. (2) A binary selection process occurs for each photon at each polarizer (transmission or no-transmission). This selection does not depend upon the orientation of the distant polarizer. In addition, we make the following assumption to allow a comparison of the

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[35] Faraci, Gutkowski, Nottarigo & Penisi. "An Experimental Test of the Epr Paradox."
[36] Kasday, Ullman & Wu. "Angular Correlation of Compton-Scattered Annihilation Photons and Hidden Variables."p.660
[37] i.e., A.R. Wilson, J. Lowe & D.K.Butt. "Measurement of the Relative Planes of Polarization of Annihilation Quanta as a Function of the Distance," *Journal of Physics G: Nuclear Physics 2* (1976):613-24.; M. Bruno, M. d'Agostini & C. Maroni. *Nuovo Cimento* 40 (1977):B142-52.
[38] E.g. see Bell, "Einstein-Podolsky-Rosen Experiments."p.88

generalization of Bell's inequality with out [sic] experiment: (3) All photons incident on a detector have a probability of detection that is independent of whether or not the photon has passed through a polarizer."[39] However, despite these assumptions, FC pull no punches: "This Letter reports the results of an experiment which are sufficiently precise to rule out local hidden variable theories with high statistical accuracy."[40] Their methodology was similar to KC's and they footnote both KC and Kocher's thesis.[41] They describe the experimental arrangement and note the efficency or otherwise of the equipment they use. They detail any calculations that are needed to compensate for real equipment being less than ideal. They conclude, "we observe no evidence for a deviation from the predictions of quantum mechanics, calculated from the measured polarization efficiencies and solid angles,..... We consider the results to be strong evidence against local hidden variable theories."[42] However, despite the important place that this experiment holds in the tradition of Bell scholarship, in 1976, Bell himself clearly regarded the FC experiment as no more conclusive than Kasday's. On account of the practical difficulties involved in the case of experiments with optical photons, Bell observes, "there is no question of actually realising a system which violates the locality inequality."[43] For Bell there is a clear distinction between confirming the prediction of quantum mechanics, which Kasday, Ullman and Wu,[44] Clauser's re-running of Pipkin and Holt's,[45] and FC do and ruling out local hidden variable theories theories definitively. For this the bar is set much higher and what Bell hopes for, in this regard, is an

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[39] FC p.939
[40] FC p.939
[41] FC p.941n8
[42] FC p.940
[43] Bell. "Einstein-Podolsky-Rosen Experiments."p.88
[44] Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons."; Kasday, Ullman & Wu. "Angular Correlation of Compton-Scattered Annihilation Photons and Hidden Variables."
[45] Clauser. "Experimental Investigation of a Polarization Correlation Anomaly."

experiment “in which the settings of the polarizers are changed while the photons are in flight.”[46]

4.1.5 An experiment on the spin correlation in proton-proton scattering

The last in the series of the first generation of experiments is the only one conducted on the spin properties of particles, as Bohm[47] and later as BA originally envisaged. The next experiment that did so was not conducted until 2001.[48] Lamehi-Rachti and Mittig’s paper outlines Bell’s 1971 derivation of his inequality and its background. [49] They describe an ideal experiment based on Bohm’s version of the EPR thought experiment and work out the quantum mechanical prediction for this ideal experiment in which the analyzer settings are switched during the flight time of the particles.[50] They outline the experiments of Kasday [51] and FC, pointing out the practical advantages of using atomic rather than annihilation photons. However, they draw attention to the conceptual problems of using photons in an experiment designed to test against the parameters of local hidden variable model. “Photons cannot be localized by a Lorentz transformation. One can attribute to photons a length, the coherence length $l=c\tau$, where c is the speed of light and τ the mean life of the state

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[46] Bell 1964 p.199
[47] David Bohm. *Quantum Theory* Englewood Cliffs NJ: Prentice-Hall, (1951).p.614
[48] Rowe, et al. “Experimental Violation of a Bell’s Inequality With Efficient Detection.”
[49] Bell. “Introduction to the Hidden Variable Question.” see Lamehi-Rachti and Mittig. “Quantum Mechanics and Hidden Variables: A Test of Bell’s Inequality By the Measurement of the Spin Correlation in Low-Energy Proton-Proton Scattering.”pp.2543-4
[50] Lamehi-Rachti, and Mittig “Quantum Mechanics and Hidden Variables: A Test of Bell’s Inequality By the Measurement of the Spin Correlation in Low-Energy Proton-Proton Scattering.”pp.2544-5
[51] Kasday. “Experimental Test of Quantum Predictions for Widely Separated Photons.” see Lamehi-Rachti and Mittig. “Quantum Mechanics and Hidden Variables: A Test of Bell’s Inequality By the Measurement of the Spin Correlation in Low-Energy Proton-Proton Scattering.”p.2545.

which produced the photon. For experiments with annihilation γ rays this length is ∼17cm and ∼300cm for the atomic cascade case. These dimensions are comparable to or bigger than the dimension of the apparatus used and therefore it is not clear that the condition of localization is respected."[52] This undermines the rationale for testing a Bell inequality with photons. The paper has been cited 274 times [53] but it is not clear whether this point has ever been answered. Testing Bell inequalities with photons continues to the present.[54] Lamehi-Rachti and Mittig describe their own experimental apparatus and methodology and outline their three assumptions: that it is possible to construct an ideal apparatus; that the experiment not fulfilling the conditions of spacelike separation does not affect the experimental results; and that the analyzing power and transmission of the measuring apparatus can be considered as constants of the apparatus and not correlated with the parameters, λ, that determine the results of the experiments. They point out that this last assumption is also common to the experiments conducted with photons. The final assumption would not be needed in an experiment that included the use of a 90° (electrostatic) deflector before one of the polarimeters. They acknowledge that the assumptions used in a test with photons are also necessary with their experimental design but that the problems with defining locality in experiments with protons does not arise. They conducted a Monte Carlo simulation of the expected experimental results based on a perfect realisation of the experimental design against which to test the gathered data. Not only did their data match well with data produced by the simulation, it confirmed the predictions of quantum mechanics, but they acknowledge, as did Bell,

[52] Lamehi-Rachti and Mittig "Quantum Mechanics and Hidden Variables: A Test of Bell's Inequality By the Measurement of the Spin Correlation in Low-Energy Proton-Proton Scattering."p.2546
[53] According to Google Scholar, accessed on 26th August 2018
[54] J H Eberly. "Bell Inequalties and Quantum Mechanics," *American Journal of Physics* 70, no. 3 (2002):276-79.

that this is not the same as violating the inequality[55] and conclude, "it would be interesting to find some other type of experiment where it could be more easy to fulfill these conditions."[56] In their 1978 review article, Clauser and Shimony do not discuss Lamehi-Rachti and Mittig's question as to the suitability of testing a locality inequality with photons, which are by definition not localized, but state that, given Lamehi-Rachti and Mittig's heavy reliance on assumptions in interpreting their data, the problems that Clauser and Shimony had noted with regard to the experiments on the polarization of annihilation photons is even more applicable to this experiment with protons.

A great deal was learned during the first generation of experiments and, as Bell noted, if experimental results in this broad range of experiments, with all their acknowledged faults were in line with the predictions of quantum mechanics, save for two results, it would be"an extraordinary conspiracy'[57] were this not to be the case should better experiments be performed. However Bell called for further experiments in which the setting of the polarizers were changed while the particles were in flight. Clauser and Shimony acknowledge that this would not be conclusive but would nevertheless render extrapolations from experimental results about the nature of the world more secure.[58]

4:1:6 The Orsay Experiments

In 1982, Alain Aspect's team reported experiments using time varying analyzers in which the detector settings were changed while the

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[55] Bell. "Einstein-Podolsky-Rosen Experiments."p.88
[56] Lamehi-Rachti and Mittig. "Quantum Mechanics and Hidden Variables: A Test of Bell's Inequality By the Measurement of the Spin Correlation in Low-Energy Proton-Proton Scattering."p.2554
[57] Bell. "Einstein-Podolsky-Rosen Experiments."p.87
[58] Clauser and Shimony. "Bell's Theorem: Experimental Tests and Implications."p.1921

photons were in flight.[59] They note the experiments done to date "clearly favour quantum mechanics,"[60] observe that the experiments using visible photons emitted in atomic cascades have "achieve[d] a good realizations of the ideal Gedankenexperiment."[61] They outline the drawback of these experiments, drawn attention to in Bell 1964: "The settings of the instruments are made sufficiently in advance to allow them to reach some mutual rapport by exchange of signals with velocity less than or equal to that of light."[62] They suggest the use of time-variable analyzers to solve this problem. In later parlance, this would be framed as closing a loophole. In 1978, Clauser and Shimony had noted that in theoretical terms it would always be impossible to close this loophole but that this inability casts a pall over all scientific experiments not simply those testing a Bell-type inequality.[63]

Aspect, Dalibard and Roger outline their set up and reframe the CHSH inequality to cover the specifics of the data gathered. They outline their methodology particularly how the switching between polarizers has been achieved. They note that this adjustment has meant a lowering of collection efficiencies, which, as Lamehi-Rachti and Mittig pointed out, was already a problem in atomic cascade experiments.[64] They note the change in polarizer settings is not truly random making an additional assumption that they function in an uncorrelated way

[59] Aspect, Dalibard & Roger. "Experimental Test of Bell Inequalities Using Time-Varying Analyzers."
[60] Aspect, Dalibard & Roger. "Experimental Test of Bell Inequalities Using Time-Varying Analyzers."p.1805
[61] Aspect, Dalibard & Roger. "Experimental Test of Bell Inequalities Using Time-Varying Analyzers."p.1805
[62] Aspect, Dalibard & Roger. "Experimental Test of Bell Inequalities Using Time-Varying Analyzers."p.1805
[63] Clauser, and Shimony. "Bell's Theorem:Experimental Tests and Implications."p.1921
[64] Lamehi-Rachti and Mittig. "Quantum Mechanics and Hidden Variables: A Test of Bell's Inequality By the Measurement of the Spin Correlation in Low-Energy Proton-Proton Scattering."pp.2545-6

necessary. The team outline how they deal with this statistically[65] and conclude, "our observed violation of Bell's inequalities indicates that the experimental accuracy was good enough for pointing out a hypothetical discrepancy with the prediction of quantum mechanics. No such effect was observed."[66] Bell hoped that the use of time varying analyzers would increase the reliability of the observed violations of Bell-type inequalities. In fact, it revealed further possibilities by which nature might have evaded capture and attempts to close down these loopholes in Bell-type experiments continue. In 2018, an experiment testing a Bell-type inequality, using computer input from people all over the world was reported to ensure the random nature of the analyzer switching.[67] Such experiments have opened up new fields of theoretical research and have developed the potential of the technology. They started as a means to test a contention of Bell's that any attempt to complete the quantum mechanical description would have to do so with a "nonlocal" mechanism, but as the years have passed more interest is being shown in what quantum mechanics allows scientists to do than how it contributes to our understanding of how the world is.

4.2 New Research Areas Opened Up

In the subject index of Tony Hey and Patrick Walters "The Quantum Universe, "[68] published in 2003, the word "entanglement" doesn't feature, although a small discussion of it can be found in the sections on quantum computers,[69] quantum cryptography,[70] and quantum

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[65] Aspect, Dalibard & Roger. "Experimental Test of Bell Inequalities Using Time-Varying Analyzers."p.1806
[66] Aspect, Dalibard & Roger. "Experimental Test of Bell Inequalities Using Time-Varying Analyzers."p.1807
[67] The BIG Bell Test Collaboration. "Challenging Local Realism With Human Choices," *Nature* 557 (2018):212-22.
[68] Tony Hey and Patrick Walters. *The New Quantum Universe* Cambridge: Cambridge University Press, (2003).
[69] Hey and Walters. *The New Quantum Universe*.pp194-203; pp305-9
[70] Hey and Walters. *The New Quantum Universe*.pp197-204

teleportation.[71] Quantum information isn't in the index despite its five page section. Once the Orsay experiments with time varying analyzers had been interpreted as evidence of nonlocal effects, the attention of many who were convinced that Bell's inequality had been violated, turned from what this nonlocality meant to what could it do.[72] In 1981, Richard Feynman had linked EPR to the possibilities of quantum computing[73] and in August 1984, Charles H Bennett and G. Brassard said that the Aspect, Grangier and Roger experiment made quantum cryptography, "within reach of the current technology."[74] That "God did not create photons as a storage medium, but rather as a communications device"[75] had been a driving force in the thinking about the design of secure means of quantum encryptions but in this paper, Bennett and Brassard note the practical possibilities of the Aspect experiments. Later that year, Bennett and Brassard noted how "the Einstein-Podolsky-Rosen (EPR) effect …. Often called a paradox"[76] offers the possibility of cheating when setting up a quantum encryption scheme based on photon polarization"[77] footnoting the

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[71] Hey, and Walters. *The New Quantum Universe*.pp.204-206
[72] QBism, an interpretation of quantum theory in which the experimental violations of Bell-type inequalities are not about the onotology of the quantum world but about our interaction with it.
[73] Richard Feynman, "Simulating Physics With Computers," *International Journal of Theoretical Physics* 21, no. 6/7 (1981):467-88.
[74] Charles H. Bennett and G Brassard, "An Update on Quantum Cryptography," in *Advances in Cryptography:Proceedings of Crypto 84,* ed. George Robert Blakley, and David Chaum, Berlin, Heidelberg, New York, Tokyo: Springer-Verlag, (1985):475-480
[75] Bennett, and Brassard. "An Update on Quantum Cryptography." p.476
[76] Charles H. Bennett, and G Brassard. "Quantum Cryptography: Public Key Distribution and Coin Tossing," *Proceedings of the IEEE International Conference on Computers, Systems, and Signal Processing, Bangalore*:175-179p.179
[77] Charles H. Bennett, G. Brassard, Seth Breidbart & Stephen J. Wiesner. "Quantum Cryptography or Unforgeable Subway Token's," in *Advances in Cryptology:Proceedings of Crypto 82,* ed. David Chaum, Ronald L. Rivests, and Alan T. Sherman. Berlin: Springer-Verlag, (1983):267-275. In this paper the phrase quantum cryptography was coined, G Brassard, "Brief History of Quantum Cryptography: A

Aspect, Grangier and Roger experiment not as evidence of the violations of Bell-type inequalities but the practical realization of the EPR effect.[78] EPR and the Aspect, Grangier and Roger[79] experiment realizing it are in the quantum cryptography literature by the mid 1980s but it is Artur Ekert that explicitly includes Bell in 1991.[80] Ekert noting the significance of Bell's work was not surprising but doing so while accepting the completeness of quantum mechanics, the very thing the EPR thought experiment was adduced to undermine, was. Bell's inequality was derived to test whether a particular feature of Bohm's theoretical completion of quantum mechanics was a necessary feature of any theory attempting to complete it but Ekert saw the potential of what the Orsay experiments did rather than focusing on what they meant. He wrote, "In this paper I will present a method in which the security of the so-called key distribution process in cryptography depends on the completeness of quantum mechanics. Here completeness means that the quantum description provides maximum possible information about any system under consideration."[81] Ekert decided to bracket what Bell-type experiments meant and enfolded them into a different theoretical and practical enterprise by concentrating on what they could do. He suggested a modification of the experimental methodology so it could provide a way of ensuring secure data transfer. Ekert placed Bell's theoretical work and the experimental work of Aspect and his team within the conceptual ambit of Bennett and Brassard's insight that "God did not create photons as a storage medium, but rather as a communications

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Personal Perspective," (2005):1-14 https://arxiv.org/pdf/quant-ph/0604072.pdf .p.3

78 Bennett and Brassard. "Quantum Cryptography: Public Key Distribution and Coin Tossing."p.179

79 Aspect, Grangier & Roger. "Experimental Realization of Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*: A New Violation of Bell's Inequalities."

80 Artur Ekert. "Quantum Cryptography Based on Bell's Theorem," *Physical Review Letters* 67, no. 6 (1991):661-63. see Brassard. "Brief History of Quantum Cryptography: A Personal Perspective."p.6

81 Ekert. "Quantum Cryptography Based on Bell's Theorem."p.661

device"[82] thereby, "changing the main objective of the experiment."[83] Ekert's work showed a use for Bell-type experiments that those who developed them had not anticipated but he had not so much changed the experiments' conceptual base as taken sides. What Ekert and those working in the wider field of quantum information have done is to embrace one of the many options of what the experimental violations of Bell-type inequalities mean and then run with it. In a rather sweeping statement, Wiseman explains it thus, "Correlations … called Bell correlations were verified experimentally more than 30 years ago…. this leaves two options for the nature of reality. The first is that reality is irreducibly random, meaning that there are no hidden variables that 'determine the results of individual measurements.' The second option is that reality is 'non-local', meaning "the setting of one measuring device can influence the reading of another instrument, however remote. Most physicists are localists…. Quantum information scientists embrace irreducible randomness as a resource for secure cryptography."[84] As Whitaker notes, "around 1994 ….entanglement, instead of being a worry, something to explain away, became an 'information resource.'"[85]

Quantum cryptography was not the only use to which EPR states or entanglement was put. In 1993, Bennett et al[86] discussed the process by which quantum information could be "teleported."[87] They

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[82] Bennett, and Brassard."An Update on Quantum Cryptography.p.476
[83] Ekert. "Quantum Cryptography Based on Bell's Theorem."p.663.
[84] H M Wiseman. "Bell's Theorem Still Reverberates," *Nature* 510 (2014):467-69.p.467-8.
[85] Whitaker. *The New Quantum Age*.p.332. Whitaker quotes A.M. Steane. "Quantum Computing" *Reports on Progress in Physics* 61 (1998):117-73.
[86] Charles H. Bennett, Gilles Brassard, Claude Crépeau, Richard Jozsa, Asher Peres & William K. Wooters. "Teleporting an Unknown Quantum State Via Dual Classical and Einstein-Podolsky-Rosen Channels," *Physical Review Letters* 70 (1993):1895.
[87] Bennett, et al. "Teleporting an Unknown Quantum State Via Dual Classical and Einstein-Podolsky-Rosen Channels."

demonstrated how “an unknown quantum state |φ⟩ can be disassembled into, then later reconstructed from, purely classical information and purely nonclassical EPR correlations.”[88] It was becoming clearer how “quantum entanglement is an information resource.”[89] By 1994, Weinfurter noted two methods of quantum communication that Bennett and colleagues had suggested, encoding two bits of information in a single two state particle alongside quantum teleportation. For this to become a used resource rather than a theoretical hope, Weinfurter pointed out that the EPR particles and their correlations would need to be stored[90] and he suggested a technique that would enable this but one that was only possible with photons produced by parametric down conversion. This is a technique whereby a high-energy photon is split into two lower energy photons. Discovered in 1970, by David Burnham and Donald Weinberg,[91] it wasn’t until 1995 that it became a means by which a reliable source of correlated photons could be produced.[92]

As work with correlated particles progressed, it was realized that the changing the polarization of one half of an correlated pair by a measurement being made on the other was a procedure and in 2007 Wiseman et al[93] produced the first paper giving sustained attention to it.[94] They noted the distinction between non-separability, steerability

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88 Bennett, et al. “Teleporting an Unknown Quantum State Via Dual Classical and Einstein-Podolsky-Rosen Channels.”p.1895
89 Steane. “Quantum Computing.”p.144
90 H. Weinfurter. “Experimental Bell-State Analysis,” *Europhysics Letters* 25, no. 8 (1994):559-64.p.563
91 Whitaker. *The New Quantum Age*.pp.216-9
92 Paul G. Kwiat, Klaus Mattle, Harald Weinfurter & Anton Zeilinger. “New High-Intensity Source of Polarization-Entangled Photon Pairs,” *Physical Review Letters* 75, no. 24 (1995):4337-40.
93 H M Wiseman, S.J. Jones & A.C. Doherty. “Steering, Entanglement, Nonlocality and the EPR Paradox,” *Physical Review Letters* 98 (2007):140402. (https://arxiv.org/pdf/quant-ph/0612147.pdf).
94 Nicolas Brunner, Daniel Cavalcanti, Stefano Pironio, Valerio Scarani & Stephanie Wehner. “Bell Nonlocality,” *Reviews of Modern Physics* 86 (2014)p.839. (https://arxiv.org/pdf/1303.2849v3.pdf p.56)

and Bell nonlocality, "Clearly steerability is stronger than nonseparability but Bell-nonlocality is stronger than steerability."[95]

While the possibilities offered by steering were researched as a resource, the specific differences between different sorts of states, once designated EPR, was also researched and work in this area continues. A review article of 2014, gives an overview of where this area had then reached. "Interestingly, it turns out that entanglement is necessary but not sufficient for steering, while steering is necessary but not sufficient for nonlocality. Hence steering represents a novel form of inseparability in quantum mechanics, intermediate between entanglement and nonlocality.[96] The quantitative relation between steering, entanglement and Bell nonlocality is yet to be fully understood."[97] If quantum computing becomes a practicable reality, then the experiments designed to test Bell's inequality will be at its heart. The work that has sprung from Bell 1964 is far beyond anything John S Bell could have imagined but the way in the experiments testing Bell-type inequalities became engines to produce for use that for which that had been designed to test is simply another example of how theory and experiment beget more theory, enable more technology and provoke more theory. In November 2017, IBM announced it had

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[95] Wiseman, Jones & Doherty. "Steering, Entanglement, Nonlocality and the EPR Paradox."p.3 of arxiv version. They define *entanglement*, the feature first drawn attention to by EPR (p.779), thus: once two systems have interacted, they are described by a common wave function but the state of each of the systems individually, however far apart they become, can only be known by measurement; *nonlocality* as the potential ability of the second system to have entirely different states depending upon what measurement is carried out on the first system even if the systems are space time separated and *steering* as the choice of which measurement to perform on system one so as to produce an effect in system two, Wiseman, Jones & Doherty. "Steering, Entanglement, Nonlocality and the EPR Paradox."p.1.
[96] D.J Saunders, S.J. Jones, H.M. Wiseman & G.J. Pryde. "Experimental EPR-Steering Using Bell-Local States," *Nature Physics* 6, no. 11 (2010):845-49.; Wiseman, Jones & Doherty. "Steering, Entanglement, Nonlocality and the EPR Paradox."
[97] Brunner et al., "Bell Nonlocality."p.56 of arxiv version

built a 50-qubit computer that had held its quantum microstate for 90 microseconds[98] so there is some way to go before quantum computers are a realistic possibility but if and when they are, Bell 1964 will have been seminal.[99]

4:3 The Experiments Continue

Thus the continuing experiments testing Bell-type inequalities are not necessarily pursuing Bell's original motivation. No one expects that a perfect experiment without caveats could ever be carried out nor that if it could be, it would fail to violate the inequality. The current experiments are not done to test the inequality nor to find out what it means but to extend technological competence and explore further to what uses that which is now called "entanglement" can be put. Bell-type inequalities have become not a means to test whether certain ways of talking about the world, when encoded mathematically, are borne out by experimental experience but a means of judging whether or not a state is entangled enough to be put to use. Thus, one of the ways in which the aims of these recent experiments are phrased is in terms of closing loopholes. An experimental loophole is a means by which an experiment that looks as if it violates locality or local realism actually does not because of avenues of causality that the experimental design has failed either to close or to test for. The continuing race to close them is not so as to be certain that Bell-type inequalities are violated but to extend the boundaries of what is technically possible to do. To gain a flavour of the experiments that are still being conducted, I shall give an account of four recent Bell tests.

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[98] Abigail Beall and Matt Reynolds, "What Are Quantum Computers and How Do They Work?," *Wired*, https://www.wired.co.uk/article/quantum-computing-explained. Accessed 28th August 2018

[99] Michael A. Nielsen and Isaac L. Chuang, *Quantum Computation and Quantum Information: 10th Anniversary Edition* Cambridge: Cambridge University Press, (2010).p.117

4:3:1 “Loophole free” experiments with photons

In 2015, a team led by Marissa Giustina, conducted an experiment they reported as “loophole free.”[100] They define three loopholes their experiment has been designed to close. “The *locality loophole* (or *communication loophole*) is open if the setting choice or the measurement result on one side could be communicated to the other side in time to influence the measurement result there.”[101] “The *freedom-of-choice loophole* refers to the requirement, formulated by Bell, that the setting choices are "free or random."[102] “The *fair-sampling loophole* (or *detection loophole*) refers to the following issue: It is conceivable under local realism that a subensemble of emitted particles violates a Bell inequality, while the total ensemble does not. The loophole is exploited if an experiment detects only this subensemble and assumes that it represents the entire ensemble.”[103] At the end of the paper, they outline two more loopholes they consider they have closed, the coincidence-time loophole and the memory loophole[104] and indicate how they have done so. They conclude, “Our experiment showed a strong violation of local realism using exacting experimental technique and rigorous statistical analysis.”[105] That collected data, when corrected in what has become to be seen appropriate ways, should violate a Bell-type inequality is now taken as a given unless the point of a test is to make sure that this is the case for a given technologically produced state. So the focus of this paper is not

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[100] Marissa Giustina, et al. “Significant-Loophole-Free Test of Bell’s Theorem With Entangled Photons,” *Physical Review Letters* 115, no. 25 (2015)pp.250401:1-7.p.250401:1
[101] Giustina, et al. “Significant-Loophole-Free Test of Bell’s Theorem With Entangled Photons.”p.250401:2. Italics original.
[102] Giustina, et al. “Significant-Loophole-Free Test of Bell’s Theorem With Entangled Photons.”p.250401:2. Italics original.
[103] Giustina, et al. “Significant-Loophole-Free Test of Bell’s Theorem With Entangled Photons.”p.250401:2. Italics original.
[104] Giustina, et al. “Significant-Loophole-Free Test of Bell’s Theorem With Entangled Photons.”p.250401:5
[105] Giustina, et al. “Significant-Loophole-Free Test of Bell’s Theorem With Entangled Photons.”p.250401:5

the result itself but the demonstration of its technical purity. The push for this sort of research is not to answer the questions which motivated the first and generation tests, i.e. whether the BA question of whether or not the Schrödinger-Furry conjecture that the entangled wave function would cease to apply to two systems that had once been in contact and then separated beyond a certain distance, or the Bell question of whether nonlocality has to be a feature of any hidden variable schemes designed to complete the quantum mechanical description. The entangled states (no ontological status should be inferred nor purely descriptive status precluded by the use of the term "state,") of which a violation of Bell's inequality is now held to be a marker, are used in technological applications and it is vital for quantum cryptography, for example, that no technological procedures are able to impact upon or get behind the entanglement. These experiments are far from esoteric. As Handsteiner et al note, "Even if nature does not exploit this loophole [i.e. the freedom of choice loophole], testing it experimentally has significant practical relevance for device-independent quantum key distribution as well as random-number generation and randomness expansion. In particular, a sophisticated adversary could undermine a variety of quantum information schemes by utilizing the freedom of choice loophole."[106]

However, as early as Clauser and Shimony's 1978 review paper,[107] it is clear that what one team of experimenters consider an acceptable closing of a loophole remains problematic for others. So, in the case of this "Significant-loophole-free Test," one of the team who had been a part of demonstrating how the loopholes noted had been closed, two

[106] Johannes Handsteiner, et al. "Cosmic Bell Test: Measurement Settings From Milky Way Stars," *Physical Review Letters* 118, no. 6 (2017)p.06041.
[107] Clauser, and Shimony. "Bell's Theorem: Experimental Tests and Implications."p.1919

years later, leads a team reporting on how the "loophole-free"[108] experiment he had been a part of conducting was not strictly loophole free at all. They note, "To the extent that recent experiments have addressed freedom of choice, they have adopted the additional strong assumption that the relevant causal influences (or "hidden variables") originate together with the entangled particles and hence cannot influence setting choices in space-like separated regions"[109] and cite Giustina's team's experiment as an example. Giustina's team acknowledges this,[110] but they still feel able to acclaim the experiment loophole free. So, one of the team involved in what is entitled a loophole free experiment is the leader of a further team that sets out, not to close, since as had now been acknowledged, this loophole can never conceivably be entirely closed, but to significantly constrain "the space-time region from which any … unknown causal influences could have affected both the measurement setting and outcomes."[111] Handsteiner's team describe how their experiment uses "the color of photons detected using real-time astronomical observations of distant stars"[112] to determine the measurement settings of the photon polarization detectors and then states, "we observed Bell violations with high statistical significance and thus conclude that any hidden causal influences that could have exploited the freedom-of-choice loophole would have to have originated from remote space-time events at least several hundred years ago, at locations seemingly

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108 Giustina, et al. "Significant-Loophole-Free Test of Bell's Theorem With Entangled Photons."
109 Handsteiner, et al. "Cosmic Bell Test: Measurement Settings From Milky Way Stars." p.2 [nb all page numbers refer to the 24 page arxiv version of the paper, (https://arxiv.org/pdf/1611.06985.pdf).
110 Handsteiner, et al. "Cosmic Bell Test: Measurement Settings From Milky Way Stars."p.2
111 Handsteiner, et al. "Cosmic Bell Test: Measurement Settings From Milky Way Stars."p.3
112 Handsteiner, et al. "Cosmic Bell Test: Measurement Settings From Milky Way Stars."p.3

unrelated to the entangled pair-creation."[113] As arcane as this procedure and its rationale might seem, the team notes that the idea of it was discussed in 1976 by Bell and d'Espagnat.[114] Given that narrowing down the opportunities for "unknown causal influences" rather than testing a Bell inequality in itself is the point of this experiment, Handsteiner's team explain how they achieved this and give its theoretical justification substantial coverage.[115] As this experiment is only designed to close this particular loophole, other loopholes remain open.[116]

The major loophole with both Giustina et al's and Handsteiner et al's experiments and to this class of experiments as a whole is entirely ignored, namely the efficacy or otherwise of using photons to test Bell-type inequalities given that, as Lamehi-Rachti and Mittig pointed out, a photon is not a conceptually localizable phenomenon.[117] As Arthur Zajonc noted, "In QED the photon is introduced as the unit of excitation associated with a quantized mode of the radiation field. As such it is associated with a plane wave of precise momentum, energy and polarization. Because of Bohr's principle of complementarity we know that a state of definite momentum and energy must be completely indefinite in space and time. This points to the first difficulty in conceiving of the photon. If it is a particle, in what sense does it have a location?"[118] This major conceptual difficulty has not been the only

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[113] Handsteiner, et al. "Cosmic Bell Test: Measurement Settings From Milky Way Stars."p.3
[114] Handsteiner, et al. "Cosmic Bell Test: Measurement Settings From Milky Way Stars."p.3
[115] Handsteiner, et al. "Cosmic Bell Test: Measurement Settings From Milky Way Stars."pp3-5; pp.10-24
[116] E.g., Handsteiner, et al. "Cosmic Bell Test: Measurement Settings From Milky Way Stars."p.24
[117] Lamehi-Rachti, and Mittig,"Quantum Mechanics and Hidden Variables: A Test of Bell's Inequality By the Measurement of the Spin Correlation in Low-Energy Proton-Proton Scattering." p.2546
[118] Arthur G. Zajonc. "Light Reconsidered," in *The Nature of Light. What is a Photon?*, ed. C Roychoudhuri, and Brian J. Thompson. Boca Raton: CRC Press Taylor and Francis, (2008).p.5

problem posed by the current conceptualization of photons for an interpretation of what is going on in Bell inequality experiments done with them. "Bell's derivation sums wave amplitudes under the assumption that waves (or photons) directly interact with one another and redistribute mutual energies to generate fringes. Again such an assumption implies wave-wave or field-field interaction, which has not been formally established either by classical or quantum physics." [119] Chandresaker Roychoudri continues somewhat pointedly, "We have stopped inquiring through which physical process and/or by what physical force the following two physical operations, implied by our causal mathematics are being carried out."[120] This is not to enter into the argument and take sides as to whether or not experiments with photons are a suitable means by which to test Bell-type inequalities, it is merely to note that while the majority of physicists, theoretical and experimental, accept without demur that experiments using photons have violated Bell-type inequalities and use the technology for various purposes, there are those who argue that the conceptual basis for photons does not provide an adequate enough conceptual base to enable such significant conclusions to be extrapolated from experiments using them. Others accept the conceptual basis but do not accept that photons are suitable for testing Bell's inequalities because what appear to be nonlocal effects are, in their view, part of the measurement apparatus. Yacob Ben-Aryeh wrote with regard to the atomic cascade experiments, "violation of Bell inequalities of polarization measurements …..may follow from correlation introduced by the measurement process and not from action at a distance. Our basic argument was that the internal polarization states of the photons in these experiments are entangled with their spatial dependence, which is described by spherical wave

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[119] Chandresaker Roychoudhuri. *Causal Physics: Photons By Non-Interaction of Waves*, Boca Raton: CRC Press, Taylor and Francis Group, (2014).pp.11-2
[120] Roychoudhuri. *Causal Physics: Photons By Non-Interaction of Waves*.pp.11-2

functions ….. The separation of the internal states from their spatial dependence is obtained by taking into account experimentally only the photons that are going in opposite directions……. I would like to explain here the violation of Bell inequality for subensembles may follow from the method of measurement and from the nonclassical properties of light but not from violation of locality."[121]

It is important for theologians to be aware of complexities like these which underlie seemingly straightforward scientific statements and to know the background of any research upon which they depend especially in points of theory about which physicists disagree.

4.3.2 Other Recent Experiments

Before the Giustina et al's "significant loophole-free experiment,"[122] B. Hensen et al, announced "the first experimental loop-hole free violation of the CHSH-Bell inequality using entangled electron spins."[123] This experiment shows that what is and what is not considered a loophole changes over time. Guillaume Adenier and Andrei Yu. Khrennikov dispute Hensen et al's claim. While Adenier and Khrennikov agree that Hensen et al have closed both the locality and detection loophole, they contend that the experiment still violates the no-signaling principle which Hensen et al have not attempted to close. The no-signaling principle means ensuring that local measurements made at one station cannot be used to send a signal to the other station when the stations are space-like separated in the sense that "Bob's outcome *y* cannot reveal anything about Alice's input *a* and the other

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[121] Y Ben-Aryeh. "The Use of Bell Inequalities in Quantum Optics," *Foundations of Physics Letters* 7, no. 5 (1994):459-66.p.460
[122] Giustina, et al., "Significant-Loophole-Free Test of Bell's Theorem With Entangled Photons."
[123] B. Hensen, et al. "Loophole-Free Bell Test Using Electron Spins in Diamond: Second Experiment and Additional Analysis," *Scientific Reports* 6 (2016):30289:1-10.p.30289:1

way round".[124] Adenier and Khrennikov underline the importance of making sure this principle is not violated. "Generally speaking, our analysis shows that inferring the fulfillment of the locality condition based on well established theory and careful timing of events is not enough. We would argue that a possible violation of the no-signaling principle should systematically be checked whenever testing for a violation of local realism."[125] While they are careful to say that Hensen's team's experiment "may" have fallen foul of the no-signaling principle, this is tantamount to refuting Hensen's team's claim that the experiment is loophole free.[126] Adenier and Khrennikov also pointed out a number of flaws in the data handling[127] and drew attention to a problem that is common to all experiments on electron spin namely the low rate at which correlations in spin are registered. Normally not mentioned, they note it specifically here claiming that the problem is greater in Hensen team's experiment because of the very low number of counts observed.[128] After the publication of the first version of Adenier and Khrennikov's paper on arxiv,[129] Hensen's team published a very speedy account of the data gathered in their first experiment not previously published, along with data from a second run of the experiment conducted five months later. Although Hensen's team do not mention Adenier and Khrennikov drawing attention to the low counts in the first run of the experiment, in the second experiment, they address the problem by setting "larger (i.e. less conservative)

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[124] Guillaume Adenier and A Khrennikov, "Test of the No-Signalling Principle in the Hensen Loophole-Free CHSH Experiment," *Fortschritte der Physik* 65, no. 9 (2017):1600096 (11 pages).p.16900096:1
[125] Adenier, and Khrennikov. "Test of the No-Signalling Principle in the Hensen Loophole-Free Chsh Experiment."p.1600096:10
[126] Adenier, and Khrennikov. "Test of the No-Signalling Principle in the Hensen Loophole-Free Chsh Experiment."p.1600096:1
[127] Adenier, and Khrennikov. "Test of the No-Signalling Principle in the Hensen Loophole-Free Chsh Experiment."
[128] Adenier, and Khrennikov. "Test of the No-Signalling Principle in the Hensen Loophole-Free Chsh Experiment."p.1600096:2
[129] Guillaume Adenier and Andrei Yu. Khrennikov, "Test of the No-Signalling Principle in the Henson Loophole-Free Chsh Experiment," (2016).

heralding windows at the event-ready detector in order to increase the data rate compared to the first experiment. We start the heralding window about 700 picoseconds[130] earlier, motivated by the data from the first test."[131] One of the features of Henson's team's experiment that Adenier and Khrennikov find "interesting"[132] is that all the data recorded at each station is preserved and available rather than being presented in the way that supports the claimed experimental result. Hensen's team decided how they were going to use the data after the data had been collected rather than deciding on a methodology and using the data thus collected in that way. While on the positive side, this practice enabled Adenier and Khrennikov to test the data for something that was not of interest to the team who produced it, they were highly critical of the practice, being concerned that it allowed the team to present the data in a way that best fitted the conclusions that they had hoped to find. "One essential principle in statistics that is particularly relevant in this context is that the rules establishing how the data is collected and how the statistical analysis is performed should be decided independently of the data. Failure to do so leaves open the possibility to tweak the acquisition or the statistical analysis toward the preferred outcome[133]."[134] While Hensen's team do not acknowledge that this point of Adenier and Khrennikov invalidates their conclusions, they nevertheless cite the paper and note the need to be aware of what effect a particular choice of statistical practices will have upon the way data is framed and therefore upon the

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[130] A picosecond is one (US) trillioneth of a second ie 10^{-12} or 1/1000,000,000,000sec.

[131] Hensen, et al. "Loophole-Free Bell Test Using Electron Spins in Diamond: Second Experiment and Additional Analysis."p.30289:2

[132] Adenier, and Khrennikov. "Test of the No-Signalling Principle in the Hensen Loophole-Free Chsh Experiment."p.1600096:5

[133] They cite the arxiv version of Wenjamin Rosenfeld, et al. "Event-Ready Bell Test Using Entangled Atoms Simultaneously Closing Detection and Locality Loopholes," *Physical Review Letters* 119 (2017): 010402:1-6., https://arxiv.org/abs/1611.04604

[134] Adenier, and Khrennikov. "Test of the No-Signalling Principle in the Hensen Loophole-Free Chsh Experiment."p.1600096:7

conclusions that will be reached.[135] Hensen's team denies the need for checking compliance with the no-signaling principle. They contend it is part of rather than additional to the locality loophole and that closing that loophole ensures compliance with the no-signaling principle by definition.[136] While some commentators would agree with them,[137] others would not.[138] Adenier and Khrennikov define no signaling as the condition "that Alice and Bob cannot use local measurements on quantum states to signal one another"[139] noting that this can be expressed mathematically, "In a no-signaling experimental framework, Alice's marginal probabilities, which are the sum of joint probabilities over all possible results at Bob's laboratory, must be independent of the measurements performed by Bob."[140] They cite Giustina et al as exemplum of good practice. While any theological reflection on recent Bell-type experiments need not take sides in such debates, it is important to be aware that the issues of importance and the motivations for conducting experiment in modern Bell-type experiments are very different from those surrounding the earlier experiments and debates. The research springing from Bell 1964 has changed enormously over the years and is changing rapidly. The discussion as to what does and does not constitute a loophole and what does and does not constitute good statistical practice is something that is still contentious and the subject of academic debate almost 50 years after the first testable Bell-type inequality was

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135 Hensen, et al. "Loophole-Free Bell Test Using Electron Spins in Diamond: Second Experiment and Additional Analysis."p.30982:4
136 Hensen, et al. "Loophole-Free Bell Test Using Electron Spins in Diamond: Second Experiment and Additional Analysis."p.30289:4
137 Brunner, et al. "Bell Nonlocality."p.6
138 Adenier and Khrennikov, "Test of the No-Signalling Principle in the Hensen Loophole-Free CHSH Experiment."p.1600096:10.Marian Kupczynski. "Is Einsteinian No-Signalling Violated in Bell Tests?," *Open Physics* 15 (2017):739-53.p.748
139 Adenier, and Khrennikov "Test of the No-Signalling Principle in the Hensen Loophole-Free Chsh Experiment."p.2
140 Adenier, and Khrennikov "Test of the No-Signalling Principle in the Hensen Loophole-Free Chsh Experiment."p.3

published. Bell's work has not yet become a well-loved museum piece. Historic it is, but it is still the site of controversy and discussion.

One of the recent experiments commended by Adenier and Khrennikov for adequate testing of the no-signaling principle[141] was that conducted in 2017 by Wenjamin Rosenfeld et al.[142] It is doubtful that they are aware of how important their good practice is, given that they commended both Giustina's team's experiment[143] and Henson's team's first experiment,[144] one praised and the other criticized by Adenier and Khrennikov. Rosenfeld's experiment is described as "event–ready" because they tested "entangled neutral atoms"[145] and so every event was a registered and statistically relevant event, meaning that no fair sampling assumption had to be made.[146] Their experimental set-up meant that the locality and detection loopholes were also closed. They decided all the relevant details of how many tests would be run and with what procedure and how the data would be analysed so as to avoid expectation bias and then conducted two runs of the experiment with 5000 registered events in each run. Several earlier test runs had been undertaken. They acknowledged that the freedom of choice loophole had not been entirely closed but

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141 Adenier, and Khrennikov. "Test of the No-Signalling Principle in the Hensen Loophole-Free CHSH Experiment."p.1600096:1

142 Rosenfeld, et al. "Event-Ready Bell Test Using Entangled Atoms Simultaneously Closing Detection and Locality Loopholes."

143 Giustina, et al. "Significant-Loophole-Free Test of Bell's Theorem With Entangled Photons."

144 B. Hensen, et al. "Experimental Loophole-Free Volation of a Bell Inequality Using Entangled Electron Spins Separated By 1.3 Km," *Nature* 526 (2015):682-86.

145 Rosenfeld, et al. "Event-Ready Bell Test Using Entangled Atoms Simultaneously Closing Detection and Locality Loopholes."p.010402:1

146 For the events that are deemed correlated to be meaningful in an experiment where only a proportion of the total events are registered, it has to be assumed that the registered events are representative of the larger sample.

announce, with this proviso, "a highly reliable event-ready Bell test, showing in several attempts a clear violation of a Bell inequality."[147]

The final experiment we shall look at was conducted in 2018 and was designed to close the freedom of choice loophole. It was conducted by 107 people, based across the world, called "The BIG Bell Test Collaboration." They note a flaw in all tests of Bell-type inequalities changing the detector settings using machines: "the use of physical devices to choose settings in a Bell test involves making assumptions about the physics that one aims to test."[148] They make it clear that they consider experiments designed to test the a Bell inequality is "a …. trial that compares experimental observations against the philosophical worldview of local realism,"[149] thus making it important to ensure that the experiment is as bias-free as possible. Thus, "here we report a set of local-realism tests using human choices, which avoids assumptions about predictability in physics."[150] They explain how their experiment has attempted to do this. "We recruited about 100,000 human participants to play an online video game that incentivizes fast, sustained input of unpredictable selections and illustrates Bell-test methodology. The participants generated 97,34,490 binary choices, which were directed via a scalable web platform to 12 laboratories on five continents, where 13 experiments tested local realism using photons, single atoms, atomic ensembles and superconducting devices. Over a 12 hour period on 30th November 2016, participants worldwide provided a sustained flow of data of over 1,000 bits a second to the experiments, which used different human-generated

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[147] Rosenfeld, et al. "Event-Ready Bell Test Using Entangled Atoms Simultaneously Closing Detection and Locality Loopholes."p.010402:5
[148] The BIG Bell Test Collaboration: et al. "Challenging Local Realism With Human Choices."p.212
[149] The BIG Bell Test Collaboration: et al."Challenging Local Realism With Human Choices."p.212
[150] The BIG Bell Test Collaboration: et al. "Challenging Local Realism With Human Choices."p.212

data to choose each measurement setting."[151] They report the observed correlations strongly contradict local realism.

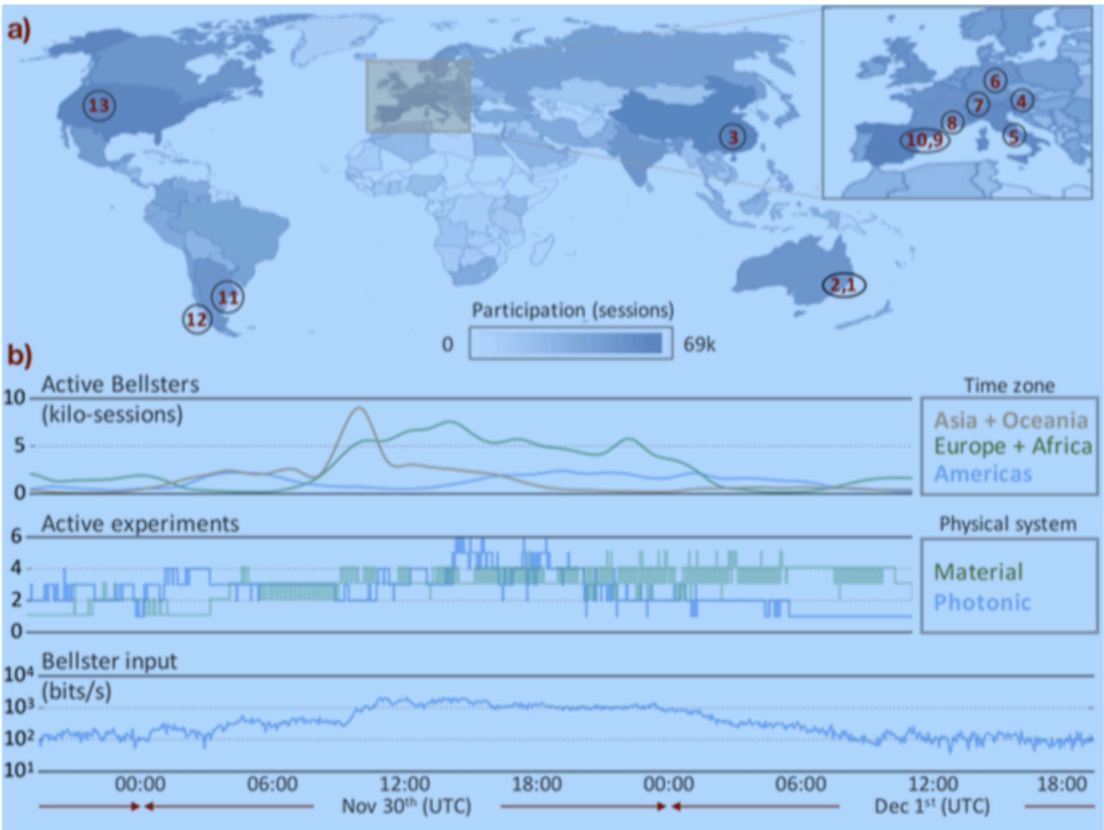

FIG. 2. Geography and timing of the BBT. a) Locations of the 13 BBT experiments, ordered from East to West. See Table I. Shading shows total sessions by country. Eight sessions from Antarctica are not shown. b) Temporal evolution of the project. (top) live sessions versus time for different continent groups, showing a strong drop-off in the local early morning in each region. The spike in Asian participation around 11:00 UTC coincides with a live-streamed event in Barcelona, translated into Chinese and re-streamed by USTC. (middle) number of connected labs versus time, divided into experiments using only photons and experiments with at least one material component, e.g. atoms or superconductors. (bottom) input bitrate versus time. Data flow remains nearly constant despite regional variations, with Asian Bellsters handing off to Bellsters from the Americas in the critical period 12:00-00:00 UTC. Session data from Google analytics.

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151 The BIG Bell Test Collaboration: et al., "Challenging Local Realism With Human Choices."p.212

152 The BIG Bell Test Collaboration: et al., "Challenging Local Realism With Human Choices."p.3 of arxiv version

[153]

TABLE I. Experiments carried out as part of the BBT, ordered by longitude, from East to West. Descriptions of the experiments are given in Methods. "Stat. Sig." (statistical significance) indicates number of standard deviations assuming i.i.d. trials, unless otherwise indicated. γ signifies photon.

ID	Lead Institution	Location	Entangled system	Rate	Inequality	Result	Stat. Sig.
①	GRIFFITH	Brisbane, AU	γ polarisation	4 bps	$S_{16} \leq 0.511$	$S_{16} = 0.965 \pm 0.008$	57σ
②	EQUS	Brisbane, AU	γ polarisation	3 bps	$\|S\| \leq 2$	$S_{AB} = 2.75 \pm 0.05$ $S_{BC} = 2.79 \pm 0.05$	15σ 16σ
③	USTC	Shanghai, CN	γ polarisation	1 kbps	PRBLG[29] $J_l \geq 0$	$I_0 = 0.10 \pm 0.05$ $J_{1/4} = -0.0181 \pm 0.0006$	N/A 30σ
④	IQOQI	Vienna, AT	γ polarisation	1.61 kbps	$\|S\| \leq 2$	$S_{HRN} = 2.639 \pm 0.008$ $S_{QRN} = 2.643 \pm 0.006$	81σ 116σ
⑤	SAPIENZA	Rome, IT	γ polarisation	0.62 bps	$B \leq 1$	$B = 1.225 \pm 0.007$	32σ
⑥	LMU	Munich, DE	γ-atom	1.7 bps	$\|S\| \leq 2$	$S_{HRN} = 2.427 \pm 0.0223$ $S_{QRN} = 2.413 \pm 0.0223$	19σ 18.5σ
⑦	ETHZ	Zurich, CH	transmon qubit	3 kbps	$\|S\| \leq 2$	$S = 2.3066 \pm 0.0012$	$p < 10^{-99}$
⑧	INPHYNI	Nice, FR	γ time-bin	2 kbps	$\|S\| \leq 2$	$S = 2.431 \pm 0.003$	140σ
⑨	ICFO	Barcelona, ES	γ-atom ensemble	125 bps	$\|S\| \leq 2$	$S = 2.29 \pm 0.10$	2.9σ
⑩	ICFO	Barcelona, ES	γ multi-frequency-bin	20 bps	$\|S\| \leq 2$	$S = 2.25 \pm 0.08$	3.1σ
⑪	CITEDEF	Buenos Aires, AR	γ polarisation	1.02 bps	$\|S\| \leq 2$	$S = 2.55 \pm 0.07$	7.8σ
⑫	CONCEPCION	Concepcion, CL	γ time-bin	51 kbps	$\|S\| \leq 2$	$S = 2.43 \pm 0.02$	20σ
⑬	NIST	Boulder, US	γ polarisation	100 kbps	$K \leq 0$	$K = (1.65 \pm 0.20) \times 10^{-4}$	8.7σ

The BIG Bell test collaboration ran an experimental test of a Bell inequality in 13 different locations and across a 12 hour period across the world's time zones. They acknowledge that human choices are too slow to enable the people who made the choices to be space-like separated from the measurement sites, however they claim that "a hidden variable theory can only exploit the locality loophole "if it has mechanisms by which the choices simultaneously influence hidden variables in all of the experiments, bringing them each to a result mimicking quantum predictions."[154] They outline for each of the experimental sites what types of experiments were carried out and which loopholes were closed and which weren't and how the inequality had been tested. They conclude the overall experiment, "demonstrated strong disagreement with local realism using measurement settings chosen by tens of thousands of globally-distributed human participants. The results also show empirically that human agency is incompatible with causal determinism, a question formerly only accessible by metaphysics."[155] It looks as if, at least in

[153] The BIG Bell Test Collaboration: et al. "Challenging Local Realism With Human Choices."p.4 of arxiv version.
[154] The BIG Bell Test Collaboration: et al. "Challenging Local Realism With Human Choices."p.3 arxiv version
[155] The BIG Bell Test Collaboration: et al. "Challenging Local Realism With Human Choices."p.4 arxiv version.

the minds of the physicists who conducted and wrote up this experiment, experimental metaphysics is back on the table.

Chapter Five: Scientists and Philosophers interpret Bell 1964

In this chapter, I survey the range of interpretations held by mathematicians, physicists and philosophers of science as to what Bell's theorem, Bell's inequality and the experiments done to test it mean. A number of things will emerge. Firstly, more than sixty years after Bell 1964 there is no consensus as to its meaning or the meaning of the experimental violations. Secondly, while some of the issues raised in the debate about how to interpret Bell's work about which mathematicians, physicists, and philosophers of science disagree are mathematical or scientific and thus raise questions that are capable of being right or wrong and therefore, at least in theory, capable of being settled, there remain vast areas of disagreement that are not capable of being mathematically or scientifically resolved and thus remain a matter of choice. Bell's original and subsequent mathematical inequalities rely on assumptions. The experiments designed to test the inequalities rely on assumptions. The processes of interpreting either the raw scores or of transforming the raw data into final experimental data rely on assumptions. Any one of these assumptions could be responsible for the experimental violations. While this choice, as to which of the assumptions is responsible for the violation, is decided upon rational and defensible grounds, it remains a choice. Deciding what the experimental violations of Bell's inequality means, for those who think the inequalities have been violated, comes down to deciding upon which assumptions Bell's inequality depends and, which of the assumptions upon which either the theory or the experiments depend has to be dropped.

Experimental metaphysics was a phrase first coined by Abner Shimony in 1980.[1] However, given that the vast range of interpretations as to the significance of the violation of Bell-type inequalities is irreducible, not being decidable on scientific grounds, this field of scholarship has not so much produced experimental answers to metaphysical questions as exposed the metaphysical assumptions upon which theoretical and experimental physics relies. This is significant for theological reflection on Bell's work. Scientists who accept that Bell inequalities have been violated, decide what the significance of Bell's work is on rational grounds, but these rational grounds are not compelled by scientific considerations and remain a matter of individual and personal choice. Where a theologian accepts that Bell inequalities have been violated, mining Bell's work for its theological significance must begin with a proper acknowledgement of the importance of prior commitments for scientists working in the field and the inescapability of making pre-scientific choices when deciding what the experimental violations scientific.

5.1 The Experimental Violations of Bell-type Inequalities mean nothing.

5.1.1 Its Algebraic and Geometric Assumptions make it irrelevant.

I begin by surveying those who hold that the experimental violations of Bell-type inequalities mean nothing. Those holding this position do so for a variety of reasons. I start with the work of Joy Christian who argues that the algebraic and geometrical assumptions upon which Bell's inequality relies undermine the relevance of Bell's result to real

[1] Abner Shimony"Critique of the Papers of Fine and Suppes," *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science* v2 (1980):572-80.p572, noted by Martin R. Jones, and Robert K Clifton, "Against Experimental Metaphysics," *Midwest Studies in Philosophy* 18, no. 1 (1993):295-316.

world experiments. Then, using a different set of algebraic and geometrical assumptions, Christian derives a locally causal physical theory that agrees with all the statistical results of quantum mechanics thus disproving Bell's theorem[2] as expressed by the late Abner Shimony: "no physical theory which is realistic as well as local in a specified sense can reproduce all of the statistical predictions of quantum mechanics."[3]

Christian notes that Bell uses scalar geometry in the derivation of his inequality, a point which is uncontentious and not unusual: "One of the first steps we often take towards measuring a physical quantity is to set up a Cartesian coordinate system in the Euclidean space $\mathbb{E}^3$. This amounts to modeling the Euclidean space as a three-fold product of the real line, $\mathbb{R}^3$. This procedure has become so familiar to use that in practice we often identify $\mathbb{E}^3$ with its Cartesian model."[4] However, scalar geometry is unable to represent everything that occurs in reality: "in the real $\mathbb{R}$ world, we can rotate an object in 3D with all six degrees of freedom at will. When we represent 3D rotation with the traditional scalar algebra and Euler angles, we can't."[5] Thus, while traditional scalar algebra can be and is used to model certain aspects

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[2] Christian uses the word "theorem" in this context as Shimony does meaning a form of words summing up what Bell's inequality is said to demonstrate. It is not a theorem in the mathematical sense, for this point, see A F Kracklauer. "Bell's "Theorem": Loopholes Vs. Conceptual Flaws," *Open Physics* 15 (2017):754-61.pp754-5n1

[3] Joy Christian, "Disproof of Bell's Theorem: Further Consolidations," (2007).p.1 see Abner Shimony, "Bell's Theorem," (2009).

[4] Christian, *Disproof of Bell's Theorem. Illuminating the Illusion of Entanglement Second Edition*.p49.

[5] Paul Snively, "Fallacy," *Paul Snively's Blog. Musings on Computer Science, Physics, Mathematics and Other Stuff*, http://web.archive.org/web/20150123015323/http://psnively.github.io/blog/2015/01/22/Fallacy/ (accessed 27th April, 2018). quoting from Joy Christian, "Disproof of Bell's Theorem: Reply to Critics," (2008).p.5

of the real world, it cannot model every aspect of experienced reality.[6] "There is….. a serious deficiency in this algebra. This deficiency is well known to aerospace engineers and computer-vision [sic] experts, but has been entirely overlooked by the practitioners of Bell's theorem. The deficiency is that the elements of scalar algebra are not capable of representing rotations in the ordinary three-dimensional space….. When one tries to represent rotations using the elements of scalar algebra—say by using Euler angles for example—one runs into what is known as a gimbal lock.[7]" Gimbal lock is a practical problem with gimbals (a device that consists of rings pivoted at right angles). The problem of modeling geometrically the 3D rotation with 6 degrees of freedom we see in the real world is an acknowledged problem for a wide range of scientists, from computer animation or simulation

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[6] For an account of different algebras used to represent physical reality see José B. Almeida, "Different Algebras for One Reality," *Physical Interpretations of Relativity Theory. Proceedings of International Scientific Meeting PIRT-2008 London, 12-15 September, 2008* (2016):102-10. Almeida notes one of the Clifford algebras "is the most common choice [to model special relativity] and it allows the formulation of most physics equations including quantum mechanics." Almeida, "Different Algebras for One Reality."p.103

[7] For the distinction between Gimbal lock and the singularities of Euler angles, see Evan G Hemingway, and Oliver M. O'Reilly, "Perspectives on Euler Angle Similarities, Gimbal Lock, and the Orthogonality of Applied Forces and Applied Moments," *Multibody Systems Dynamics* https://doi.org/10.1007/s11044-018-9620-0 (2018):1-26.p.4. Christian. "Disproof of Bell's Theorem: Reply to Critics."p.5. "Gimbal lock is the loss of one degree of freedom in a three-dimensional, three-gimbal mechanism that occurs when the axes of two of the three gimbals are driven into a parallel configuration, "locking" the system into rotation in a degenerate two-dimensional space. The word lock is misleading: no gimbal is restrained. All three gimbals can still rotate freely about their respective axes of suspension. Nevertheless, because of the parallel orientation of two of the gimbals' axes there is no gimbal available to accommodate rotation along one axis." For a gif that displays it see: https://en.wikipedia.org/wiki/Gimbal_lock#/media/File:Gimbal_3_axes_rotation.gif In a YouTube video showing gimbal lock, the path that gets the three gimbals running freely again shows the jump necessary to get out of gimbal local when modeling 3D rotation with six degrees of freedom in Euclidean space, thus modeling the "nonlocality": see https://www.youtube.com/watch?v=zc8b2Jo7mno 2.57 minutes in.

designers[8] to aircraft engineers and astronauts.[9] For example, "Gimbal lock occurs when an aircraft maneuvers to such an extreme degree that the measuring instrument cannot follow. For example, a simple three gyroscope gimbal system cannot measure the movement of an airplane going exactly vertical; this is gimbal lock. The airplane can fly beyond the ability of the instruments to measure." [10] This is the crux of Christian's point: the algebra Bell uses to represent the real physical world does not do so and that therefore no valid conclusions about the nature of the world can be derived from experiments designed to test the equality Bell has derived in this algebra. Christian draws attention to the implications of the failure to attend to the vital conceptual distinction between models and what is being modeled and cites both EPR and Bell1964 as examples of this failure. "[T]his seemingly, innocuous act of convenience comes with a heavy price: It is largely responsible for the illusion of quantum nonlocality."[11] Outside Bell scholarship, acknowledging that differing algebras are used to model

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[8] For how to avoid gimbal lock in designing computer animations and simulations see Jernej Barbic, "Quaternions and Rotations," http://run.usc.edu/cs520-s15/quaternions/quaternions-cs520.pdf (accessed 28th May 2018.)

[9] For mention of manoevring so as to avoid gimbal lock see the Apollo 11 transcript:
"04 08 59 35 (CapCom): Columbia, Houston. we noticed you are maneuvering very close to gimbal lock. I suggest you move back away. Over
04 08 59 43 (Michael Collins): Yes. I am going around it, doing this <u>CMC</u> AUTO maneuvers to the PAD values of roll 270, pitch 101, yaw 45.
04 08 59 52 (CapCom): Roger, Columbia
04 09 00 30 (Michael Collins): How about sending me a fourth gimbal for Christmas
04 09 00 40 (CapCom): Columbia, Houston. You were unreadable. Say again please." "Apollo 11 Space Log," http://apollo11.spacelog.org/page/04:08:40:46/. 04 08 59 35 to 04 08 00 40."

[10] Mark J. Englund-Krieger. *The Presbyterian Pendulum. Seeing Providence in the Wild Diversity of the Church*, Eugene, OR: Wift and Stock, (2010).p.207

[11] Joy Christian. "Restoring Local Causality and Objective Reality to the Entangled Photons,"(2012).p.1

different physical theories because some work better in some contexts than others is uncontentious.[12] The experimental violations of Bell's inequalities demonstrate that nonlocality emerges when real space is modeled with Euclidean geometry. Christian points to a Clifford algebra[13] which can be used to model real space that avoids this: "instead of comparing the quantum correlations with the correlations between the points on a real line, [as Bell does in his inequality] it ought to be comparing them with the correlations between the points of a 3 or 7 sphere …. When this is done correctly, no incompatibility between the predictions of quantum mechanics and local realism arises."[14]

A. F. Kracklauer also notes the importance of geometry when assessing Bell's work. He doesn't discuss the geometry that underpins Bell's original inequality, although he notes the significance of Christian's discussion.[15] Kracklauer says that the theory underpinning spin and electromagnetic polarization and many of the experiments by which

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[12] e.g. see David Hestenes. *Clifford Algebra to Geometric Calculus. A Unified Language for Mathematics and Physics*. Springer, (1984).; C Doran, and A Lasenby, *Geometric Algebra for Physicists*. Cambridge: Cambridge University Press (2003).; Martin Erik Horn, "An Introduction to Geometric Algebra With Some Preliminary Thoughts on the Geometric Meaning of Quantum Mechanics," *Journal of Physics: Conference Series* 538 (2014):.012010:1-15.; Almeida, "Different Algebras for One Reality."Clifford Algebras are noncommutative meaning that the order in which mathematical operations take place will alter the result. This is a feature of matrix multiplication. Alain Connes notes "Heisenberg's discovery shows that the phase-space of microscopic systems is noncommutative inasmuch as the coordinates on that space no longer satisfy the commutative rule of ordinary algebra." Alain Connes, "On the Fine Structure of Spacetime," in *On Space and Time.* Cambridge: Cambridge University Press, (2008).p.205. For the importance of noncommutative geometry for physics see, e.g. Alain Connes, *Non-Commutative Geometry*, New York and London: Academic Press, (1994).; Connes, "On the Fine Structure of Spacetime."

[13] $Cl_{3,0}$

[14] Christian. *Disproof of Bell's Theorem. Illuminating the Illusion of Entanglement Second Edition*.p.135-6

[15] Kracklauer. "Bell's "Theorem": Loopholes Vs. Conceptual Flaws." p.755

Bell inequalities are tested "can be entirely explained in terms of noncommutative geometry: …it is just a matter of geometry."[16]

Christian's second point builds on his first. If nothing about the real world can be extrapolated from the violation of Bell's inequality because the inequality has been derived using algebra that cannot model it then Bell's theorem is disprovable. Using a different algebra and one whose utility for representing quantum mechanics is acknowledged,[17] Christian outlines a locally causal theory that accounts for the experimental violations of Bell's inequality thus disproving Bell's theorem.[18]

To say Christian's work is contentious is a considerable understatement. His work on Bell's mathematics and Bell's theorem has produced not simply disagreement but provoked outrage.[19] Christian Els uses Joy Christian's experience as a case study on how scholars with unpopular viewpoints are not simply disagreed with but branded as "cranks."[20] Despite the vicious attacks his work still attracts, Christian's work on the relevance of Clifford algebras for the elucidation of quantum theory continues to be cited by those working in the field of quantum games theory.[21] Furthermore, in an article published in the volume celebrating fifty years of Bell's theorem and

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[16] Kracklauer. "Bell's "Theorem": Loopholes Vs. Conceptual Flaws." p.758
[17] Almeida. "Different Algebras for One Reality."pp.103-4
[18] Christian. *Disproof of Bell's Theorem. Illuminating the Illusion of Entanglement Second Edition*.pp.29-38.
[19] e.g. see Scott Aaronson, "Bell's-Inequality-Denialist Joy Christian Offers Me $200k if Scalable Quantum Computers Are Built," (2012).
[20] Christian Els, "The Construction of Crank Science," https://static1.squarespace.com/static/559921a3e4b02c1d7480f8f4/t/585c388c37c58146456084ac/1482438808884/Els.pdf..
[21] James M. Chappell, Azhar Iqbal & Derek Abbott. "Analyzing Three-Player Quantum Games in an EPR Type Setup," *Plos One* 6, no. 7 (2011):e21623:1-11.; James M. Chappell, Azhar Iqbal & Derek Abbott. "Geometric Algebra: A Natural Representation of Three-Space," (2016):1-26.

co-edited by Mary Bell, Basil Hiley, a proponent of Bohm's nonlocal theory, makes the very same point as has drawn such opprobrium upon Christian. "The Clifford Group, the spin group, describes the global features of the rotation group and gives a natural account of the differences between the 2π and 4π rotations.[[22]]This is a feature of the rotational properties of space and has, a priori, little to do with quantum phenomena. It is rather that physical processes exploit these global properties, with quantum nonlocality being merely a consequence of these global features. This would account for the appearance of nonlocality in spin correlation."[23]

5.1.2 Experiments cause branching so specific results globally meaningless

There are others who, for entirely different reasons think the experimental violations of Bell's inequalities mean nothing. In answer to the question posed by Maximillian Schlosshauer "What do the experimentally observed violations of Bell's inequalities tell us about nature?" David Wallace answered, rather carefully, "if the Everett interpretation is wrong, violation of Bell's inequalities tells us that there are faster-than-light interactions..... Of course, if you buy into the Everett interpretation, then it's of rather theoretical interest... But I am told not everyone does buy the Everett interpretation."[24] He explains, "there is a tacit premise in Bell's argument: that the results of

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[22] For an straightforward explanation of the significance of the difference between 2π and 4π rotations, often known the Dirac belt trick, see Mark Staley, "Understanding Quaternions and the Dirac Belt Trick," (2010) https://arxiv.org/pdf/1001.1778.pdf:1-19..
[23] Basil J. Hiley, "Some Personal Reflections on Quantum Nonlocality and the Contributions of John Bell," in *Quantum Nonlocality and Reality: 50 Years of Bell's Theorem*, ed. Mary Bell, and Shan Gao Cambridge: Cambridge University Press, (2016).p.356.
[24] Schlosshauer, *Elegance and Enigma. The Quantum Interviews*.pp.178-9

measurements actually have definite outcomes. This looks pretty innocuous, because if measurement results are macroscopic, of course they are definite. But of course, that is exactly what the Everett interpretation of quantum mechanics denies[[25]]. Or, more accurately, measurement outcomes are relative to a branch."[26] Thus, for Many Worlds/Many Minds theorists, Bell and Bell-type experiments can mean nothing[27] because everything that could happen in an experiment, does happen but, by happening, causes branching.[28] If Bell experiments don't have definite outcomes per se but only definite outcomes relative to a branch, it is hard to see how the specific outcome observed in any particular branch can mean anything. The implications of this position for the practice of science are far wider than interpreting the results of Bell and Bell-type experiments.

5.1.3 Raw data cannot bear the weight of the supposed results

Some think Bell's reasoning is flawed, others see the flaws in the experiments. The late Caroline Thompson, a statistician, thought the way raw data had been interpreted in some experiments was not

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[25] This is not only relevant re Bell and Bell-type inequalities. As Kent points out, it also undermines any attempt to justify Many Worlds theory by experimental evidence and fails to account for the success of quantum theory. See Adrian Kent. "One World Versus Many: The Inadequacy of Everettian Accounts of Evolution, Probability, and Scientific Confirmation," in *Many Worlds? Everett, Quantum Theory and Reality*, ed. Simon Saunders, Jonathan Barrett, Adrian Kent, and David Wallace Oxford: Oxford University Press, (2010). p.325.
[26] Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.178
[27] What significance if any they can be said to have within each branch is a question Wallace does not address.
[28] see Lev Vaidman. "On Schizophrenic Experiences of the Neutron or Why We Should Believe in the Many-Worlds Interpretation of Quantum Theory," *International Studies in the Philosophy of Science* 12 (1998):245-61. Whether it is the world or the mind of the observer that splits is a debated point, see David Wallace. "Decoherence and Ontology," in *Many Worlds*, eds Simon Saunders, Jonathan Barrett, Adrian Kent and David Wallace. Oxford: Oxford University Press, (2010).p.55

statistically valid meaning that at the time of writing her paper, (1999), Bell's inequality had not been irrefutably violated. Thompson says the problem lies with the "'subtraction of accidentals' .....—that, in almost all cases, forces their test statistic up and over its limit. The subtraction changes results that can be explained realistically into ones that require quantum magic. There is no mention in the published papers of the assumptions behind the adjustment and insufficient data was given for the reader to work out what the unadjusted data was."[29] Thompson summarizes data from Alain Aspect's PhD thesis in which she shows the impact the subtraction of data has on the interpretation of the results.

Table I Raw and Adjusted Coincidence Rates[30]

Angle between polarizers	0.0˚	22.5˚	45.0˚	67.5˚	90.0˚	One polarizer absent	Both absent
Raw coincident rate	96	87	63	38	28	126	248
'Accidental' rate	23	23	23	23	23	46	90
Adjusted rate	73	64	40	16	5	81	158

She writes, "One can judge the significance of the adjustment just by looking at the first five columns. They show that the raw coincident rate decreases as angle increases, and this follows a sinusoidal curve as expected. It does not, however, decrease to zero, as QM predicts. Its visibility is 0.55, not significantly above the expected realist value. Subtract the 'accidentals', however, and you get 0.87, a very considerable change."[31] She notes that other scholars have identified the problem[32] and that Aspect replied[33] but with reference to data

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[29] Caroline Thompson. "The Tangled Methods of Quantum Entanglement Experiments," *Accountability in Research* 6 (1999):311-32.p.317 italics original.
[30] Thompson. "The Tangled Methods of Quantum Entanglement Experiments."p.317
[31] Thompson. "The Tangled Methods of Quantum Entanglement Experiments."p.317
[32] T. W. Marshall, Emilio Santos & Franco Selleri. "Collective Effects in the Atomic-Cascade Experimental Test of Bell Inequalities," *Lettere al Nuovo Cimento* 38, no. 12 (1983):417-20.

from a two channel experiment conducted without the subtraction rather than the single channel experiment with the subtraction to which Marshall et al's point applies.[34] Furthermore, subsequent experiments, also claiming to violate local realism have continued to subtract accidentals without discussion as to the significance of this move.[35] Thompson notes that this problem does not arise in experiments with low emission rates, such as Freedman and Clauser's,[36] but that their experiment cannot be adduced as solving the problem conclusively because it relies heavily on other assumptions.[37] Making the same point in a later paper, Thompson refers to a paper in which the matter of the subtraction is not discussed and where, without the subtraction, the claimed violation of Bell' inequality does not occur.[38]

5.1.4. Experiments with photons cannot test Bell's inequality

While Lamehi-Rachti and Mittig said that the non localizability of photons meant their use in Bell experiments was inappropriate,[39] Kracklauer disputes the relevance of these experiments because they

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[33] Alain Aspect and P Grangier, "About Resonant Scattering and Other Hypothetical Effects in the Orsay Atomic-Cascade Experiment Tests of Bell Inequalities: A Discussion and Some New Experimental Data," *Lettere al Nuovo Cimento* 43, no. 8 (1985):345-48.
[34] Thompson. "The Tangled Methods of Quantum Entanglement Experiments."p.331
[35] W. Tittel, et al., "Experimental Demonstration of Quantum Correlations Over More Than 10km," *Physical Review A* 57, no. 5 (1998):3229-32.
[36] FC
[37] Caroline Thompson. "Behind the Scenes At the EPR Magic Show," in *Open Questions in Relativistic Physics*, ed. F Selleri, Montreal: Apeiron, (1998).p.356 The other assumption upon which it relies is the detection loophole, FC p.939.
[38] Tittel, et al. "Experimental Demonstration of Quantum Correlations Over More Than 10km."; Thompson. "Behind the Scenes At the EPR Magic Show."p.354
[39] Lamehi-Racht and Mittig. "Quantum Mechanics and Hidden Variables: A Test of Bell's Inequality By the Measurement of the Spin Correlation in Low-Energy Proton-Proton Scattering."p.2546

cannot fulfill one of Bell's own requirements that "the result B for particle 2 does not depend on the setting $\vec{a}$, or the magnet for particle 1, nor A on $\vec{b}$."[40] As Kracklauer notes, this cannot apply in experiments with correlated photons: "the relative intensity of two polarisation measurements is dependant on the relative angular difference regardless of the polarisation of the incoming signal; i.e. the conditional probability is a function of the parameter of the distant measuring station and not the hidden variable."[41] He concludes that such experiments cannot therefore be used to test Bell's inequality.

5.1.5 A definitive experiment has not yet been done

Lucien Hardy, a faculty member at the Perimeter Institute for Theoretical Physics at Waterloo in Canada is convinced that the nonlocality of quantum theory is a feature of the world and that a completely loophole-free experiment would show a violation of Bell's inequality, the mathematics of which he accepts. Hardy does not, however, think that any such experiment has yet been done. Even the experiment he proposes, in which the detector settings would be switched by human beings while the photons were between the emitter and the detector, he admits, would not itself be loophole-free[42] and therefore would not be a conclusive demonstration of an inequality violation.

There is a considerable literature concerned with the loopholes that place caveats as to how the results of experiments testing Bell inequalities can be interpreted. A great amount of experimental effort and ingenuity has been expended in the attempt at closing them.

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[40] Bell 1964 p.196
[41] A F Kracklauer. ""La 'Théorie' De Bell, Est-Elle La Plus Grande Méprise De L'Histoire De La Physique?" *Annales de la Fondation Louis de Broglie* 25, no. 2 (2000):193-207.p.197
[42] Lucien Hardy."Proposal to Use Humans to Switch Settings in a Bell Experiment," (2017).p.9. Hardy does not propose to attempt to close the fair sampling loophole.

Expertise has developed as to how to close individual loopholes and now the race is on to close them all simultaneously. There are four loopholes that are commonly referred to in the literature: the causality or freedom of choice loophole, the efficiency loophole, the fair sampling loophole, and the locality loophole. The causality or freedom of choice loophole, Hardy describes thus, with reference to the Freedman and Clauser experiment with photons,[43] "measurements at the two ends of the experiment were chosen in the backward light cone of the photons being emitted from the source. Consequently, there is the possibility of this choice affecting the properties of the photons when they were emitted from the source."[44] This loophole has been closed in a number of experiments, most dramatically in 2017, using observations from the light from milky way stars to dictate the choice of polarizer settings.[45] This particular experiment does not close the fair sampling loophole however.[46]

The efficency loophole was first noted by Philip Pearle, who developed a local hidden variable model exploiting it.[47] This loophole refers to the fact that not every run of a Bell experiment records a correlation. One or other or both of the particles may not register and it is not certain whether or not this will skew the results, one way or another. Experiments have closed this loophole[48] but with a varying degree of

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[43] FC
[44] Schlosshauer.*Elegance and Enigma. The Quantum Interviews*.p.174
[45] Handsteiner, et al., "Cosmic Bell Test: Measurement Settings From Milky Way Stars."
[46] Previous experiments seeking to close this loophole did so by making " the additional strong assumption that the relevant causal influences (or "hidden variables") originate together with the entangled particles and hence cannot influence setting choices in space like separated regions." Handsteiner, et al. "Cosmic Bell Test: Measurement Settings From Milky Way Stars."p.2
[47] Pearle. "Hidden-Variable Example Based Upon Data Rejection."p.2
[48]Firstly by Rowe's team: Rowe, et al. "Experimental Violation of a Bell's Inequality With Efficient Detection.", then e.g. D.N Matsukevich, et al. "Bell Inequality Violation With Two Remote Atomic Qubits" *Physical Review Letters* 100 (2008):150404. & Julian Hofmann, et al.

susceptibility to the locality loophole. Furthermore, experimenters do not always stress that, while the loophole is often called the detection efficiency loophole, it is the efficiency of the whole experiment that is at issue, including the efficiency of the source. Related to this loophole is the fair-sampling loophole, where the detection rates of the particles are not high enough to exclude the possibility that "the sub-ensemble of detected events agrees with quantum mechanics even though the entire ensemble satisfies Bell's inequalities."[49] Experimenters can close loopholes either by the design of the experiment or by the inequality they choose to test. The first experiment to have closed the fair sampling loophole did so by using Eberhard's[50] version of Bell's inequality.[51] Another loophole is the locality loophole, meaning that the two detectors in the experimental arrangement are not sufficiently distant to preclude information about measurements being exchanged between them. The stronger version of this loophole is called the "light-cone" loophole, which remains open so long as the possibility of subluminal communication between both detectors remains feasible. The distances between detectors in Bell-type experiments have been increasing year on year. In the first published test of a Bell inequality the polarizers were placed in the same room,[52] while in 2015, an

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"Heralded Entanglement Between Widely Separated Atoms," *Science* 337 (2012):72-75. See Jan-Åke Larrson, "Loopholes in Bell Inequality Tests of Local Realism," *Journal of Physics A: Mathematical and Theoretical* 47 (42), no. 42 (2014):424003(1-40).p18

[49] Rowe, et al., "Experimental Violation of a Bell's Inequality With Efficient Detection."p.791

[50] Philippe Eberhard, "Background Level and Counter Efficiencies Required for a Loophole Free Einstein-Podolsky-Rosen Experiment," *Physical Review A* 47 (1993)pp.747-50.

[51] e.g. Marissa Giustina, et al. "Bell Violation With Entangled Photons, Free of the Fair-Sampling Assumption," *Nature* 497 (2013):227-30. This was the first experiment with photons to close the loophole.

[52] FC

experiment was conducted in which the polarizers were 143km apart on different sides of a strait.[53]

By now, experiments have been conducted to close the most significant loopholes[54] and experimentalists are continuing to develop technology to push back the likelihood that any of these loopholes are responsible for the experimental violations of the inequality in question.[55] However, in the first experiment to close the locality, free choice and fair sampling loopholes (which they elide with the detection loophole[56]) at the same time, the team add the caveat that "…..empirically closing a loophole might still require the validity of some specific assumptions about the experiment..."[57] There are other loopholes that have been identified alongside or as specific instances of the main four. For example in 1989, Paul Werbos identified the implicit assumption of time-forward causality operating in Bell experiments,[58] an assumption which seems obvious but is not necessary and is something that Einstein dispensed with in his explanation of the photo-electric effect using the wave theory of light.[59] Theodorus Nieuwenhuizen highlights the contextuality

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53 Thomas Herbst et al. "Teleportation of Entanglement Over 143km," *Proceedings of the National Academy of Sciences of the United States of America* 112, no. 46 (2015):14202-14205.

54 e.g. Giustina et al. "Significant-Loophole-Free Test of Bell's Theorem With Entangled Photons."; Shalm, et al. "Strong Loophole-Free Test of Local Realism."; Hensen et al. "Loophole-Free Bell Test Using Electron Spins in Diamond: Second Experiment and Additional Analysis."

55 E.g. Carlos Abellán et al. "Generation of Fresh and Pure Random Numbers for Loophole-Free Bell Tests," *Physics Review Letters* 115 (2015):250403.

56 Giustina et al. "Significant-Loophole-Free Test of Bell's Theorem With Entangled Photons."p.250401:2

57 Giustina, et al., "Significant-Loophole-Free Test of Bell's Theorem With Entangled Photons."pp.250401:1-2

58 P. Werbos. "Bell's Theorem, the Forgotten Loophole and How to Exploit it," in *Bell's Theorem, Quantum Theory and Conceptions of the Universe*, ed. Menas Kafatos, Dodrecht: Kluwer, (1989).

59 Werbos."Bell's Theorem, the Forgotten Loophole and How to Exploit it."p.83

loophole,[60] an assumption that Bell made in the thought experiment that underlies his inequality, that each measurement can be assumed to be measuring the same thing. This is impossible to implement in practice. In every Bell experiment, averaging takes place over values that are obtained from different runs of the experimental set up and there is no way of ensuring that the same thing is being measured in each case. Thus it is a loophole to which every Bell experiment is susceptible.

The quest to close the loopholes is not simply about settling theoretical questions. Experimentalists develop more and more sophisticated experiments not only to test theory but also because of the usefulness of the technologies developed in the process.

5.2 Bell 1964 is about probability theory

We now explore the various different ways in which mathematicians, physicists and philosophers who accept that the inequalities are mathematically cogent and that they have been decisively violated attribute significance to the violations. We consider first those who think the significance of Bell's work lies in its contribution to probability theory. There is a considerable pedigree for this position,[61] first noted by L. R. Kasday. He stated that no local model would be able to "reproduce quantum predictions for the ideal measurements [because] setting the ideal analyzers to several different angles corresponds to measuring several *noncommuting observables*. Quantum theory does not supply a joint probability function .... for noncommuting observables, so the model cannot be constructed."[62]

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[60] T.M. Nieuwenhuizen. "Is the Contextuality Loophole Fatal for the Derivation of the Bell Inequalities," *Foundations of Physics* 41 (2011):580-91.
[61] see references 4-53 in A Khrennikov. "Bell as the Copernicus of Probability," (2015):1-37. https://arxiv.org/pdf/1412.6987.pdf
[62] Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons."p.200 Italics original.

While often seen as means of defending local realism, in the hands of people such as Arthur Fine, Itamar Pitowsky and Khrennikov, it has become a positive claim about the significance of Bell's work not for the quantum world but for quantum theory, more specifically for probability theory in the quantum domain. Without knowing of Kasday's work, Arthur Fine noted it in 1974,[63] likewise Georges Lochak in 1976[64], with no awareness of either Fine or Kasday's work. While Lochak concluded from it that Bell's work had "no general meaning,"[65] Fine said, Bell, albeit without intending to, had established that, "the joint distribution principle is inconsistent with quantum theory."[66] It was Fine who saw this not, as Lochak thought, as something that "vitiates [Bell's] reasoning"[67] but as a significant point in its own right. Fine clearly states the point he thinks Bell has demonstrated, "It is shown that the following statements about a quantum correlation experiment are mutually equivalent. (1) There is a deterministic hidden-variables model for the experiment. (2) There is a factorizable, stochastic model. (3) There is one joint distribution for all observables of the experiment, returning the experimental probabilities. (4) There are well-defined, compatible joint distributions for all pairs and triples of commuting and noncommuting observables. (5) The Bell inequalities hold."[68] Fine acknowledged this was " not the lesson… drawn by many, who focus just on the locality assumption featured in many accounts."[69] Fine concludes that the only way that the experimental violations of Bell's inequality have to be interpreted

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63 Arthur Fine. "On the Completeness of Quantum Theory," *Synthese* 29, no. 1/4 (1974):257-89.

64 Georges Lochak. "Has Bell's Inequality a General Meaning for Hidden Variable Theories?" *Foundations of Physics* 6, no. 2 (1976):173-84.

65 Lochak. "Has Bell's Inequality a General Meaning for Hidden Variable Theories?"p.173

66 Fine. "On the Completeness of Quantum Theory."p.270

67 Lochak. "Has Bell's Inequality a General Meaning for Hidden Variable Theories?"p.76

68 Arthur Fine. "Hidden Variables, Joint Probability and the Bell Inequalities," *Physical Review Letters* 48, no. 5 (1982):291-95.p.291

69 Schlosshauer, *Elegance and Enigma. The Quantum Interviews*.p.170

is that they demonstrate that the experimental results cannot be modeled with a joint probability distribution for all the measurements. As Accardi had noted, "Quantum theory is so much a new probability as it is a new mechanics."[70]

While much of the literature in this part of the debate around the significance or otherwise of the experimental violations of Bell's inequalities takes up issues of probability so as to argue against those who contend that the experimental violations have established nonlocality, Fine's and Accardi's early contentions that Bell's result is significant in its own right for our understanding of probability is a position that has gained ground. In 1989, Itamar Pitowsky demonstrated that Bell's inequality is simply a restatement of one of Boole's conditions of possible experience.[71] "One thing should be clear at the outset: none of Boole's conditions of possible experience can ever be violated when all the relative frequencies involved have been measured in a single sample space."[72] As Khrennikov explains "probabilities for some group of random observations cannot be embedded in the Boolean algebra. He [Boole] even investigated the standard Bell situation. There are given three dichotomous random observables. It is possible to perform their pairwise measurements and the corresponding joint probability distributions are given. The natural question arises: Is it always possible to define the joint probability distribution for this triple of observables? Boole presented the inequality which is nowadays known as Bell's inequality as a

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[70] Luigi Accardi. "Topics in Quantum Probability," *Physics Reports (Review Section of Physics Letters)* 77, no. 3 (1981):169-92.p.169
[71] Itamar Pitowsky. "From George Boole to John Bell: The Origins of Bell's Inequality," in *Bell's Theorem, Quantum Theory and Conceptions of the Universe*, ed. Menas Kafatos. Dodrecht: Kluwer, (1989).
[72] Itamar Pitowsky. "George Boole's 'Conditions of Possible Experience' and the Quantum Puzzle," *The British Journal for the Philosophy of Science* 45, no. 1 (1994):95-125.p.105. This is disputed in Thomas Müller and Tomasz Placek, "Against a Minimalist Reading of Bell's Theorem: Lessons From Fine," *Synthese* 128, no. 3 (2001):343-79.

necessary condition for the existence of this probability."[73] The implications of Boole's result for Kolmogorovian probability theory had been elucidated by N. Vorob'ev in 1962.[74] Thus, as Khrennikov makes clear, "the Bell argument led to the recognition that the classical Kolmogorov model of probability which served so well for classical statistical physics has to be rejected and one has to use the quantum model of probability."[75] Khrennikov adds, making Accardi's point, "And (!) nothing more."[76] The violation of Bell's inequalities are an example of the necessity of deriving a new post- Boolean, post-Kolmogorovian probability theory suitable for working with the random observations of quantum mechanics. Khrennikov explains, "Roughly speaking for any fixed experimental context a Kolmogorov space can be used. Probabilistic data collected in a fixed experiment in quantum (as well as in classical) physics can be described by the conventional measure-theoretic model, but not data collected for a few incompatible observables. If one understood this, then such mystical things as….the

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[73] Khrennikov, "Bell as the Copernicus of Probability." https://arxiv.org/pdf/1412.6987.pdf note 2,p.3. This is the arxiv preprint of A Khrennikov, "Bell Could Become the Copernicus of Probability," *Open Systems and Information Dynamics* 23, no. 02 (2016)p.165008. All references are from this preprint.

[74] N.N. Vorob'ev "Consistent Families of Measures and Their Extensions," *Theory of Probability and Its Applications* 7, no. 2 (1962):147-63. noted in A Khrennikov. "A Mathematician's Viewpoint to Bell's Theorem: In Memory of Walter Philipp," *AIP Conference Proceedings- Foundations of Probability and Physics III* 889, no. 1 (2007):1-16.p2. Khrennikov noted Walter Schipp had brought this to his attention.

[75] Khrennikov. "Bell as the Copernicus of Probability."p.1 See Andrei Khrennikov, "Contextual Approach to Quantum Mechanics and the Theory of the Fundamental Prespace," *Journal of Mathematical Physics* 45 (2004):902-21. for examples of a quantum approach to probability. Nikolævitch Kolmogorov in 1933 "changed the character of the calculus of probability, moving it from a collection of calculations into a mathematical theory" David Nualart "Kolmogorov and Probability Theory", *Arbor*, CLXXVIII, 704:607-19 p.607

[76] Khrennikov. "Bell as the Copernicus of Probability."p.1 Pitowsky disagrees. He is a frequentist re probability, seeing probabilities as reflective of the behaviour of underlying events, see Pitowsky, "George Boole's 'Conditions of Possible Experience' and the Quantum Puzzle."p.112

violation of Bell's inequality can easily be explained in the classical approach, but based on intelligent taking into account context-dependence of probabilities [sic]."[77] Khrennikov expresses his exasperation that "all previous attempts ….. to communicate with the physics community about Kolmogorovness/non-Komolgorovness issue of Bell's argument were not successful [sic]."[78] He cites forty-nine papers that have raised this point[79] and comments, "the majority of physicists are poorly educated in probability theory."[80]

5.3 Assumptions upon which Bell's inequality might rest

While Bell derived his inequality as a means by which to determine whether any hidden variable theory that could match the predictions of quantum theory would necessarily be nonlocal, the problem posed by the experimental violations is now usually framed as a decision as to which of the range of assumptions Bell made in the derivation of his inequality has to be dispensed with, although a number of commentators are adamant that the only assumption upon which Bell 1964 was based was that of locality.[81] It is important to be clear about the distinction between a loophole and an assumption. A loophole is a defect in the experimental arrangement that is capable of skewing the data and which is, at least theoretically, capable of being experimentally rectified, while an assumption is one of the theoretical premises upon which the derivation of the mathematical inequality relies. Unsurprisingly, precisely which assumptions Bell based his inequalities upon and which of them cause or causes the conflict with the experimentally derived statistics is contested. We shall discuss what each assumption means and then discuss how the experimental

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[77] A Khrennikov. *Interpretations of Probability. 2nd Revised Edition* Berlin: Walter de Gruyter, (2009).p.vii
[78] Khrennikov. "Bell as the Copernicus of Probability."p.2.
[79] Khrennikov. "Bell as the Copernicus of Probability."p.2
[80] Khrennikov. "Bell as the Copernicus of Probability."pp.3-4
[81] E.g., see Maudlin. "Space-Time in the Quantum World."; Travis. "Against "Realism"."

violations of Bell's inequalities are interpreted depending on which of these assumptions is dropped. Valdenbro gives a comprehensive account of the assumptions underlying Bell Inequalities and it is his schema that I shall follow.[82] He details the following assumptions: realism; the fair distribution of microstates in the tested population; the fair sampling assumption; that measurement settings are independent of the system tested; that there is no backward causality, and finally, locality.

5.3.1 Realism

In this context, realism is an umbrella term meaning that "the outcome of a measurement is not created by the measurement but corresponds to properties possessed by the measured system prior to the measurement."[83] This assumption is variously named in literature: realism, determinism, causality, property definiteness and counterfactual definiteness, a strong version of realism, meaning that not only are there existant causes for experiments that are actually performed but also "for all possible experiments that could be performed on an individual system, no matter whether any experiment—and which experiment— is actually performed."[84] Anthony Leggett's version of this assumption is "*macroscopic counterfactual definiteness* meaning that the hypothetical "outcome" of measurements that were not in fact performed can be treated as a fixed fact about the world."[85] Leggett's version of the assumption only speaks about what happens in the laboratory rather than making statements about what is happening in the putative quantum world. There are also definitions of realism that don't include ascriptions about what the results might have been in experiments that were not

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[82] Angel Valdenebro. "Assumptions Underlying Bell's Inequalities," *European Journal of Physics* 23, no. 5 (2002):569-77., omitting the Joint Probability Distribution which has already been discussed.
[83] Valdenebro. "Assumptions Underlying Bell's Inequalities."p.572
[84] Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.166
[85] Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.175

performed. A famous paper by Asher Peres expounding this was entitled "Unperformed experiments have no results"[86] in which he demonstrated that, in a Bell type scenario, counterfactual reasoning could not apply but then goes on to conclude that this means a failure of separability rather than realism.[87] If the assumption of realism is deemed to be the assumption responsible for the violations and therefore has to be sacrificed, it is concluded that the system being tested in Bell experiments has no properties until a measurement is performed. As we have seen, Many World theorists believe that when a quantum measurement is performed, branching takes places. Therefore, a further ascription to the realism assumption has to be added, namely that reality is single valued ie "each measurement has only one actual outcome."[88]

5.3.2 Fair Distribution of Microstates

The fair distribution of the total microstates assumption means that "the distribution of microstates in the ensemble depends only on the macrostate…….[and] no matter the pair of compatible observables selected, for any sufficiently long run of joint measures, the microstates on which the measurements are effectively performed are representative of the same general distribution."[89] There are no arguments made in the literature that this is the assumption responsible for the violation.

5.3.3.The Fair Sampling Assumption

The fair sampling assumption means that if the detection efficiency is less than perfect, this does not bias the micro-ensemble actually

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[86] Asher Peres."Unperformed Experiments Have No Results," *American Journal of Physics* 46, no. 7 (1978):745-47.
[87] Peres. "Unperformed Experiments Have No Results."
[88] Valdenebro. "Assumptions Underlying Bell's Inequalities."p.572
[89] Valdenebro. "Assumptions Underlying Bell's Inequalities."p.573

recorded so as to prevent it fairly representing the whole sample. This assumption became particularly important after Philip Pearle derived a hidden variable model that violated Bell Inequalities "provided the experimenter rejects the "anomalous" data in which only one particle is detected."[90] Thus from being an assumption, it became a loophole, as we have noted. However inequalities, not using this assumption, were derived[91] to counter it.

5.3.4. The No Conspiracy Assumption

The "no conspiracy" assumption means that the measurement settings of the detectors are independent of the microstate of the system being tested and that the choices of the experimenters as to which direction of polarization is measured at each detector are not correlated with the microstate of the system. The state of the system, therefore, does not determine how the measurement settings interact with it. As a means to retain locality, Arthur Fine discusses the possibility that this assumption fails and that each specific setting of the detector does select out a subset of the total ensemble.[92]

5.3.5 No Backward Causation

The "no backward causation" assumption implies that "hidden variables are independent of later measurements. A posterior event

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[90] Pearle."Hidden-Variable Example Based Upon Data Rejection." p.1418

[91] e.g. John F Clauser, and Michael A Horne. "Experimental Consequences of Objective Local Theories," *Physical Review D* 10 (1974):526-35. ; Eberhard. "Background Level and Counter Efficiencies Required for a Loophole Free Einstein-Podolsky-Rosen Experiment."

[92] Arthur Fine. "Correlations and Physical Locality," *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association* II (1981):535-62.; Fine,."Hidden Variables, Joint Probability and the Bell Inequalities." & Arthur Fine. "Antimonies of Entanglement: The Puzzling Case of the Tangled Statistics," *The Journal of Philosophy* 79, no. 12 (1982):733-47.

(the choice of experiments) cannot influence a previous fact (the microstate of the system)."[93] Neither can a later measurement influence the nature of the measurement that was previously performed. However obvious this may seem, a number of quantum theorists select this as the assumption responsible for the experimental violations. In 1986 John Cramer's outlined his transactional interpretation of quantum theory on the assumption that backwards causality[94] happens in quantum interactions. He is continuing to develop and test this model.[95] This interpretation is nonlocal but fully causal. Cramer put forward a physical model of how this retrospective causality might happen on a microlevel, while leaving the normal arrow of time untouched. Huw Price developed a local model in which events could influence events in its former light cone.[96]

5.3.6. Locality

What it means to assume locality in experiments designed to test Bell inequalities is much discussed. Sometimes locality is said to mean factorability or separability. This means that "[g]iven the spatial separation of the A-type and B-type measurements, it seems reasonable to assume that the probability of obtaining the value a_i for A depends only on the microstate of the system, and not on another measurement performed arbitrarily far away with an independent

[93] Valdenebro. "Assumptions Underlying Bell's Inequalities."p.574
[94] John G Cramer. "The Transactional Interpretation of Quantum Mechanics," *Reviews of Modern Physics* 58, no. 3 (1986):647-987.
[95] Alan Boyle."Physicist's Weird Reverse-Causality Experiment Goes in a New Direction," *NBC News*, https://www.nbcnews.com/science/physicists-weird-reverse-causality-experiment-goes-new-direction-2D11867397 (accessed June 6th 2018.)
[96] E.g, Huw Price. "Does Time-Symmetry Imply Retrocausality? How the Quantum World Says "Maybe." *Studies in History and Philosophy of Modern Physics* 43 (2012):75-83.

experimental device."[97] In other words, the whole experimental set up of two measuring stations can be factored as two separate systems. "Hence, obtaining the value a_i for A and obtaining the value b_k for B……are stochastically independent events, and we can factorize them in the form

$$p(A=a_i, B=b_k|\lambda)=p(A=a_i|\lambda)p(B=b_k|\lambda)$$". [98]

Valdenebro points out that those who, on the basis on the experimental violation of the equalities, wish to declare this form of the locality assumption false, can do so and retain Einstein's theory of relativity."[99] However, as Valdenebro notes, Jarret[100] concluded that this assumption is itself a combination of two others which Shimony[101] later named "parameter independence" and "outcome independence." Parameter independence means that "for a given microstate, the probability of an outcome of an observation on the "A" side, is (stochastically) independent of the experimental setting (the parameters of the experimental device) on the "B" side." While outcome independence means that "for a given microstate, the probability of an outcome of an observation on the "A" side is (stochastically) independent of the outcome of observations on the "B" side."[102] Should the experimental violations of Bell or Bell-type experiments lead a commentator to assume that it was the factorability assumption that had to go, either of these assumptions, or indeed both, could be sacrificed. Most commentators, according to Valdenebro see parameter independence, the nonfulfilment of which

97 Valdenebro. "Assumptions Underlying Bell's Inequalities."p.574
98 Valdenebro. "Assumptions Underlying Bell's Inequalities."p.575
99 Valdenebro. "Assumptions Underlying Bell's Inequalities."p.575
100 Jarret. "On the Phyiscal Significance of the Locality Conditions in the Bell Arguments."
101 Abner Shimony. "Events and Processes in the Quantum World," in *Quantum Concepts in Space and Time*, ed. Roger Penrose, and C J Isham Oxford: Oxford University Press, (1986).
102 Valdenebro."Assumptions Underlying Bell's Inequalities."p.575

"conflicts with relativity,"[103] as the more fundamental. As nonlocality is a feature of Bohm's hidden variable theory, locality was the assumption Bell derived his inequality to encode.[104]

5.4 The only "matter of fact": it all comes down to choice

For those who accept that the Bell inequalities have been experimentally violated, one of these assumptions can no longer be said to apply to the world being tested by the experiments, but which? There is no consensus on this amongst mathematicians, physicists and philophers of science. The experimental results and the theories behind them do not lead definitively to any one particular interpretation of them. It all comes down to choice. After fifty years of sustained thought, discussion at conferences, forests of published papers, after nearly fifty years of planning and running experiment after experiment, the answer to the question of which assumption cannot be said to hold in the real world remains a choice, not a simple choice but simply a choice, nevertheless. As Schlosshauer, Köfler and Zeilinger say about the result of a question they asked in a survey at the end of a conference on quantum foundations held in the Internation Academy Traunkirchen, Austria in 2011, "Bell's inequalities are a wonderful example of how we can have a rigorous theoretical result tested by numerous experiments, and yet disagree about the implications."[105] Schlosshauer et al published the results of their small questionnaire and to the question, "What is the message of the observed violations of Bell's inequalities?" the results were as follows:

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[103] Valdenebro."Assumptions Underlying Bell's Inequalities."p.575
[104] Bell 1964 p.195
[105] Maximillian Schlosshauer, Joannes Kofler & Anton Zeilinger. "A Snapshot of Foundational Attitudes Towards Quantum Mechanics," *Studies in History and Philosophy of Modern Physics* 44 (2013):222-30.p.224

"local realism is untenable"	64%
"Action at a distance in the physical world"	12%
"Some notion of nonlocality"	36%
"Unperformed experiments have no results"	52%
"Let's not jump the gun — let's take the loopholes more seriously"	6%"[106]

This snapshot expresses the inescapable reality that in quantum physics, more than fifty years of experimentally testing a mathematical expression published in one short paper has produced no consensus as to what it means. This is the startling and indisputable fact to emerge from this scientific field. It is the only undisputed fact to emerge. Provided a scholar in this field accepts that the algebra and probability Bell used in his derivation are appropriate, that the theory bases used in the experiments are suitable, that the loopholes in the experiments have either been closed or not relevant, and therefore that Bell's inequality has been violated, the answer to the question of what the experimental violations mean is not one science can answer. The answer to this question remains a choice, a rational choice, but nevertheless a choice. In Boyle's terms, fifty years of demonstration and debate has not produced a "matter of fact"[107] beyond that of the violation itself.

In my view, this is the most significant thing to emerge from the field of Bell scholarship: what the results of these experiments mean, in this most stringent of scientific disciplines, in the end, comes down to the personal choice of the scholar. It is not an undisciplined choice. It is a choice made in concert with the scholar's most deeply held convictions

[106] Schlosshauer, Kofler & Zeilinger, "A Snapshot of Foundational Attitudes Towards Quantum Mechanics."p.224 These percentages, adding up to more than 100%, are taken verbatim from the published article.
[107] Shapin and Schaffer. *Leviathan and the Air Pump: Hobbes, Boyle and the Experimental Life*.

about the nature of the world itself or the nature of the scientific enterprise. It is not a choice without reference to facts but the facts in question do not determine how they should be interpreted. The facts in question, Bell 1964 and the experimental results of the experiments conducted to test a Bell-type inequality, do not compel a particular interpretation. The choice of which interpretation of the paper and its experimental consequences to espouse by those who hold that they are significant (and as we have seen, not all do) comes down in the end to a personal choice that depends upon a scientific or philosophical instinct or upon a belief as to how the world is and has to be. While it is clear that E.M. Purcell's claim that the experimental violations of a Bell-type inequality demonstrate that a philosophical problem has been solved in the laboratory is entirely unfounded,[108] nevertheless we see how the metaphysical prior commitments about the nature of science or of the world provide the grounds by which a decision is made as to how the significance of the experimental violations of Bell's inequalities is interpreted.

To give an overview as to the breadth of the debate, we shall explore the answers to the question, "What do the experimentally observed violations of Bell's inequalities tell us about nature?"[109] given by the seventeen physicists, mathematicians and philosophers surveyed by Maximillian Schlosshauer in *Elegance and Enigma*.[110] Those interviewed were Guido Bacciagaluppi, Časlav Brukner, Jeffrey Bub, Arthur Fine, Christopher Fuchs, GianCarlo Ghirardi, Shelley Goldstein, Daniel Greenberger, Lucien Hardy, Anthony Leggett, Tim Maudlin, David Mermin, Lee Smolin, Anthony Valentini, David Wallace, Anton Zeilinger and Wojciech Zurek.

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[108] Jon P Jarret. "Bell's Theorem: A Guide to the Implications," in *Philosophical Consequences of Quantum Theory*, ed. James T Cushing, and Ernan McMullan. Notre Dame: University of Nortre Dame Press (1989).p.60
[109] Schlosshauer, *Elegance and Enigma. The Quantum Interviews*.p.161
[110] Schlosshauer, *Elegance and Enigma. The Quantum Interviews*.pp161-180

While a small sample, their answers reflect the wider spread and they are draw from across the disciplines of scholars that contribute to the debate. Eight out of the seventeen surveyed are willing to accept the reality of nonlocality, non-separability or non factorizability, whether in its non-outcome independence or non-parameter independence form while the remainder of the respondents, those who wish to keep locality, have widely differing views as to how the experiment violations of Bell's inequality should then be understood. What will emerge, is that while the arguments adduced for the retaining or dispensing with one of the undergirding assumptions are all scientifically cogent and entirely rational, deciding between them comes down to choice, based on the prior commitments and understanding of each individual. This remains true even amongst those whose choice is to dispense with locality amongst whom there is no consensus as to what the locality is with which they are dispensing nor what then follows. That too, comes down to choice.

5.5 Dispensing with the assumption of locality

"Nature is nonlocal" as Tim Maudlin says.[111] Guido Bacciagaluppi says, "they show that the distant correlations present in nature cannot be understood in terms of what seem to be quite general forms of local models...... I am happy to call that nonlocality."[112] Anthony Valentini more circumspectly notes "locality is violated"[113] and Shelly Goldstein, even more circumspectly, " for any theory to predict [the] violations, it must be a nonlocal theory."[114] Lee Smolin notes "there are real physical nonlocal correlations in nature. It seems simplest to suppose

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111 Providing experiments have unique outcomes and the loopholes have been closed. Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.176.
112 Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.165.
113 Valentini's provisos are that there be no backward causation and that the "many worlds" interpretation does not hold. Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p177.
114 Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p177.

these are evidence for nonlocal interactions."[115] Lucien Hardy is not convinced that all the experimental loopholes have yet been closed but should that ever be the case, he concludes "we would have to admit that nature is nonlocal."[116] Just under half of the group surveyed would intepret the experimental violations of Bell's inequality as indicating some form of nonlocality, but in all sorts of different ways. This is indicated by the range of their answers to another question put to them by Schlosshauer, "what intepretative program can make the best sense of quantum mechanics, and why?"[117] Their answers range from the de-Broglie-Bohm, some form of Ghirardi-Rimini-Weber collapse theory, the traditional Copenhagen interpretation, theories in which correlations or information were the primitives, to theories that ensured the reality of "local beables." Bacciagaluppi is sure that Bell's inequalities cannot be explained by any underlying local models but does not commit to any particular theory. They are all prepared to sacrifice the locality assumption but with no common clarity as to why.

5.6 Keeping locality

The other nine surveyed were unwilling to abandon the locality assumption, whether because to do so would seem to them to undermine the practice of science[118] or because they contend that attempts to save it lead to the development of models that " add to the structure of quantum theory…..[things that are] not needed to explain any observable phenomena but are themselves unobservable."[119] We observe a number of different strategies by which locality is retained. It is important to note again at this point, that Maudlin and Norsen claim that locality is the only assumption needed to derive Bell's

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[115] Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p177.
[116] Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.175
[117] Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.
[118] see Christopher Fuch's defence of the importance of locality Schlosshauer. *Elegance and Enigma. The Quantum Interviews*. p.171
[119] Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.167 Brukner likens Bohm's model to Ptolemaic epicycles.

inequality and that attempts to claim otherwise are to misunderstand Bell's argument.[120]

5.6.1 Dispensing with realism

In this context realism covers determinism, property definiteness, micro and macro counterfactual definiteness. Anton Zeilinger, who rather hedges his bets when answering Schlosshauer's question, says "Bell's inequalities are generally seen to disprove local realism, that is the joint assumption of locality and realism."[121] Nevertheless, when push comes to shove, he notes "it is most likely the idea of realism that we have to give up."[122] As Daniel Greenberger puts it "Bell's theorem is based on the idea that there exist sets of instructions that determine future events as consequences of past events. The violations of Bell's theorem tell us that there exist situations that do not follow from such sets of instructions." David Mermin couches the realism assumption he rejects in terms of counterfactual definiteness. He quotes Asher Peres' famous phrase "Unperformed experiments have no results"[123] and says that the experiments done with the GHZ version of Bell's inequalities demonstrate further "the outcome of the test you actually performed is incompatible with each and every possible set of outcomes for all the tests you might have performed and didn't. This adds a word to Asher's famous title: "Unperformed experiments have no *conceivable* outcome. The irreducible probability that follows from the rejection of realism Časlav Brukner stresses, applies just as much to "correlations between outcomes measured on several systems"[124] as to a single system. He accounts for this by saying that "all systems of the same information-carrying capacity are equivalent."[125] Wojciech

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[120] Maudlin. "Space-Time in the Quantum World."; Travis. "Against "Realism"."
[121] Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.179
[122] Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.179
[123] Peres. "Unperformed Experiments Have No Results."
[124] Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.167
[125] Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.167

Zurek also stresses the primary and objective nature of quantum probabilities but he does not couch what he takes the experimental violations of Bell inequalities to mean in terms of assumptions that can be kept or dispensed with. For Zurek all the assumptions of classical physics are suspect: he concludes "the basic message is that our universe is quantum not classical."[126]

Christopher Fuchs has another take on what the experimental violations mean. Fuchs agrees with Asher Peres that unperformed experiments have no outcome. " Quantum measurement results do not preexist in any logically determined way before the act of measurement."[127] But Fuch's view of what a quantum measurement is is distinctive: "the place where the quantum measurement outcome "happens" is exactly at the agent who took the action on the quantum system in the first place."[128] For Fuchs and the adherents of the Qbist interpretation (which Fuchs holds is simply the straightforward Copenhagen interpretation[129]), the wave function is a description of what the human experimenter knows and not a description of the world independent of us. Thus what the experimental violation of Bell's inequalities tells us is "our actions matter indelibly for the rest of the universe (pluriverse) …… It signals the world's plasticity …… With every quantum measurement set by an experimenter's free will, the world is shaped just a little as it participates in a moment of birth."[130] Fuchs calls this idea, "participatory realism."[131] He accepts Peres' view that unperformed experiments have no results and therefore rejects both micro and macro counterfactual definiteness however he does

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126 Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.179
127 Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.170
128 Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.171
129 Christopher A Fuchs and A Peres, "Quantum Theory Needs No 'Interpretation'," *Physics Today* 53, no. 3 (2000):70-71.
130 Schlosshauer. *Elegance and Enigma. The Quantum Interviews*. pp.171-2
131 Christopher A Fuchs. "On Participatory Realism," Information and Interaction: Eddington, Wheeler and the Limits of Knowledge (2017):113-34.

not see this as a statement about what is going on in the microworld. He simply claims that quantum experiments give answers as to what happens in the macro world where experimenters act rather than being a description of what is going on in a micro world underneath.

5.6.2 Dispensing with no retrospective causation

Anthony Leggett, a Nobel Laureate, carefully outlines the assumptions that undergird Bell's inequality, holds onto locality and substitutes the assumption he calls "microscopic realism" with "macroscopic counterfactual definiteness," like Fuchs, placing the condition on what is observed in the macro world rather than what is assumed as going on in the micro world. Macroscopic counterfactual definiteness Leggett defines as the assumption that "the hypothetical "outcome" of measurements that were not in fact performed can be treated as a fixed fact about the world."[132] Wishing to hold onto both this assumption and the assumption of locality, Leggett states he "takes very seriously the possibility" that it is the no retrospective causation assumption that has to go. Leggett is the only representative of this view amongst Schlosshauer's sample but there are interpretations of quantum mechanics that have been developed on the basis of doing without a privileged arrow of time. Oliver Costa de Beauregard was the first to note the possibility.[133] In John G Cramer's Transactional interpretation,[134] retrospective causation is held to apply within specific quantum interactions while Huw Price holds that the assumptions as to the direction of the arrow of time are simply the result of human perception.[135] It is still a matter of current debate.[136]

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[132] Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.175
[133] O Costa de Beauregard " Une Résponse À L'Argument Dirigé Par Einstein, Podolsky Et Rosen Contre L'Interprétation Bohrienne Des Phénomènes Quantiques," *Comptes Rendus de l'Académie des Sciences* 236 (1953):1632-1634.;
[134] Cramer. "The Transactional Interpretation of Quantum Mechanics."
[135] E.g. Price. "Does Time-Symmetry Imply Retrocausality? How the Quantum World Says "Maybe"."

5.6.3 Dispensing with the assumption that experiments have definite outcomes

David Wallace, an adherent of the Everett Many Worlds interpretation, also holds onto locality and realism and rejects a different "tacit premise in Bell's argument: that the results of measurements actually have definite outcomes."[137]

5.6.4 Dispensing with the joint probability distribution assumption

Finally amongst Schlosshauer's sample is Arthur Fine. In his answer to Schlosshauer's question, Fine is not dogmatic about whether probabilities are objective or subjective and concludes that the minimum that the experimental violations tell us is that "this much is clear: satisfaction of the Bell inequalities makes certain joint distributions for observables that do not commute well-defined"[138] i.e. the reason that the inequalities are violated is because it is not possible to represent the observables in Bell experiments in one probability space. This simple statement can itself be interpreted in different ways. On the basis of an objective theory of probability such as von Mises, this is telling us something about nature whereas for those who hold a Bayesian position, it is telling us something about probability theory.

The question of whether or not Bell inequalities have been violated, and if they have been, what that might mean is complex. There is no indication that this debate will be resolved. There are questions in this field that are capable of being answered mathematically and

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[136] Matthew S. Leifer and Matthew F. Pusey "Is a Time Symmetric Interpretation of Quantum Theory Possible Without Retrocausality?" *Proceedings of the Royal Society A:* 473, no. 2202 (2017):1-25.
[137] Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.178
[138] Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.169

scientifically: Christian's questions about the significance of Bell's use of scalar algebra; Thompson's questions about the way statistics are used to massage the experimental results in a direction favourable to those who accept Bell inequalities have been violated; and Fine, Accardi and Khrennikov's discussion of probability theory. However, these issues are generally held to be irrelevant by those who believe the inequalities have been violated who are then faced with a choice as to how to interpret them. The choice of which assumption to drop can be rationally defended but there is still no sign that the choice of how to interpret the violation of Bell's inequality, should you believe it has been, can be scientifically mandated. It remains a matter of choice, dictated by prior commitments about the nature of science and of the world and, for the mathematicians, philosophers and physicists in the field, this choice remains wide open. This is the only incontrovertible fact to emerge from the 48 year debate as to what the experimental violations of Bell-type inequalities mean since Kasday, Ullman and Wu conducted the first experiment in 1970.[139] In the next chapter, we shall explore how theologians have navigated these complex waters.

[139] Reported on by Kasday in 1971: Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons."

Chapter Six: Theologians interpret Bell 1964 Part I

Theological interest in Bell 1964 began with articles published by Patrick A Heelan S.J.[1] and Charles Hartshorne[2] in 1977. Having outlined the different ways in which physicists, philosophers and mathematicians have interpreted the significance of Bell's work, we now survey how theologians view their meaning. This chapter covers the period from Heelan and Hartshorne's 1977 references to William P. Brown's casual reference to Bell 1964 in 2010.[3]

6.1 1977-1979

Heelan's article "Quantum Relativity and the Cosmic Observer"[4] does not make a theological point but mentions Bell 1964 as part of the "attack"[5] launched by the EPR[6] paper on quantum mechanics because of its incompatibility with relativistic physics. Only Heelan cited his chapter,[7] so it does not contribute to further theological discussion. In two 1977[8] articles Hartshorne acclaims Bell as providing a way out of a specific problem that Hartshorne believed relativity theory had posed for process philosophy. He mentions it first in the "The Neglect

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[1] Heelan S.J. "Quantum Relativity and the Cosmic Observer."
[2] Hartshorne. "The Neglect of Relative Predicates in Modern Philosophy."; Charles Hartshorne. "Bell's Theorem and Stapp's Revised View of Space-Time," *Process Studies* 7, no. 3 (1977):183-91.
[3] William P. Brown. *The Seven Pillars of Creation. The Bible, Science and the Ecology of Wonder.* Oxford: Oxford University Press (2010).
[4] Heelan S.J. "Quantum Relativity and the Cosmic Observer."
[5] Heelan S.J. "Quantum Relativity and the Cosmic Observer."p.29.
[6] EPR
[7] According to Google Scholar, July 7th 2018. All data regarding citations is from Google Scholar.
[8] Hartshorne. "The Neglect of Relative Predicates in Modern Philosophy."; Hartshorne."Bell's Theorem and Stapp's Revised View of Space-Time."

of Relative Predicates in Modern Philosophy,"[9] and explores it more fully in "Bell's Theorem and Stapp's Revised View of Space-Time."[10] Relativity theory posits the block universe as existing in three spatial dimensions plus time. Causal connections propagate forward within the backward light cone of that which is caused and propogate only into the forward light cone from where they originate. Most of the block universe is thereby unconnected and therefore symmetrically, i.e. mutally independent, meaning that process philosophers or theologians could not claim that there is a sequential ordering of all events known to God, "[t]he 'past' has no clear meaning in relativity physics. There is an 'absolute past' of a given event and its absolute future, but between them a 'present' teeming with relations of before and after."[11] Hartshorne sums up the difficulty: "relativity physics has seemed to compel us to accept the symmetrical independence of spatially separated events. For decades I suffered philosophically from this seeming necessity."[12]

Hartshorne became aware of Bell's work through Henry Stapp. In "The Neglect of Relative Predicates in Modern Philosophy,"[13] the first paper to indicate the significance of Bell's work for theism, Hartshorne references two papers of Stapp's.[14] In "Bell's Theorem and Stapp's Revised View of Space-Time,"[15] Hartshorne quotes a personal communication with Stapp and references Stapp's "S-Matric

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[9] Hartshorne. "The Neglect of Relative Predicates in Modern Philosophy."
[10] Hartshorne. "Bell's Theorem and Stapp's Revised View of Space-Time."
[11] Hartshorne. "Bell's Theorem and Stapp's Revised View of Space-Time."
[12] Hartshorne. "Bell's Theorem and Stapp's Revised View of Space-Time."p.185
[13] Hartshorne. "The Neglect of Relative Predicates in Modern Philosophy."
[14] Henry P Stapp. "Theory of Reality," *Foundation of Physics* 7, no. 5-6 (1977):313-23. & Stapp."Bell's Theorem and World Process."
[15] Hartshorne. "Bell's Theorem and Stapp's Revised View of Space-Time."

Interpretation of Quantum Theory."[16] Hartshorne writes, "Bell's philosophically exciting theorem, ... implies that if certain very subtle influences, incapable of conveying messages, are taken into account, spatially separated events are not wholly independent of one another, and that not all influences are limited to the speed of light." [17] In this Hartshorne detects the possibility of a universal "now" and thinks Bell has provided the means to "revise and strengthen process philosphy by the elimination of symmetrical independence."[18] Quoting Stapp, Hartshorne says that Bell's work has demonstrated that "causal effects can be transmitted over large distances without the possibility of material conveyance"[19] and therefore that "'spatially separated parts of reality must be related in some way that goes beyond the familiar idea that causal connections propagate only into the forward light-cone.'"[20] "Thus the famous Einsteinian concept of the space-time structure, standard for nearly sixty years, received at last some qualification."[21]

Hartshorne claims this is hugely significant. "Bell's discovery is philosophically as revolutionary as Heisenberg's:"[22] "[it] simplifies, if it does not first make possible, the influence upon the world that Whitehead attributes to divine decisions. They need only be inserted between successive events in the ultimate series. Only those who know the trouble process philosophers have had trying to insert divine influences into the world of mutually independent contemporaries

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[16] Stapp. "S-Matrix Interpretation of Quantum Theory."
[17] Hartshorne. "The Neglect of Relative Predicates in Modern Philosophy."p.318n.16
[18] Hartshorne. "The Neglect of Relative Predicates in Modern Philosophy."p.318n.16
[19] Hartshorne. "Bell's Theorem and Stapp's Revised View of Space-Time."p.184
[20] Hartshorne. "Bell's Theorem and Stapp's Revised View of Space-Time."p.184
[21] Hartshorne. "Bell's Theorem and Stapp's Revised View of Space-Time."p.184, re Hartshorne'spersonal communication with Stapp.
[22] Hartshorne. "Bell's Theorem and Stapp's Revised View of Space-Time."p.187

know what a relief this doctrine affords."[23] However, Hartshorne becomes somewhat more sanguine, noting seven years later, "It is supposed to follow from quantum physics (Bell's theorem) that not all influences are limited by the speed of light"[24] adding "I am appalled by the difficulties."[25] As David Ray Griffin points out, by 1991, Hartshorne seems to see Bell's work more as part of the problem posed by relativity theory to his process theism than as part of the answer. Criticising an article about his work by James Devlin,[26] Hartshorne's writes, "he does not mention my puzzle over Bell's theorem in quantum theory or my admitted inability to relate what I call divine time to worldly time as known to us through physics."[27] Even more clearly, responding to William L. Reese's article in the same volume,[28] Hartshorne comments, noting that "the problem, for me: [is] how God as prehending, caring for, sensitive to, the creatures is to be conceived, given the current non-Newtonian idea of physical relativity, according to which there is apparently no unique cosmic present or unambiguous simultaneity."[29] The problem he hailed Bell as solving for him in 1977 remains unsolved in 1991.

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[23] Hartshorne."Bell's Theorem and Stapp's Revised View of Space-Time."p.187
[24] Charles Hartshorne. "Hartshorne: Response to Weiss," in *Existence and Actuality. Conversations With Charles Hartshorne*, ed. John B. Cobb Jnr, and Franklin I. Gamwell, Chicago: University of Chicago Press, (1984).p.129
[25] Hartshorne."Hartshorne: Response to Weiss."p.129
[26] James P. Devlin. "Hartshorne's Metaphysical Asymmetry," in *The Philosophy of Charles Hartshorne*, ed. Lewis Hahn, La Salle, Illinois: Open Court, (1991).
[27] Charles Hartshorne. "A Reply to My Critics," in *The Philosophy of Charles Hartshorne*, ed. Lewis Hahn, Illinois: Open Court, (1991).p.631, cited in David Ray Griffin."Hartshorne, God and Relativity Physics," *Process Studies* 21 (1992):85-112. (online version not paginated).
[28] William L. Reese. "The "Trouble" With Panentheism—And the Divine Event," in *The Philosphy of Charles Hartshorne*, ed. Lewis Hahn, Illinois: Open Court, (1991).
[29] Hartshorne. "A Reply to My Critics."

"Bell's Theorem and Stapp's Revised View of Space-Time"[30] has been cited 18 times between 1977 and 2016, 13 of which are by process theists.[31] Despite Hartshorne's own careful attention as to how Bell's paper was being interpreted scientifically, by 2005, amongst those for

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[30] Hartshorne."Bell's Theorem and Stapp's Revised View of Space-Time."

[31] In date order these citations are: William B Jones. "Bell's Theorem, H.P. Stapp, and Process Theism," *Process Studies* 7, no. 4 (1977):250-61.; Donald Wayne Viney. "Charles Hartshorne's Global Argument for God's Existence: An Analysis and Assessment" PhD, The University of Oklahoma Graduate College, (1982).; George Lucas Jnr. "Outside the Camp: Recent Work on Whitehead's Philosophy, Part II," *Transactions of the Charles S. Pierce Society* 21, no. 3 (1985):327-82.; Ronnie Leross Cooper. "Heidegger and Whitehead: A Phenomenological Investigation Into the Intelligibility of Experience" Rutgers, the State University of New Jersey, (1990).; Brian G. Henning. "A Genuine Ethical Universe: Beauty, Morality and Nature in a Progressive Cosmos" PhD, Fordham University, Ann Arbour (2003).; Michael Epperson. *Quantum Mechanics and the Philosophy of Alfred North Whitehead* Fordham University Press, (2004).; Brian G. Henning. *The Ethics of Creativity: Beauty, Morality and Nature in a Progressive Cosmos* Pittsburgh: University of Pittsburgh Press, (2005).; David Ray Griffin. *Whitehead's Radically Different Postmodern Philosophy. An Argument for Its Contemporary Relevance*, Suny Series on Philosophy, Albany: State University of New York Press, (2007).; Joachim Klose."Time and Temporality - From Whitehead to Quantum Physics" & "Process Ontology From Whitehead to Quantum Physics" (Papers presented at the "Beyond Metaphysics? Transcontinental Explorations in Alfred North Whitehead's late thought,"Conference, Dec 4th-6th, Claremont, California, (2008).; C S Peirce. *Collected Papers* Cambridge MA: The Belnap Press of Harvard University Press, (1931).; George W. Shields, "A Logical Analysis of Relational Realism," in *Physics and Speculative Philosophy: Potentiality in Modern Science*, ed. Timothy E. Eastman, Michael Epperson, and David Ray Griffin de Gruyter, (2016).:127-142. Of the remaining six citations, one is in the field of Japanese Studies, (Makoto Ozaki. *Inviduum, Society, Humankind: The Triadic Logic of the Species According to Hajime Tanabe*, Brill's Japanese Studies Library, Leiden: Brill, (2001).), one of Buddhist thought, (V.W. Bhaskar. *Faith and Philosophy of Buddhism*, Kalpaz Publications, (2009).), one in philosophy (H.H. Oliver. *A Relational Metaphysic* Netherlands: Springer, (1981).), one in the philosophy of religion (Andy Sanders, and Kristof de Ridder. *Fifty Years of Philosophy of Religion*, Leiden: Brill, (2007).) and two in theology (William Lane Craig. *Time and the Metaphysics of Relativity*, Springer, (2000).; Chandra Wickramasinghe and Theodore Walker. *The Big Bang and God: An Astrotheology* New York: Palgrave Macmillan, (2015).)

whom Hartshorne provides their knowledge of Bell's work, Bell has become a trope. He is rolled out by Brian G. Henning in a footnote to back up Charles Peirce's doctrine of synechism without any further explanation.[32] Hartshorne's paper on Bell is in Henning's bibliography but with no awareness that Hartshorne's position on what the significance of the experimental violations of Bell's inequality might be had changed over time. Likewise, in the most recent citation of Hartshorne's paper, George W Shields also seems unaware of Hartshorne's later misgivings and states,[33] incorrectly, that Hartshorne's mention of Bell's theorem implies Hartshorne's acceptance of the possibility of supraliminal communication, something that Hartshorne specifically rules out.[34] This lack of engagement with the complexity of Hartshorne's thinking about the significance of Bell's work is underlined by the total lack of engagement by those who cited Hartshorne's article[35] and specifically with William B. Jones' article[36] that critically engages with Hartshorne's. As the next engagement with Bell in a theistic context after Hartshorne's own, Jones' article should be of direct relevance to those who cite Hartshorne's. However, Jones' article is only cited twice, first in 2007[37] and finally in 2012.[38] Citing an article like "Bell's Theorem and Stapp's Revised View of Space-Time"[39] does not necessarily imply engagement with either the implications or the trajectory of its author's thought. Hartshorne's article on Bell's work

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[32] Henning. *The Ethics of Creativity: Beauty, Morality and Nature in a Progressive Cosmos*.p.194n.23
[33] Shields. "A Logical Analysis of Relational Realism."p.135
[34] "Thus the veto on messages sent faster than the speed of light still stands." Hartshorne. "Bell's Theorem and Stapp's Revised View of Space-Time."p.186
[35] Ferdinand Santos and Santiago Sia. *Personal Identity, the Self and Ethics*, AIAA, (2007).
[36] Jones. "Bell's Theorem, H.P. Stapp, and Process Theism."
[37] Santos and Sia. *Personal Identity, the Self and Ethics*.
[38] Griffin. *Whitehead's Radically Different Postmodern Philosophy. An Argument for Its Contemporary Relevance*.
[39] Hartshorne. "Bell's Theorem and Stapp's Revised View of Space-Time."

has not been cited by a theologian or theistic philosopher interested in the significance of Bell's work for theology. Kirk Wegter-McNelly, the theologian who has written most extensively on Bell's work,[40] does have a book by Hartshorne in his bibliography,[41] but does not reference Hartshorne's work on Bell. The most recent theologian to draw on Bell's work, Catherine Keller,[42] also draws on Stapp's work and process theism, but while mentioning Hartshorne's work,[43] likewise does not mention his work on Bell. This will be a recurrent theme.

William B. Jones' article,[44] also published in 1977, notes Hartshorne's work but it is more a study of Stapp's own derivation of a Bell inequality than of Bell's work itself.[45]

6.2 1980-89

The next theologian to discuss Bell's work concentrates on Stapp's interpretation. Dean Fowler suggests interdisciplinary criteria for working in the field of theology and science. [46] He notes that scientists no less than theologians, explicitly or implicitly, develop world views that frame their theories and cites David Bohm's implicate order[47] and Stapp's S-matrix interpretation of quantum theory[48] as examples.

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[40] Wegter-McNelly. *The Entangled God: Divine Relationality and Quantum Physics*.
[41] Charles Hartshorne. *The Divine Relativity: A Social Conception of God*, New Haven, CT: Yale University Press, (1948).
[42] Catherine Keller. *Cloud of the Impossible: Negative Theology and Planetary Entanglement* New York: Columbia University Press, (2015).
[43] Keller. *Cloud of the Impossible: Negative Theology and Planetary Entanglement*.p.37
[44] Jones. "Bell's Theorem, H.P. Stapp, and Process Theism."
[45] Jones. "Bell's Theorem, H.P. Stapp, and Process Theism."p.261.
[46] Dean Fowler. "Quantum Physics and Christian Anthropology," *Horizons* 7, no. 2 (1980):205-18.
[47] Fowler cites David Bohm, and Dean Fowler. "The Implicate Order: A New Order for Physics," *Process Studies* (1978):73-102.
[48] Fowler cites Stapp. "S-Matrix Interpretation of Quantum Theory."

Fowler mentions Bell's work because of its significance for Stapp's[49] thus seeing Bell's work from Stapp's nonlocal perspective. "Quantum Physics and Christian Anthropology"[50] is cited only once, ten years later, in K.J. Sharpe's research proposal to base a theology on Bohm's holomovement metaphysics.[51]

The next theologian to reference Bell's work, Carl Raschke based his work[52] on Gary Zukav's *The Dancing Wu Li Masters*.[53] Despite this being a very cogent account of science from Young's slits to the Aspect experiments, it fuelled speculations far beyond the borders of mainstream science.[54] Quoting Zukav, Raschke concluded, "In 1964 nuclear physicist J.S.Bell demonstrated that all the 'separate parts of the universe are connected in an intimate and immediate way.'[55] Here is an early example of a scholar wheeling out Bell's inequality to support a particular position they hold on the strength of someone else's assessment of Bell's work, with little or no attempt to address or acknowledge the complexity involved in interpreting it. Raschke seems unaware of the complicated debate over which he has so deftly skated. His article has been cited twice: once by Sharpe in his outline of a

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[49] Fowler. "Quantum Physics and Christian Anthropology."p.211
[50] Fowler. "Quantum Physics and Christian Anthropology."
[51] K.J. Sharpe. "A Theology Based on David Bohm's Holomovement Metaphysics: An Outline for Possible Research" http://www.ksharpe.com/word/BM09.htm.
[52] Carl Raschke. "From God to Infinity, or How Science Raided Religion's Patent on Mystery" *Zygon. Journal for Religion and Science* 17, no. 3 (1982):227-42.
[53] Gary Zukav. *The Dancing Wu Li Masters*, New York: William Morrow, (1979).
[54] By 2018, it has been cited 1759 times in books that range from management theory (Evert Gummesson. *Quantative Methods in Management Research* Thousand Oaks, CA, London & Dehli: Sage Publications, (1999).) to Kinesiology (David R. Hawkins. *Power Vs Force. The Hidden Determinants of Human Behaviour*, Veritas Books, (1995).) through reincarnation (Christopher M. Bache. *Life Cycles: Reincarnation and the Web of Life* Paragon House Publishers, (1994).).
[55] Zukav, *The Dancing Wu Li Masters*.p.282

research proposal into Bohm's holomovement metapahysics[56] and in an article on Michael Polanyi's Taoism.[57]

The next theologian to comment on Bell's work was John Polkinghorne, in his popular science book, *The Quantum World* [58] Polkinghorne is one of the main figures in the development of religion and science.[59] *The Quantum World*[60] is cited in a number of theological books and articles that cite either Bell or Aspect's work: e.g. "Realism and Reverence;"[61] "Theology and the Heisenberg Uncertainty Principle"[62] and *Quantum Theology. Spiritual Implications of the New Physics* [63] In all of these, the authors, following Polkinghorne, interpret Bell's work as affirming realism at the cost of nonlocality.[64]

Robert John Russell, also a major figure in the Science and Religion movement, was the next theologian to mention Bell's work. David Bohm's work is the main theme of Russell's 1985 article and Bell's work is cited, quite surprisingly, as undermining realism, "Recently the realist approach has been severely challenged, at least within physics, by Bell's theorem (Bell 1964), which implies that realism is

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[56] Sharpe. "A Theology Based on David Bohm's Holomovement Metaphysics: An Outline for Possible Research."
[57] James W. Stines. "I Am the Way: Michael Polanyi's Taoism," *Zygon* 20, no. 1 (1985):59-77.
[58] John Polkinghorne. *The Quantum World*, Princeton NJ: Princeton University Press, (1984).p.75.
[59] Fabio Gironi. "The Theological Hijacking of Realism. Critical Realism in "Science and Religion."" *Journal of Critical Realism* 11, no. 1 (2012):40-75.p.41
[60] John Polkinghorne. *The Quantum World*
[61] Walter R. Thorson."Realism and Reverence," *Perspectives on Science and Christian Faith* 39 (1987):75-87..
[62] Christopher F Mooney S.J., "Theology and the Heisenberg Uncertainty Principle," *The Heyrthop Journal* 34 (1993):247-73;373-86.
[63] Diarmuid O'Murchu M.S.C. *Quantum Theology. Spiritual Implications of the New Physics*, New York: The Crossroads Publishing Company, (1997).
[64] e.g.Mooney S.J. "Theology and the Heisenberg Uncertainty Principle."p.293n.42

inconsistent with quantum physics."[65] Russell acknowledges that it is local realism that Bell's work undermines but he still implies that Bohm's work is a counter weight to Bell's, "Hence I would argue that [the] critical realist interpretation of physics based on nonlocal hidden variable theories such as Bohm's is viable in spite of the more general challenge to realism by Bell's theorem,"[66] when in fact Bell himself is clear that a violation of his inequality would show that the "grossly nonlocal structure" of Bohm's interpretation " is characteristic"[67] of any theory that reproduces exactly the predictions of quantum mechanics.[68] Such an important misunderstanding of Bell's 1964 paper by such a careful scientist and scholar is significant and prompts the question as to whether or not Russell had been able to read Bell's article. This article[69] has been cited 14 times, from the first in 1986[70] in an article about physics, Buddhism and postmodernism to its most recent citing, a book by Heidi Russell in which she reflects theologically on the physics of David Bohm and Lee Smolin.[71] Despite

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[65] Robert John Russell. "The Physics of David Bohm and Its Relevance to Philosophy and Theology," *Zygon* 20, no. 2 (1985):135-58.p.149
[66] Russell."The Physics of David Bohm and Its Relevance to Philosophy and Theology."p.149
[67] Bell 1964 p.195
[68] In 1993, Russell is still characterizing Bell's work as undermining realism (Robert John Russell, "Introduction," in *Quantum Cosmology and the Laws of Nature. Scientific Perspectives on Divine Action*, ed. Robert J Russell, Nancey Murphey, and C. J. Isham, Vatican State, Berkeley, California: Vatican Observatory & The Centre for Theology and the Natural Sciences, (1996).p15) but by his 2001 Introduction to "Quantum Mechanics. Scientific Perspectives on Divine Action", he refers to Bell's work as "describing" "delicate (nonlocal) correlations (Robert John Russell. "Introduction," in *Quantum Mechanics. Scientific Perspectives on Divine Action. Volume 5*, ed. Robert John Russell, Philip Clayton, Kirk Wegter-McNelly, and John Polkinghorne, Vatican City & Berkeley, CA: Vatican Observatory Publications & Center for Theology and the Natural Sciences, (2001). p vii)
[69] Russell. "The Physics of David Bohm and Its Relevance to Philosophy and Theology."
[70] Dawne C. McCance. "Physics, Buddhism and Postmodern Interpretation," *Zygon* 21, no. 3 (1986):287-96.
[71] Heidi Russell, *The Source of All Love: Catholicity and the Trinity*, New York: Orbis Books, (2017).

Robert John Russell's own confusion, a substantial number of these citations are in works that, like his article, reflect on David Bohm's metaphysics and therefore in these later articles or books, John Bell's work is adduced straightforwardly in support of Bohm's nonlocality.[72]

In 1988, in an article published in the first book of the Divine Action series, Polkinghorne discusses the issues raised by Bell's work but without mentioning Bell. [73] Polkinghorne acknowledges his own philosophical commitment to realism and, after a discussion about EPR, states that Alain Aspect's experiments "have revealed that ……..'nonlocality' is to be found in nature."[74] Polkinghorne does not give the slightest indication that, while being an entirely legitimate extrapolation from an acceptance that Bell's inequality has been violated, the acceptance of the nonlocality of the quantum world follows as a result of a choice made to adhere to realism, a choice that could equally be made in the opposite direction. In the same volume,[75] Robert John Russell, while coming to the same conclusion as Polkinghorne, continues to give a confusing account of Bell's work. While he notes simply and accurately, that it "underscores the dramatic difference between classical and quantum statistics"[76] in contrast to his comments in his earlier essay,[77] Russell draws the same realist conclusion as Hartshorne, Polkinghorne and Brown, albeit, initially, somewhat more tentatively: "the processes producing [the

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[72] e.g. K.J. Sharpe. "Holomovement Metaphysics and Theology," *Zygon* 28, no. 1 (1993):47-60.p.49

[73] Polkinghorne. "The Quantum World."in *Physics, Philosophy and Quantum Mechanics,* Robert John Russell, William R. Stoeger,S.J. & George V. Coyne (eds) Vatican City:Vatican Observatory (2000):333-342.

[74] Polkinghorne. "The Quantum World."p.338

[75] Robert John Russell. "Quantum Physics in Philosophical and Theological Perspective," in *Physics, Philosophy and Theology*, Vatican City State: Vatican Observatory, (2000).

[76] Russell. "Quantum Physics in Philosophical and Theological Perspective."p.346

[77] Russell. "The Physics of David Bohm and Its Relevance to Philosophy and Theology."p.152

measures on the two separated electrons] are to a certain extent inseparable."[78] Nevertheless, Russell concludes this part of this argument with confidence, "nature reveals a highly non-local and holistic character at the quantum level which is strikingly different from the separability of nature in our ordinary experience."[79] This is not Russell's final position on Bell's work in this chapter, however. Later Russell repeats his 1985 contention[80] that Bell's theorem poses a "challenge to realism."[81] Interpretation of the experimental violations of Bell's inequality hinges on the choice made as to which of the assumptions upon which Bell based his inequality is responsible for the violations. Russell seems to want to hold onto the assumptions of both locality and realism. He is driven by an adherence to an existing metaphysical position, not to an interpretation of quantum physics espoused for scientific reasons but an adherence to critical realism, a metaphysical position held for theological reasons. Russell does not make it clear, however, how espousing critical realism enables him to avoid choosing between realism and locality. Polkinghorne is also a critical realist but is clear in all his writings that a choice has to be made and he chooses to sacrifice locality. Critical Realism is a philosophy developed[82] amongst the Religion and Science community, drawing on the philosophy of science of the same name developed by the late Roy Bhasker.[83] Originally formulated by the late Ian Barbour in

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[78] Russell. "Quantum Physics in Philosophical and Theological Perspective."p.347
[79] Russell. "Quantum Physics in Philosophical and Theological Perspective."p.348
[80] Russell. "The Physics of David Bohm and Its Relevance to Philosophy and Theology."p.152
[81] Russell. "Quantum Physics in Philosophical and Theological Perspective."p.354
[82] Gironi,would say "appropriated", Gironi, "The Theological Hijacking of Realism. Critical Realism in "Science and Religion.""p.41.
[83] Roy Bhaskar. *A Realist Theory of Science*, Leeds Books, (1975).

his book, *Issues in Science and Religion* [84] it was further developed by Alister McGrath.[85]

As part of his discussion of Bell's theorem in "Quantum Physics in Philosophical and Theological Perspective," Russell observes, "If one is satisfied with physical theories taken as computational devices, then quantum theory can be considered adequate and further speculation about ' the underlying reality' become pointless. On the other hand, if one wants physical theory to yield insights about the ontological character of nature, then the inference to the non-local aspect of these underlying processes may well force one to rethink the metaphysical assumptions (including the atomistic model of matter) on which classical physics is based."[86] In some sense, Russell is saying no more than the physicists, philosophers of science and mathematicians already surveyed have said. If one wishes to hold onto a philosophy of science that enables the results of scientific experiments to be interpreted as telling us something about nature rather than the results of experiments, then the "inference to the non-local aspect of these underlying processes" has to be made with the consequences Russell indicates. Thus Russell moves from his 1985 position, "Bell's theorem ….. implies that realism is inconsistent with quantum physics"[87] to his 1988 position "nature reveals a highly non-local and holistic character at the quantum level"[88] because of a commitment to critical realism but he acknowledges that a realist interpretation of Bell's work and of quantum physics as a whole needs to be defended and argued for rather than just stated. However, Russell cannot bring

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[84] Ian G. Barbour. *Issues in Science and Religion*, Prentice Hall, (1966).
[85] Gironi."The Theological Hijacking of Realism. Critical Realism in "Science and Religion.""pp.57-65.
[86] Russell. "Quantum Physics in Philosophical and Theological Perspective."p.351
[87] Russell. "The Physics of David Bohm and Its Relevance to Philosophy and Theology."p.149
[88] Russell. "Quantum Physics in Philosophical and Theological Perspective."p.348

himself to dispense with locality. Russell's later reflections on the significance of Bell's work remain unclear. Russell's "Quantum Physics in Philosophical and Theological Perspective"[89] has been cited 21 times in English in works relating to science and theology.[90]

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[89] Russell. "Quantum Physics in Philosophical and Theological Perspective."

[90] K. Helmut Reich. "The Relation Between Science and Theology: The Case for Complementarity Revisited," *Zygon* 25, no. 4 (1990):369-90.; Wilhelm B Drees. "Update. Quantum Cosmologies and the "Beginning"," *Zygon* 26, no. 3 (1991):373-96.; M Głódź. "Search for "Eternal Information" in Science -Two Perspectives," in *The Science and Theology of Information*, Geneva: Labor et Fides, (1992).:333-336; Małgorzata Głódź. "On the Edge of Promise and Misuse: Contemporary Dialogue Between Science and Religion," *Theoria et Historia Scientiarum* Vol 3 (1993):32-36.; Robert J Russell. "Religion and the Theories of Science: A Response to Barbour," *Zygon* 31, no. 1 (1996):29-41.; Carl S. Helrich. "The Teachers' File. Thermodynamics: What One Needs to Know," *Zygon* 34, no. 3 (1999):501-14.; Robert J. Brecha. "Schrödinger's Cat and Divine Action: Some Comments on the Use of Quantum Uncertainty to Allow for God's Action in the World," *Zygon* 37, no. 4 (2002):909-24.; Nicholas T Saunders. *Divine Action and Modern Science* Cambridge: Cambridge University Press, (2002).; Robert John Russell and Kirk Wegter-McNelly. "Science," in *The Blackwell Companion to Modern Theology*, ed. Gareth Jones, Oxford: Blackwell, (2004).; Günter Thomas. "Complexity in Systematic Theology: The Case for the Christian Concept of 'New Creation' in the Dialogue With Science," in *The Significance of Complexity: Approaching a Complex World Through Science, Theology and the Humanities*, eds. Kees van Kooten Niekerk, and Hans Buhl, Aldershot: Ashgate, (2004).; Antje Jackelén. *Time and Eternity: The Question of Time in Church, Science and Theology*, West Conshohocken, PA: Templeton Foundation, (2005).; Peter E Hodgson. *Theology and Modern Physics*, Aldershot and Burlington, Vermont: Ashgate, (2005).; Jürgen Audretsch. "View into the quantum world II: entanglement and its consequences" *in Entangled World. The Fascination of Quantum Information and Computation*, ed Jürgen Audretsch. Wiley (2005):39-64; Gennaro Auletta. "Science, Philosophy and Religion Today: Some Reflections," *Theology and Science* 5, no. 3 (2007):267-87.; Alvin Platinga. "What is "Intervention"?," *Theology and Science* 6, no. 4 (2008):.369-401.; Paul O Ingram. "Constrained By Boundaries," in *The Boundaries of Knowledge in Buddhism, Christianity and Science*, ed. Paul David Numrich, Göttengen: Vandenhoeck & Ruprecht, (2008).; John Cheng Wai-leung. "How Physics Affects Metaphysics and the Concept of God in the History of Western Thought: An Outline," Danshui (Taipei), Taiwan, (2011).; Jitse M. van der Meer. "Is There a Created Order for Cosmic Evolution in the Philosophy of Herman Dooyeweerd?" in *The*

The first of these citations is by Russell himself in an article responding to Ian Barbour's Gifford Lectures.[91] Russell expresses clearly the horns of the dilemma on which he has impaled himself: "the challenge to Barbour, as to the rest of us who defend 'locality' (i.e. special relativity) in spite of quantum correlations with spacelike separations, and who do so while supporting realism (even if 'critically'), is to produce a metaphysical system through which the 'nonseparability' ontology of quantum systems, their radical wholeness, can be made intelligible. Again this is an outstanding and unsolved problem in our field."[92] Russell seems to be denying that a choice has to be made between saving realism or saving locality. This is a defensible position held by a number of physicists and philosophers of science who comment on Bell's work, but it requires either an entirely alternative explanation as to how the violations can be accounted for or an account of why either Bell's original formulation or the experiments done on the basis of them are flawed. Russell takes neither of those routes, plumping instead for a new "metaphysical system" in which "nonseparability" can cohere with a locality that respects special relativity. Compared to the forensic discussions by the physicists, philosophers and mathematicians in response to Schlosshauer's question as to what the violation of Bell's inequality tells us,[93] Russell's account is confusing, even misleading.

Future of Creation Order Vol. 1, Philosophical, Scientific, and Religious Perspectives on Order and Emergence, Springer, (2017).; Arnold O. Benz. "Astrophysics and Creation: Perceiving the Universe Through Science and Participation," *Zygon* 52, no. 1 (2017):186-95. & Paul J. Schutz, "Ineffable Cosmos, Ineffable Love: Divine Action and the 'Laws of Nature' in the Theology of William R. Stoeger, S.J." PhD Fordham University, (2017).

[91] Ian Barbour, *Religion in an Age of Science (Gifford Lectures 1989-91 Vol 1)* Harper Collins, (1990).

[92] Russell. "Religion and the Theories of Science: A Response to Barbour."p.31

[93] Schlosshauer, *Elegance and Enigma. The Quantum Interviews*.pp.161-180

The confusion that was evident in his 1988 article[94] remains in his response to Barbour's.[95] Peter Hodgson, who cites Russell's 1988 article follows Russell in defending both realism and locality but does so for mathematical rather than metaphysical reasons. Like Kasday, Fine and Khrennikov, Hodgson believes that the experimental violations show that the joint measureability assumption that Bell makes does not hold.[96] The authors of the two most recent works that cite these articles by Russell, while reflecting on the implications of Bell's work in a theological context, choose uncomplicatedly, like Polkinghorne, to sacrifice locality. Ernest L. Simmons plumps for a straightforward nonlocality[97] and Jürgen Audretsch, for an ontological as opposed to a mathematical interpretation of entanglement.[98] Of the articles citing Russell's, it is Robert J. Brecha's 2002 Zygon[99] article that brings the most clarity to the debate. Unfortunately, Brecha's article is not itself cited by anyone in Theology and Science or Religion and Science circles who is interested in the implications of Bell's work.[100]

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[94] Russell. "Quantum Physics in Philosophical and Theological Perspective."p.354
[95] Russell. "Religion and the Theories of Science: A Response to Barbour."p.31.
[96] Hodgson. *Theology and Modern Physics*.p.159
[97] Ernest L. Simmons. "Beyond Dialogue: The Role of Science Within Theology," *Dialog: A Journal of Theology* 46, no. 3 (2007):189-98.p.195
[98] Audretsch. "View into the quantum world II: entanglement and its consequences,"
[99] Brecha. "Schrödinger's Cat and Divine Action: Some Comments on the Use of Quantum Uncertainty to Allow for God's Action in the World."
[100] cited in Ian J. Thompson. "Discrete Degrees Within and Between Nature and Mind," in *Psycho-Physical Dualism Today. An Interdisciplinary Approach*, ed. Alessandro Antonietti, and Antonella Corradini, Lanham, MD: Lexington Books, (2008).":99-126; Richard M. Daniels. "The Rosminian Doctrine of the Soul: A Critical Inquiry Into the Philosophical and Theological Relevance of Antonio Rosmini's Understanding of the Existence and Nature of the Human Soul in Light of Modern Scientific Claims" PhD, Southeastern Baptist Theological Seminary, (2015).; David L. Bradnick. "Loosing and Binding the Spirits: An Emergentist Theology of the Demonic" PhD, Regent School of

This observed commonality whereby Bell's work is adduced as establishing something about the world by theologians or scientists writing in a theistic context without giving proper attention to the complexity of Bell's work or to the history of its interpretation continued. In a book published in 1989, the year after the articles of Russell and Polkinghorne, the theologian William C Placher[101], cites the Aspect experiments as endorsing indeterminism rather than nonlocality. He and Vern Poythress are the only theologians to do so.[102] Placher notes the work of John Bell and the subsequent experiments as pointing to the lack of "consensus amongst physicists as to the possibility of *any* 'realistic' interpretation of quantum theory."[103] Placher is unaware of the work of Polkinghorne or Russell and has learned of Bell and Aspect through the physicist, Bernard D'Espagnat. D'Espagnat's article is clear that it is "local realistic" theories that the Aspect experiments undermine but Placher does not pick up on the significance of the word "local" used in this context, implying as it does d'Espagnat's view that realism can be maintained providing locality is dispensed with.

6.3 1990-1999

K. J. Sharpe also skates over the complexity of Bell's work. In "Relating the Physics and Religion of David Bohm,"[104] Sharpe reads Bell's work as endorsing the nonlocality of Bohm's system, not acknowledging that there are other legitimate choices as to how the significance of Bell's

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Divinity, (2015). & Benz. "Astrophysics and Creation: Perceiving the Universe Through Science and Participation."

[101] William Carl Placher. *Unapologetic Theology. A Christian Voice in a Pluralistic Conversation*, Westminister: John Knox Press, (1989).p.139

[102] Vern Poythress. *Chance and the Sovereignty of God*, Wheaton, Illinois:Crossway (2014)

[103] Placher. *Unapologetic Theology. A Christian Voice in a Pluralistic Conversation*.p.139

[104] K.J. Sharpe."Relating the Physics and Religion of David Bohm," *Zygon: Journal of Religon and Science* 25, no. 1 (1990):105-22.

work can be interpreted. Sharpe knows of Stapp's work on Bell but doesn't refer to Hartshorne's article nor Jones' critique of Stapp. Sharpe's article has been cited regularly since but only twice in places where Bell's work is mentioned. One of these citations is by Sharpe himself,[105] in an article in which he claims that Aspect's experiments show that "that nonlocality exists at the quantum level."[106] The second citation is in Mark Worthing's 1996 book, "God, Creation and Contemporary Physics," in which Bell's work is not just mentioned but discussed. However, despite his careful caveats, Worthing also assumes that the experimental violations of Bell's inequality has established the reality of nonlocality.[107] William E. Brown is the next theologian to mention Bell's work.[108] Writing two years after Polkinghorne's and Russell's[109] articles and four years after Polkinghorne's book,[110] Brown does not appear to know of either theologians' work. Like Placher, Brown's source for Bell's work is Bernard d'Espagnat. Brown interprets the experimental violations of Bell's theorem from a realist perspective.[111] Without any nuance or acknowledgement of the complexity of interpreting what the experimental violations may or may not mean, Brown writes, "Bell's theory simply claims that any model of reality must be connected by influences that travel faster than the speed of light. Bell's theorem, which is a mathematical formula, has been demonstrated experimentally."[112] Brown knows it is necessary to defend his

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[105] Sharpe. "Holomovement Metaphysics and Theology."
[106] Sharpe. "Holomovement Metaphysics and Theology."p.49
[107] Mark William Worthing. *God, Creation and Contemporary Physics* Minneapolis: Ausburg Fortress, (1996).p.128
[108] William E. Brown. "Quantum Theology: Christianity and the New Physics," *Journal of the Evangelical Theological Society* 33, no. 4 (1990):477-87.
[109] Polkinghorne. "The Quantum World."
[110] Polkinghorne. *The Quantum World*.
[111] Brown. "Quantum Theology: Christianity and the New Physics." see p481n7 where he references Bernard d'Espagnat, "The Quantum Theory and Reality," *Scientific American* 241 (1979):158-81.
[112] Brown. "Quantum Theology: Christianity and the New Physics." p.481

commitment to realism but does so rather heavy-handedly and defensively, "Biblically, Christians are committed to realism - the belief that the universe actually exists apart from observation. God created the world before there was any human observer to bring it into existence. To take an antirealist position is to trivialize science as a study of nature. Einstein's comment is appropriate: ' I cannot imagine that a mouse could drastically change the universe by merely looking at it.' Is it really so absurd to believe that our observations genuinely apprehend that which is objectively real?"[113]

Unashamedly realist and underplaying the complexities that beset any interpretation of Bell's work, Sharpe, speaking about Bohm's work in 1990, again says Aspect's experiments prove "nonlocality"[114] proving Einstein's disquiet with quantum mechanics. Einstein's point was precisely the opposite. For Einstein, EPR was designed to show that quantum theory is necessarily incomplete not that the world was "nonlocal," an idea with which Einstein profoundly disagreed.[115] In Barbour's discussion of Bell's work in his Gifford Lectures published in 1990, [116] he clearly expressed the choice offered when interpreting the experimental violations of Bell's inequality: "Most physicists conclude that we should follow Bohr here,[117] *giving up classical realism and keeping locality..........* Another option is to keep classical realism and give up locality."[118] Nevertheless, ignoring this choice, Barbour

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113 Brown. "Quantum Theology: Christianity and the New Physics." pp.482-3
114 K.J. Sharpe. "Misusing Quantum Physics," in *The Theology and Science of Information. Proceedings of the Third European Conference on Science and Theology, Geneva, March 29th -April 1st 1990*, ed. Christoph Wasserman, Richard Kirby, and Bernard Rordorf, Geneva: Editions Labor et Fides, (1992).p.138
115 Howard. "Einstein on Locality and Separability.";
116 Barbour. *Religion in an Age of Science (Gifford Lectures 1989-91 Vol 1)*.
117 Italics original. Barbour would have been aware that Bohr had died before Bell formulated his inequality.
118 Barbour. *Religion in an Age of Science (Gifford Lectures 1989-91 Vol 1)*.p.107

suggests that within the framework of critical realism, nonlocality, in combination with indeterminacy, can be tempered into "a more limited form of holism"[119] despite the fact that if the assumption of determinism[120] is sacrificed, the assumption of locality can be saved. Barbour seems content to lose both. In a footnote[121] Barbour lists the books from which he has gained his understanding of Bell's work: they are all popular science books[122] save Fritz Rohrlich's article in Science[123] in which the implications of sacrificing the assumption of classical realism are clearly explained. Barbour's book is the most widely cited of all the books or articles that mention Bell in a theological context. [124] It is unfortunate therefore that his discussion of the implications of the experimental violations are less than clear.

In the following year, Polkinghorne writes more fully in his 1991 book, *Reason and Reality*[125] about the implications of Bell's work, this time mentioning John Bell by name.[126] As a respected scholar in both theoretical physics and theology, whose writings on his area of prior expertise, theoretical physics, will be heard with the utmost seriousness by theologians, his statement in "Reality and Reason"[127] is misleading. Overlooking the choice that has to be made to interpret the experimental violations of Bell's inequality in the way he does, he

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[119] Barbour. *Religion in an Age of Science (Gifford Lectures 1989-91 Vol 1)*.p.108
[120] In the debate about how to interpret the experimental violations determinism equates to realism.
[121] Barbour. *Religion in an Age of Science (Gifford Lectures 1989-91 Vol 1)*.p.278n.18
[122] Heinz Pagels. *The Cosmic Code*, New York: Bantam Books, (1983).; Polkinghorne. *The Quantum World*.; Paul Davies. *Other Worlds.* London: Abacus, (1982).; Paul Davies. *God and the New Physics*, London: J. M. Dent & Sons, (1983).; P.C.W. Davies and Julian R. Brown. *The Ghost in the Atom*, Cambridge: Cambridge University Press (1986).
[123] Fritz Rohrlich. "Facing Quantum Mechanical Reality," *Science* 221, no. 4617 (1983):1251-55.
[124] to July 10th 2018, 748 citations, 18 in 2018.
[125] John Polkinghorne. *Reason and Reality* London: S.P.C.K., (1991).
[126] Polkinghorne. *Reason and Reality*.p.43
[127] Polkinghorne. *Reason and Reality*.p.43

writes baldly and without qualification, "the theoretical analyses of John Bell and the experimental investigations of Alain Aspect and his collaborators have made it clear that there is an inescapable non-locality involved in the phenomena."[128] The following year K.J. Sharpe's discussion is more nuanced. In his writing so far, Sharpe has stated, without hesitation, that Aspect's experimental testing of Bell's inequality has established nonlocality but in "Misusing Quantum Physics,"[129] this is counterbalanced by his acknowledgement that relating scientific theories to theology is complex. However, unlike Sharpe's less nuanced contributions, "Misusing Quantum Physics,"[130] has not been cited at all since its publication. In 1993, the late Christopher F. Mooney S.J published two articles[131] and a book chapter under the title "Theology and the Heisenberg Uncertainty Principle"[132] in which he considered Bell 1964 and its implications. Mooney's discussion of Bell is measured and clear.[133] He acknowledges that the interpretation of Bell's work boils down to a choice as to which of the assumptions upon which the inequality is based has to be dropped following the inequality's violation by experiment. "To conform experimentally to the statistical probabilities of standard quantum theory, one or other of these assumptions had to be abandoned. In other words, experimental agreeement .... has to mean either that particles are not objective in the classical sense or that there is instantaneous nonlocal communication between them."[134] Mooney is

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[128] Polkinghorne. *Reason and Reality*.p.43
[129] Sharpe. "Misusing Quantum Physics."
[130] Sharpe. "Misusing Quantum Physics."
[131] Mooney S.J. "Theology and the Heisenberg Uncertainty Principle.":247-73; 373-86.
[132] Christopher F Mooney S.J. (Forward by John E. Theil & Afterword by Margaret A. Farley), "Theology and the Heisenberg Uncertainty Principle," in *Theology and Scientific Knowledge. Changing Models of God's Presence in the World*, London: University of Notre Dame Press, (1996).
[133] Mooney S.J. "Theology and the Heisenberg Uncertainty Principle."pp.94-97
[134] Mooney S.J., "Theology and the Heisenberg Uncertainty Principle." pp.267-8

the only theologian who correctly summarizes this point. However, Mooney follows the line of thinking we have seen in Russell and Barbour, that somehow this choice can be sidestepped and the implications of Bell made more palatable by framing it as a evidence of a metaphysical holism. Polkinghorne is the only theologian whose work on Bell Mooney cites[135] but from his popular science book, *The Quantum World*[136] rather than from any of his theological discussions of Bell's work. Mooney's article has not been cited by theologians.

The next theological discussion of John Bell's work is by A.A. Grib,[137] who derives his own Bell-type inequality. While most of the theologians and theistic philosophers, whom we have already considered, sacrifice locality to save realism, in Grib's discussion of the implications of the experimental violations of Bell-type inequalities he dispenses with classical realism and also with a straightforward locality. He reframes discussion of nonlocality in terms of an incompatibility of quantum properties with relativity.[138] Grib's article has not been cited in later theological reflections on Bell's work,[139]

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135 Referencing Bell, Mooney cites Jeremy Berstein. *Quantum Profiles* Princeton, New Jersey: Princeton University Press, (1991).:50-89; James T Cushing and Ernan McMullin. *Philosophical Consequences of Quantum Theory. Reflections on Bell's Theorem*, vol. II, Studies in Science and the Humanities, Notre Dame, Indiana: University of Notre Dame Press, (1989).; F. David Peat. *Einstein's Moon Bell's Theorem and the Curious Quest for Quantum Reality* Chicago: Contemporary Books, (1990).; Pagels.*The Cosmic Code*. & Polkinghorne. *The Quantum World*.
136 Polkinghorne. *The Quantum World*.
137 Andrey Anatoljevitch Grib. "Quantum Cosmology, the Role of the Observer, Quantum Logic," in *Quantum Cosmology and the Laws of Nature*, ed. Robert J Russell, Nancey Murphy, and Christopher J. Isham, Vatican City: Vatican Observatory, (1993).pp.165-7 & pp.179-181
138 Grib does not dispense with realism entirely, rather "their existence [ie properties described by non-commuting operators] is a quantum logical existence and does not correspond to the existence of objective events in space-time." Grib. "Quantum Cosmology, the Role of the Observer, Quantum Logic."p.172
139 It is cited in Jackelén. *Time and Eternity: The Question of Time in Church, Science and Theology*.p.154

although Russell does comment on it in his "Introduction"[140] to the volume in which it was published, writing with a clarity, albeit not hitherto seen in his own comments on Bell's work about the choice Bell's work presents to the commentator, "John Bell['s] …. famous theorem forces us to chose between idealism (in which quantum objects with non-commuting properties only exist when observed)[141] and realism (in which quantum objects with non-commuting properties have a qualified existence independent of observation)."[142] However, Russell still misses the point that sacrificing determinism at the quantum level is not the same as adopting idealism *per se*. Three years later, Russell again refers to Bell's work in his Zygon article commenting on Barbour's Gifford Lectures[143] and states his approbation of Barbour's position, namely, despite accepting that Bell's inequality has been violated, defending both locality and realism by producing "a metaphysical system through which the 'nonseparability' ontology of quantum systems, their radical wholeness, can be made intelligible."[144] We shall see how this plays out later when we consider the foremost theological reflection on Bell's work, KW-M.

The scientific and theological significance of the experimental violations of Bell-type inequalities is a theme taken up in 1996 by Mark Worthing, who follows K.J. Sharpe[145] and reads Bell's work through Henry Stapp. Worthing takes the experimental violations to imply the nonlocality of the world.[146] This is, as we have seen, a perfectly

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[140] Russell. "Introduction."
[141] While philosophical idealism is not the same as solipsism, Russell is correct in attributing a belief about the non-existence of the properties of quantum objects before they are measured to scientists and philosophers of science who wish to retain locality.
[142] Russell. "Introduction."p.15
[143] Russell. "Religion and the Theories of Science: A Response to Barbour."
[144] Russell. "Religion and the Theories of Science: A Response to Barbour."p.31
[145] See Worthing. *God, Creation and Contemporary Physics*.p.127.
[146] Worthing. *God, Creation and Contemporary Physics*.p.128.

legitimate stance to take, but it is not as straightforward as Worthing contends. Worthing's *God, Creation and Contemporary Physics* is widely cited,[147] most recently by Ted Peters in 2018.[148] However, despite Worthing's considered reflection on Bell's work, he is not cited by the theologian who has researched this area most thoroughly, Kirk Wegter-McNelly.

Assuming that Bell's theorem has been violated and the nonlocality of the world demonstrated,[149] Alfred Driessen and Antoine Suarez take for granted the theological relevance of Bell's work. In their 1997 book[150] they take the experimental violations of Bell's inequality as pointing to the limits of human knowledge, and while disavowing a "God of the gaps" theology, they see it pointing to a deeper reality, undergirding all that we experience, to which human science points but cannot reach but that is accessible to other human ways of knowing of which human God-talk is one.[151]

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[147] Of the 120 citations (5th July 2018), only three (Brown. *The Seven Pillars of Creation. The Bible, Science and the Ecology of Wonder*.; Jackelén. *Time and Eternity: The Question of Time in Church, Science and Theology*.; Joyce Ann Konigsburg. "Relational Interreligious Dialogue: Interdisciplinary Arguments From Creator/Creature Theology and Quantum Entanglement" PhD, Duquesne University, (2017).) allude to the work of John Bell, of which only one mentions Bell in the text (Brown. *The Seven Pillars of Creation. The Bible, Science and the Ecology of Wonder*.p.170).

[148] Ted Peters. "Science and Religion: Ten Models of War, Truce and Partnership," *Theology and Science* 16, no. 1 (2018):11-53.

[149] Alfred Driessen and Antoine Suarez, *Mathematical Undecidability, Quantum Nonlocality and the Question of the Existence of God* Netherlands: Springer, (1997). e.g. see pp.ix, 101,115-7, in which local realism is conflated with realism. Bell's lecture in the book is more nuanced, John S Bell. "Indeterminism and Nonlocality," in *Mathematical Undecidability, Quantum Nonlocality and the Question of the Existence of God*, ed. A Driessen, and A Suarez (Springer, 1997).

[150] Driessen and Suarez. *Mathematical Undecidability, Quantum Nonlocality and the Question of the Existence of God*.

[151] Alfred Driessen and Antoine Suarez. "Final Remarks: Becoming Aware of Our Fundamental Limits in Knowing and Doing, Implications for the Question of the Existence of God," in *Mathematical Undecidability, Quantum Non-Locality and the Question of the Existence*

By the late 1980s and early 1990s, quantum physics, including EPR, the work of John Bell and the Aspect experiments, had been mined for its relevance for thinking about human consciousness and spirituality far beyond the purview of science. *The Dancing Wu Li Masters*[152] by Gary Zukav, one of the early members of the Fundamental Fysiks Group,[153] became the means by which interpretations of quantum physics fuelled speculations far beyond the borders of scientific reflection and inquiry. Thus the next theologian to cite Bell's work Diarmud O'Murchu[154] read the Aspect experiments not only through scientifically cogent accounts such as those of Russell, Murphy and Isham,[155] Polkinghorne,[156] Herbert,[157] and Zukav[158] but also through the lens of management thinkers, like Danah Zohar,[159] who have assumed, on the basis of Bell's work, that nonlocality is an uncontestable fact about the world and have extrapolated the significance of this far beyond its original field of application.[160]

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of God, ed. Alfred Driessen, and Antoine Suarez, Netherlands: Springer, (1997).

152 Zukav. *The Dancing Wu Li Masters*..

153 An informal seminar held at Berkeley, CA. see Kaiser. *How the Hippies Saved Physics. Science, Counterculture, and the Quantum Revival*.p.xvii

154 O'Murchu M.S.C. *Quantum Theology. Spiritual Implications of the New Physics*.

155 Robert J Russell, et al. *Quantum Cosmology and the Laws of Nature. Scientific Perspectives on Divine Action 2nd Edition*, Vatican City and Notre Dame, Indiana: Vatican Observatory &The Center for Theology and Science, (1993).;

156 Polkinghorne. *The Quantum World*.

157 Nick Herbert. *Quantum Reality Beyond the New Physics*, New York: Random House: Anchor Books, (1985).

158 Zukav. *The Dancing Wu Li Masters*.

159 On the website of one of her publishers (https://www.bloomsbury.com/uk/spiritual-intelligence-9780747536444/) Zohar is described as a "Physicist, philosopher management educator." O'Murchu cites two of her books, Danah Zohar, *The Quantum Self*, New York: HarperCollins, (1991).; and *The Quantum Society*, London: Bloomsbury, (1993).

160 e.g. "The extent to which correlated nonlocal influences exist between apparently separate bodies or events depends on the extent

O'Murchu assumes Aspect's experiments have established the truth of Bohm's holographic theory and concludes, "One of the disturbing consequences of this discovery is that the tangible realm of our everyday lives is understood to be a kind of illusion (what the Buddhists call maya). It is the deeper realm of experience, the implicate order, that gives birth to all the objects and experiences of our physical world in much the same way that a piece of holographic film can manifest the entire holographic picture."[161] While Ian Barbour, who commented on Bell's work in the1998 edition of *Religion and Science* outlines what he thinks the violations of Bell's inequality has established in a more measured way, his conclusion is still as definite as O'Murchu's. In a section headed "Wholeness and Emergence" he writes, "The correlations between distant events shown in the Bell's theorem experiments is a dramatic example of …. interconnectedness."[162] While the physicists, philosophers of science and mathematicians we have surveyed in chapter five who accept that Bell's inequalites have been violated were often equally definite in the conclusion they reached as to what the violations of Bell's inequality meant, they were all aware that to decide what the experimental violations mean was to make a choice between valid competing explanations. There is little awareness amongst theologians of the range of conflicting interpretations that remain open to them. Also in 1998, in a chapter in which his only cited authority for his interpretation of "the implications of quantum physics and particularly Bell's theorem"[163] is his own earlier work,[164] Russell misleads his

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to which a system is in a "particle" or a "wave" state........ I shall return to this in later chapters when discussing personal identity and the roots of alienation." Zohar. *The Quantum Self*.p.37

161 O'Murchu M.S.C. *Quantum Theology. Spiritual Implications of the New Physics*.p.57

162 Ian Barbour. *Religion and Science: Historical and Contemporary Issues. A Revised and Expanded Edtion of Religion in an Age of Science* (London: SCM, 1998).p.193

163 Robert John Russell. "Does the God Who Acts Really Act in Nature?" in *Science and Theology. The New Consonance*, ed. Ted Peters, Boulder, Colorado: Westview Press, (1998).p.89

readers by claiming in measured tones that quantum physics, "particularly Bell's theorem" means that theologians can conclude that God acts at the quantum level generally to produce the features of the classical world and that, specifically but indirectly, God acts at the quantum level to produce events of "special providence"[165] at the macroscopic level. Russell's chapter is cited by nine English language publications[166] all of which engage with the points that he is making about how God can be thought to act within the world.

In 1999, Bell's work reaches a milestone in relation to the science and theology debate: it is mentioned both cogently and succinctly in a text-book. In a chapter on Theology and the New Physics,[167] Bell's contribution to the debate about the interpretation of quantum mechanics is summed up thus, "Some years later, a quantum logician turned this paradox [ie EPR] into a testable prediction that now bears his name - Bell's inequality. This is an equation which should be true if two principles (assumed by Einstein and his colleagues in formulating the EPR paradox) hold in the world:

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164 Russell. "Quantum Physics in Philosophical and Theological Perspective."
165 Russell. "Does the God Who Acts Really Act in Nature?"p.89
166 John Henry, and Mariusz Tabaczek. "Causation," in *Science and Religion: A Historical Introduction*, ed. Gary B. Ferngren (1998).; Brecha. "Schrödinger's Cat and Divine Action: Some Comments on the Use of Quantum Uncertainty to Allow for God's Action in the World."; Elizabeth M. Hall. "God as Cause or Error? Academic Psychology as as a Christian Vocation," *Journal of Psychology and Theology*, 32 no 3:200-209; Niels Henrik Gregersen. "Divine Action, Compatibilism, and Coherence Theory: A Response to Russell, Clayton and Murphy," *Theology and Science* 4, no. 3 (2006):215-28.; Sanders and de Ridder. *Fifty Years of Philosophy of Religion*.; Simmons. "Beyond Dialogue: The Role of Science Within Theology."; Glenn B. Siniscalchi. "Contemporary Trends in Atheist Criticism of Thomist Natural Theology," *The Heythrop Journal* 54, no. 2 (2013).; Schultz and Winslow. 2013, Occasionalism East and West. 4th-5th May 2013 Harvard University:1-15; Glenn B. Siniscalchi. "Fine-Tuning, Atheist Criticism, and the Fifth Way," *Theology and Science* 12, no. 1 (2014):64-77..
167 Christopher Southgate, et al. *God, Humanity and the Cosmos* Edinburgh: T & T Clark, (1999).p.113

The principle of reality: that we can predict a physical quantity with certainty without disturbing the system, and

The locality principle: that a measurement in one of two isolated systems can produce no real change in the other.

Taken together, these principles imply an upper limit to the degree of co-operation that is possible between isolated systems. In 1982 a team of physicists at the University of Paris led by Alain Aspect demonstrated experimentally that this limit is exceeded in nature. In other words, our physical descriptions of the world in which we live cannot be both real and local in the above sense."[168]

While no work is specifically referenced in this chapter for details about John Bell's work, further reading for the whole chapter is suggested. Four of the suggested books reference Bell's work: two are by John Polkinghorne, in both of which he champions realism and therefore interprets the violations of Bell's inequality as demonstrating nonlocality; one is by Paul Davies in which he champions locality and therefore interprets the violations as establishing "reality triggered only by observation."[169] Davies notes both the challenge to realism and the challenge to locality but combines them and therefore gives no hint that this is mostly read in the wider scientific and philosophical debate as an either or choice: realism or locality. The fourth of the suggested books is Mark Worthing's and is the only book in the list by a professional theologian. Following Sharpe and therefore Stapp, Worthing too, assumes realism and therefore nonlocality.[170] While including Bell in a Theology and Science textbook indicates how relevant the editors consider it to be, this citation history is telling and representative of the ways by which Bell's work had come into the purview of theologians. Despite the 22 year history of Bell's work being referenced in theological works, Lawrence Osborn, the lead writer of this chapter had read only one

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[168] Southgate, et al. *God, Humanity and the Cosmos*.p.113
[169] Davies. *God and the New Physics*.p.107
[170] Worthing. *God, Creation and Contemporary Physics*.p.130

theologian with reference to Bell's work and it therefore seems most likely that he has become aware of Bell's work through his own reading in the area of quantum theory.

Apart from Heelan, Russell and Sharp who cite Bell's 1964 paper directly and do not reference any one else's work for their knowledge of it, the authors of theological books and articles in which Bell's inequality or theorem or the Aspect experiments are mentioned prior to the discussion of them in *God, Humanity and the Cosmos*[171] discover them, as if for the first time, from discussion by scientists or in popular science books. Hartshorne, Jones, Fowler and Viney know of Bell's work through Stapp, although Jones and Viney also draw on Hartshorne with Jones also commenting on Freedman and Clauser's paper.[172] Raschke[173] draws on Zukav,[174] while Thorson[175] cites the Aspect experiments. Placher reads Bell through d'Espagnat, as does Brown, who also cites Nick Herbert's *Quantum Reality beyond the New Physics.*[176] In contrast, Mooney's dicussion of Bell's significance draws on a significant number of authors[177] but not on any of the theologians who have commented on Bell's work previously, with the exception of Polkinghorne. In his discussion of Bell's work,[178] Worthing cites

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171 Southgate, et al. *God, Humanity and the Cosmos*.
172 FC
173 Raschke. "From God to Infinity, or How Science Raided Religion's Patent on Mystery."p.241n.6
174 Zukav. *The Dancing Wu Li Masters*.
175 Thorson. "Realism and Reverence."
176 Herbert. *Quantum Reality Beyond the New Physics*.
177 Berstein. *Quantum Profiles*.; Cushing, and McMullin. *Philosophical Consequences of Quantum Theory. Reflections on Bell's Theorem*.; Peat. *Einstein's Moon Bell's Theorem and the Curious Quest for Quantum Reality*.; Pagels. *The Cosmic Code*.; Polkinghorne. "The Quantum World."; Zukav. *The Dancing Wu Li Masters*.; Richard Schlegel. *Superposition and Interaction*, Chicago: University of Chicago Press, (1980).; John L. Casti. *Paradigms Lost*, London: William Morrow, (1989). & Roger Penrose. *The Emperor's New Mind*, Oxford: Oxford University Press, (1989).
178 Worthing. *God, Creation and Contemporary Physics*.pp.124-130

Sharpe,[179] Stapp,[180] Bell[181] and Aspect[182] themselves but, for his interpretation of Bell and what Aspect's work means, Worthing relies on Nick Herbert, who takes it to demonstrate nonlocality.[183] While Worthing, following Polkinghorne, draws back from embracing Bohm's implicate order, he assumes Bell's work can be taken as indicating the reality of nonlocality and some sort of "interconnectedness of matter."[184]

Even though Bell's work was considered significant enough to have been included in a text book in theology and science, it had not yet become itself an important topic in the field despite the very significant claims about the different and counter-intuitive ways in which reality was being interpreted based upon it. This sense that theologians or scientists writing in the area of religion and science or theology and science light on Bell directly through their reading of popular science books rather than through a theological tradition of appreciation has been suggested by noting the citations of those who have written on Bell's work and following how the books and articles mentioning Bell's work have themselves been cited. Of the authors who have, by 1999, mentioned Bell's work or the Aspect experiments only a few of them, as we have seen, go on to be cited in this regard by others.

6.4 2000-2010

The next cogent discussion of Bell's work by someone in the theology and science field is Robert Brecha's article in Zygon in 2002.[185]

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179 Sharpe. "Relating the Physics and Religion of David Bohm."
180 Henry P Stapp. "Quantum Mechanics, Local Causality and Process Philosophy," *Process Studies* 7, no. 3 (1977):173-82.
181 Worthing. *God, Creation and Contemporary Physics*.p.128
182 Worthing. *God, Creation and Contemporary Physics*.p.128
183 Worthing. *God, Creation and Contemporary Physics*.p.128
184 Worthing. *God, Creation and Contemporary Physics*.p.130
185 Brecha. "Schrödinger's Cat and Divine Action: Some Comments on the Use of Quantum Uncertainty to Allow for God's Action in the World."

Between the 1999 discussion of the violations of Bell's inequalities in a theology and science text book and Brecha's article, there were 16 mentions of Bell's work in a theistic or theological context. Three of these mentions were in the context of a discussion of process theism[186] and one of the possibility of divine action;[187] three proclaim the existence of nonlocality[188] and one absolute simultaneity.[189] Two mention Bell's work in passing: William R. Stoeger S.J. put the words "Bell inequalities" in brackets implying they are evidence for a mention of "quantum nonseparability, "[190] while Thomas Tracy, more carefully, notes that John Bell showed "that the theoretical predictions of quantum mechanics are incompatible with local hidden variable theories."[191] Six of those who mention Bell are more cautious: three note the difficulty of intepreting either Bell's theorem or Aspect's

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186 Duane Voskuil. "Hartshorne, God and Metaphysics: How the Cosmically Inclusive Personal Nexus and the World Interact," *Process Studies* 28, no. 3/4 (1999):212-30.p.11n.22; Lewis S. Ford. *Transforming Process Theism*, Series in Philosophy, New York: SUNY Press, (2000).p.201 & Joseph A. Bracken. *The One in the Many: A Contemporary Reconstruction of the God World Relationship*, Grand Rapids: William B. Eerdmans, (2001).p.206n.95 (and on p.96n.61 implicitly).

187 Thomas Tracy. "Divine Action and Quantum Theory," *Zygon* 35, no. 4 (2000):891-900.;

188 Craig. *Time and the Metaphysics of Relativity*.p.225; K.J. Sharpe. *Sleuthing the Divine: Nexus of Science and Spirit*, Ausberg Press, (2000). p.16; Abner Shimony. "The Reality of the Quantum World," in *Quantum Mechanics: Scientific Perspectives on Divine Action*, ed. Robert J Russell, et al, Scientific Perspectives on Divine Action, Vatican City, Berkeley, California: Vatican Observatory Publications, Centre for Theology and Natural Sciences, (2001).p.10

189 William Lane Craig. *God, Time and Eternity* Dodrecht: Kluwer Academic Publishers, (2001).p.54;

190 William R. Stoeger S.J. "Epistemological and Ontological Issues Arising From Quantum Theory," in *Quantum Mechanics. Scientific Perspectives on Divine Action. Volume 5*, Vatican City State & Berkeley, California: Vatican Observatory Publications & Center for Theology and the Natural Sciences (2001).

191 Thomas Tracy. "Creation, Providence and Quantum Chance," in *Quantum Mechanics: Scientific Perspectives on Divine Action (Volume 5)* Vatican City: Vatican Observatory Publications, (2001).

experiments, with either determinism or locality being ruled out[192] while one says there is a probability of nonlocal causality[193] and another that Bell's work points to "causal anomalies."[194] The sixth, Philip Clayton, doesn't himself discuss Bell but, in a section where he discusses the attempts of some scholars to provide an overarching interpretative framework such that the conundrums of quantum theory are dissolved, quotes a remark by Henry Stapp about Bell's theorem which Clayton points out is then taken out of context so as to give credence to the holism of Eastern traditions.[195]

There are two fuller discussions of Bell's work in theistic contexts during this period. The title of the late Shimon Malin's book gives away the presupposition which underpins his work, *Nature Loves to hide: Quantum Physics and the Nature of Reality, a Western Perspective*.[196] Malin's clear explanation of Bell's inequality reframes d'Espagnat's explanation of Bell's reasoning: [197] "there is nothing mysterious about Bell's inequalities. Once the assumption of local realism is accepted,

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[192] Mariano Artigas. *The Mind of the Universe Understanding Science and Religion* Philadelphia, London: The Templeton Foundation Press, (2000).p.85; Michael Redhead. "The Tangled Story of Nonlocality in Quantum Mechanics," in *Quantum Mechanics. Scientific Perspectives on Divine Action Vol 5*, ed. Robert J Russell, et al. Vatican State, Berkeley, California: Vatican Observatory, The Centre for Theology and the Natural Sciences, (2001).p.143; James T Cushing."Determinism Versus Indeterminism in Quantum Mechanics," in *Quantum Mechanics: Scientific Perspectives on Divine Action Vol 5*, ed. Robert J Russell, et al. (2001).p.107;
[193] Dean W. Zimmerman. "The Compatibility of Materialism and Survival: The Falling Elevator Model," *Faith and Philosophy* 16, no. 2 (1999):194-212.p.341;
[194] Nicholas T Saunders. "Does God Cheat At Dice? Divine Action and Quantum Possibilities," *Zygon* 35, no. 3 (2000):517-44.p.536
[195] Clayton. "Tracing the Lines: Constraint and Freedom in the Movement From Quantum Physics to Theology."p.229
[196] Shimon Malin. *Nature Loves to Hide: Quantum Physics and the Nature of Reality, a Western Perpsective*, Oxford: Oxford University Press, (2001).
[197] see Malin. *Nature Loves to Hide: Quantum Physics and the Nature of Reality, a Western Perpsective*.p.37. Malin cites d'Espagnat, "The Quantum Theory and Reality."

the proof amounts to nothing more than a sophisticated exercise in counting."[198] Malin carefully outlines the point that most theologians miss, that the experimental violations merely indicate that one of the assumptions upon which the inequality is based is flawed.[199] He is careful to express what the violations establish about "nature" is that "local realism" has to go[200] and, in the remainder of the book, puts forward Whitehead's process philosophy as an alternative system. Malin finds this helpful in resolving the problems posed by the violations to common sense realism because in Whitehead's thought "realism is only an abstraction."[201] However, while Malin sees the mutual relevance of process philosophy and the experimental violations of Bell's inequality, he is not cogniscent of the previous work in the field by Hartshorne, whose papers on the experimental violations of Bell's inequalities[202] do not occur in his bibliography. Nor does he include the work of the physicist Henry Stapp who has written about the significance of Bell's work for process philosophy since the 1970s. Malin's conclusions as to the relationship between Bell's work and Whitehead's are subtly different from Stapp's and Hartshorne's initial position. Hartshorne and Stapp saw in the experimental violations of Bell's inequality the possible resolution of the problem Hartshorne saw posed by relativity theory to Whitehead's process philosophy, namely the lack of absolute simultaneity. For Hartshorne, at least initially, the experimental violations of Bell's inequality offered the hope that Whitehead's process philosophy could be a scientifically cogent account of the world as we experienced it. For Malin, it is the

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[198] Malin. *Nature Loves to Hide: Quantum Physics and the Nature of Reality, a Western Perpsective*.p.80
[199] Malin. *Nature Loves to Hide: Quantum Physics and the Nature of Reality, a Western Perpsective*.p.79; p.80.
[200] Malin. *Nature Loves to Hide: Quantum Physics and the Nature of Reality, a Western Perpsective*.p.87
[201] Malin. *Nature Loves to Hide: Quantum Physics and the Nature of Reality, a Western Perpsective*.p.87
[202] Hartshorne. "The Neglect of Relative Predicates in Modern Philosophy."; Hartshorne, "Bell's Theorem and Stapp's Revised View of Space-Time."

polar opposite, Whitehead's process philosophy offers the hope of embedding the experimental violations of Bell's inequality within a cogent account of reality as we experience it. Thus Hartshorne adduces the experimental violations to make process philosophy scientifically cogent, while Malin adduces process philosophy to make the fact of the experimental violations metaphysically cogent.

The next discussion of Bell is simply misleading. Raymond Chiao firstly states that the experimental violations of Bell's inequalities prove that in the quantum realm, things do not have properties until the property in question is measured[203] while simultaneously claiming that the experimental violations have established nonlocality or nonseperability.[204] Chiao acknowledges the importance of the assumptions that Bell made in formulating his inequality for coming to a conclusion as to what the experimental violations have established, while also wanting to bracket consideration of them out of the discussion.[205] Six of the mentions of Bell's work we have just covered occur in the same volume,[206] the fifth volume in the Scientific Perspectives on Divine Action series, devoted to Quantum Mechanics[207] and it is to the discussion of divine action that Robert Brecha's article is a contribution. In his 2002 article, Brecha notes the difficulty of extrapolating meaning about the macroworld from the

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[203] Raymond Chiao."Quantum Nonlocalities: Experimental Evidence," in *Quantum Mechanics. Scientific Perspectives on Divine Action. Vol 5*, eds. Robert John Russell, et al. Vatican State,Berkeley, California: Vatican Observatory Centre for the Natural Sciences and Theology, (2001).p.23
[204] Chiao."Quantum Nonlocalities: Experimental Evidence."p.24
[205] Chiao. "Quantum Nonlocalities: Experimental Evidence."pp.23-4
[206] Shimony. "The Reality of the Quantum World."; Chiao. "Quantum Nonlocalities: Experimental Evidence."; Cushing. "Determinism Versus Indeterminism in Quantum Mechanics."; Redhead. "The Tangled Story of Nonlocality in Quantum Mechanics."
[207] Robert John Russell, et al., *Quantum Mechanics. Scientific Perspectives on Divine Action. Volume 5*, Vatican City State & Berkeley, California: Vatican Observatory & Center for Theology and the Natural Sciences, (2001).

results of quantum experiments,[208] he notes that in common with all those writing in the divine action debate, Russell's interpretation of quantum physics, including his interpretation of the violations of Bell's inequality, is determined by his prior metaphysical commitment to a realist position.[209] This is significant given that the best theological reflection on John Bell's work, published nine years later in 2011, KW-M, began life as Wegter-McNelly's 2003 PhD thesis[210] for which Russell was his advisor[211] and which Wegter-McNelly wrote while studying at the Center for Theology and Natural Sciences, the home of divine action. The core theme of Wegter-McNelly's thesis is that entanglement has been experimentally confirmed by the Aspect experiments amongst others.[212] Wegter-McNelly is aware that entanglement, in Schrödinger's original usage of the term,[213] is a feature of the mathematics of quantum theory and not something that is ontological[214] but he chooses to use the word to describe the behaviour of particles nevertheless,[215] justified by his metaphysical choice of critical realism.[216]

Between Wegter-McNelly's PhD thesis and KW-M, the theologians who have mentioned Bell's work or Aspects experiments, are confident in

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[208] Brecha. "Schrödinger's Cat and Divine Action: Some Comments on the Use of Quantum Uncertainty to Allow for God's Action in the World."p.919
[209] Brecha. "Schrödinger's Cat and Divine Action: Some Comments on the Use of Quantum Uncertainty to Allow for God's Action in the World."pp.910-11
[210] Kirk Wegter-McNelly. "The World, Entanglement and God: Quantum Theory and the Christian Doctrine of Creation" PhD, Berkeley, California, (2003).
[211] Wegter-McNelly. "The World, Entanglement and God: Quantum Theory and the Christian Doctrine of Creation."p.xi
[212] Wegter-McNelly. "The World, Entanglement and God: Quantum Theory and the Christian Doctrine of Creation."p.vii
[213] Schrödinger. "Discussion of Probability Relations Between Separated Systems."p.555
[214] KW-M.p.20
[215] KW-M.p104
[216] KW-M.pp102 & 111

their attribution of meaning to Bell's work but, apart from Peter Hodgson who thinks that the violation of Bell's inequalities is due to the failure of the joint probability distribution,[217] many of these are unaware of the complexity of this debate. Simmons, in a 2006 article, says, following the Aspect experiments, "Quantum indeterminacy and non-local holism are now seen as descriptive of the quantum world and experimentally verified"[218] which in the following year he calls, "nonlocal relationality."[219] Initially Roger P. Paul, in 2006, explained the significance of the experimental violations thus, "The results of this beautifully designed experiment [Aspect's 1982] were consistent with the predictions of quantum theory, and not with the assumption of separability,"[220] yet adds six pages later in total contradiction, "Therefore, the potentialities that quantum mechanics define in the wave function are knowable because through measurement they become actualities. Before the event of measurement, they cannot be thought of as existing, but on measurement, becoming actual, and therefore receiving actual form, they are capable of being known."[221] In 2009, mention of Bell within discussion of Whitehead's process theology re-emerges. Clayton notes Bell's work as a possible indication of the credibility of event metaphysics.[222] In the same year, Stoyan Tanev, like Paul, accepted that both nonlocality and the property of

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[217] Hodgson. *Theology and Modern Physics*.p.159.
[218] Ernest L. Simmons. "Quantum Perichoresis: Quantum Field Theory and the Trinity," *Theology and Science* 4, no. 2 (2006):137-50.p142
[219] Simmons. "Beyond Dialogue: The Role of Science Within Theology." p.195
[220] Roger P. Paul. "Subjectivist - Observing and Objective-Participant Perspectives on the World: Kant, Aquinas and Quantum Mechanics," *Theology and Science* 4, no. 2 (2006):151-69.p.159
[221] Paul. "Subjectivist - Observing and Objective-Participant Perspectives on the World: Kant, Aquinas and Quantum Mechanics."p.165 Paul shows no awareness that if this is his position re quantum mechanics, he does not have to accept that the experimental violations contradict separability since they merely demonstrate it.
[222] Philip Clayton. "Introduction," in *Physics and Whitehead. Quantum, Process and Experience*, ed. Timothy E. Eastman, and Hanks Keeton New York: State University of New York Press, (2009).p.11

quantum “entities” only becoming real when tested both followed from the experimental violations. Tanev writes that according to the Copenhagen intepretation all descriptors about what a quantum experiment is testing apply “to certain physically complex and non-localized entities, each involving the whole experimental arrangement, rather than to single and localized-in-space physical entities. ...... We are forced to recognize that our knowledge of physical system is in principle local and therefore incomplete. Recent modern physics experiments by the groups of A. Aspect in 1981 and N. Gisin in 1998 have clearly confirmed this view.”[223] Yes, the violation of Bell’s inequalities bears out the prediction of quantum mechanics but Bell would be most surprised to hear that therefore it supports the Copenhagen interpretation. Niels Bohr would be most surprised to know that his strictures on respecting the context of each experimental situation in extrapolating meaning from experimental results has been stretched into the contention that quantum entities are therefore “physically complex and nonlocal.” Bell’s work has become a trope, something dropped in to give scientific credence to a metaphysical or theological position, its usage resting on the authority of a previous reference to it rather than springing from any kind of nuanced understanding.

If 1993 marked a watershed in theological appreciation of Bell’s work because of the experimental violations were given consideration in a theology and science text book, 2006 is significant because their status as a trope has reached the point that they are simply included in an entry in an online course for undergraduates, *Introduction to Philosophy of Religion*, to back up a point at issue. At Lander University, Greenwood, South Carolina, in an entry headed, “Thomas Aquinas,

[223] Stoyan Tanev. “Essence and Energy: An Exploration in Orthodox Theology and Physics,” *Logos: A Journal of Eastern Christian Studies* 50, no. 1-2 (2009):89-153.p.115

'The Argument from Efficient Cause,' "[224] Lee C. Archie drops the bracketed words 'Bell's Theorem and quantum entanglement', into a paragraph outlining one of the common objections to Aquinas' arguments from cause, "Thomas oversimplifies the nature of causality in terms of a temporal sequence of causes. Contemporary physics (as the best epistemological result to date) has many different notions of relations of events—including no causality (only correlations between events), simultaneous causation, backward causation, causation at a distance (cf. Bell's Theorem or quantum entanglement), or merely mathematical description."[225] Both "Bell's Theorem" and "quantum entanglement" in this paragraph are hyperlinks. If "Bell's Theorem" is clicked, the following text box opens, "The principle of locality is that instantaneous action at a distance cannot take place. Bell proved that if quantum mechanics is true, the principle of locality is false."[226] Two years later , in a book written as an overview of the relationship between science and the Christian faith, Ross H. McKenzie and Benjamin Myers truthfully inform their readers that experimental tests of Bell's inequalities confirm the predictions of quantum mechanics, however they have preceded this by the rather less straightforward statement, "Entanglement occurs when two (or more) particles or systems become intertwined in an inseparable way so that the state of one of the particles completely determines the state of the other particle. Entanglement leads to Bell's inequalities......."[227] Then in 2010, in a book about the theological concept of creation, William P. Brown was able to drop mention of Bell's work producing the

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[224] Lee Archie. "Thomas Aquinas, "the Argument From Efficient Cause"," *The Philosophy of Religion*, http://philosophy.lander.edu/intro/cause.shtml., accessed 22nd July 2018 http://philosophy.lander.edu/intro/cause.shtml

[225] Archie. "Thomas Aquinas, "the Argument From Efficient Cause"." accessed 22nd July 2018.

[226] Archie. "Thomas Aquinas, "the Argument From Efficient Cause"." accessed July 25th 2018

[227] Ross H. McKenzie and Benjamin Myers. "Dialectical Critical Realism in Science and Theology: Quantum Physics and Karl Barth," *Science and Christian Belief,* 20, no. 1 (2008):49-66.p.61

experimental evidence for entanglement into a discussion of Wisdom's role in creation in the Septuagint's book of Proverbs.[228] Thus by 2010, Bell's work had become, for some theologians, a trope to be dropped into an argument to give the appearance of scientific cogency but apart from Wegter-McNelly's PhD thesis, there had been no stringent attempt by theologians to understand Bell's work in its own terms and therefore whether the use to which they wish to put it was justifiable. It is Wegter-McNelly in 2011 in his seminal book, KW-M, who does just that. In the next chapter, we shall give an overview of Wegter-McNelly's work on Bell. We shall see that, as fine a book as KW-M is, in the end, Wegter-McNelly's view of the signficance of Bell's work is explicitly dictated by Wegter-McNelly's commitment to critical realism.[229]

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228 Brown. *The Seven Pillars of Creation. The Bible, Science and the Ecology of Wonder*.pp.169-170
229 E.g. see KW-M.p.102

Chapter Seven: Theologians interpret Bell 1964 Part II

7.1 *The Entangled God* by Kirk Wegter-McNelly[1]

In KW-M, Kirk Wegter-McNelly gives the fullest account of Bell-type inequalities of any theologian before or since, even deriving his own version[2] of the CHSH inequality. Wegter-McNelly is clear that rigorous interdisciplinary work with science is vital. If theology turns it back on the "world as it is revealed through the sciences, we risk involving a god who created some imaginary world instead of the God who created ours."[3] However KW-M is an exercise in metaphorical constructive dogmatic theology and not a theological reflection on Bell's work. Wegter-McNelly uses entanglement to explore the idea of the intra-divine relationality and God's relationality to all that is and his comprehensive treatment of Bell's work is part of this trajectory. Wegter-McNelly sought to explore the potential of the scientific conception of entanglement, drawn from quantum physics, to provide metaphors that might assist in sketching out a contemporary Christian doctrine of God and his considerable work on Bell fits into this and therefore must be read within this context. Although Wegter-McNelly's treatment of entanglement is extremely detailed and scientifically cogent, it has been done in service of this wider aim: "This book aims to increase the storehouse of models available to Christian theologians and communities."[4] His intention is to enrich the already fertile contemporary theological reflection on divine relationality (which he outlines extensively in the book's second chapter[5]) with the twentieth

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[1] In this chapter, all references are to KW-M, unless otherwise stated.
[2] p.71
[3] p.3
[4] p.8
[5] p.22-45

century “discovery”[6] of entanglement. In doing this, he pays laudable attention to the scientific discourse about it. He admits, “this book may not occasion the kind of experience one typically associates with reading a theological text, but that is because the interdisciplinarity promoted herein implicates not only the act of writing but also the act of reading. This is not just a book with interdisciplinary origins, but one meant to facilitate an interdisciplinary experience.”[7] Wegter-McNelly attends to the varied discourse around entanglement and then uses it to enrich further theological reflection on the existing theological topos of divine relationality.

For the entanglement of quantum physics to have any purchase in discussion of divine relationality however, Wegter-McNelly first has to take sides in the scientific discussion of entanglement. For Schrödinger, who coined the term in 1935,[8] entanglement was a feature of the mathematics of quantum theory, it was the wave functions that are entangled after the interaction between the quantum systems, “By the interaction the two representatives [or ψ-functions] have become entangled.”[9] However for Wegter-McNelly, entanglement is an ontological feature of the world. This is clear right at the start of *KW-M* where the violation of a Bell inequality is called “The empirical confirmation of entanglement.”[10] As we have seen, a majority of quantum physicists, would agree with Wegter-McNelly that entanglement is an ontological feature of the world, but very many others choose an alternative way to interpret Bell’s work. This is something that Wegter McNelly discusses but frames not as a rational

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[6] p.9
[7] p.2
[8] Schrödinger.“Discussion of Probability Relations Between Separated Systems.”Schrödinger coined the term in English in this paper and went on to find a German word into which to translate it.
[9] Schrödinger. “Discussion of Probability Relations Between Separated Systems.”p.555
[10] p.2 McNelly assumes the entanglement is ontological. Bell seeks empirical confirmation of the nonlocal feature of Bohm’s theory.

scientific or even a philosophical choice but almost as a moral choice, "We must join those physicists and philosophers who, unwilling to content themselves with predictive success, have attempted to say something about the ontological implications of the series of discoveries that has led physicists to use the term "entanglement" when referring to the correlations they observe in Bell-type experiments. This is controversial territory, but it is unavoidable for anyone wishing to go beyond the confines of bare empiricism."[11] This is the key to Wegter-McNelly's understanding and interpretation of Bell's work.

Having set out his vision and rationale for his interdisciplinary project, Wegter-McNelly offers an overview of the theology of divine relationality.[12] He outlines what he is aiming to achieve and lays out the existing theological thought on the topic. Wegter-McNelly discusses what he takes to be three grounding principles of classical physics thus setting out the scientific context for his discussion.[13] Then he discusses quantum entanglement, the scientific concept which he thinks offers potential for use as a theological metaphor. [14] Chapter three is concerned with classical physics and it is at the end of this chapter that Wegter-McNelly derives his own Bell-type inequality. Wegter-McNelly is aware that what Bell was seeking to achieve in his inequality was to encode the general logic of local classical physics such that it could be tested against a quantum mechanical experiment. Wegter-McNelly accepts that Bell inequalities have been violated by experiment and interprets this to mean that these experiments demonstrate the reality of quantum entanglement. Wegter-McNelly then reflects on the philosophical implications of this[15] in preparation for a return to a consideration of how entanglement might be a fruitful

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[11] p.102
[12] pp.22-45.
[13] pp.46-73
[14] pp.74-101
[15] p.102-123

metaphor for the theological topic of divine relationality with which he began.[16]

In *KW-M*, Wegter-McNelly gives Bell's inequality the most sustained and rigorous attention of any theologian before or since but Wegter-McNelly's aim is not to explore Bell's work *per se* but to place Bell's work within the context of his own project, which is to enrich theological talk of divine relationality using as a metaphor the *motif* of entanglement, drawn from quantum physics. This directs his discussion of Bell's work. The existence of entanglement is what Wegter-McNelly needs the experimental violations of Bell's inequality to demonstrate. "This book aims to contribute to ongoing theological discussions about divine relationality by introducing a theological audience to one of the most significant scientific discoveries of the twentieth century—the detection of correlated or "entangled" behavior in the physical world."[17] Wegter-McNelly begins with the assumption that entanglement is behaviour. My aim will not be to demonstrate that Wegter-McNelly is right or wrong but to clarify that his treatment of Bell depends upon the prior choices he has made, mathematical, scientific and metaphysical choices, which he defends strongly but does not explore.[18]

The aim of third chapter of *KW-M*,[19] at the end of which Wegter-McNelly derives his own Bell-type inequality, is "to introduce three key suppositions underlying the *classical* perspective and then to follow Bell's footsteps by examining what they imply for the outcome of a particular experiment."[20] Wegter-McNelly identifies the three key suppositions as "property definiteness,"[21] state separability[22] and

[16] pp.124-151
[17] p.1
[18] p.102
[19] pp.46-73
[20] italics original.
[21] p.47-8

cause locality.[23] Bell does not discuss his presuppositions in this way but the terms feature in later discussions of his work. Property definiteness means that "if a physical object has a property, it will necessarily have that property in a "determinate" or "definite" way."[24] State separability means that "an object's state can be fully described without reference to the state of any other object"[25] and cause locality means the assumption "that the causal interaction of distinct objects is always mediated by a series of 'local' events."[26] Having outlined the three assumptions he takes to be central to classical as opposed to quantum physics, Wegter-McNelly then discusses them in the context of "thinking 'classically' about the polarization of photons."[27] He describes what happens when light of various polarizations encounter detectors and gives an account of how that can be explained classically, imagining " the beam of light, therefore as a collection of photons all travelling in the same direction and all having the same orientation in space, i.e. the same polarization."[28] Wegter-McNelly admits the difficulty of conceptualizing "a single photon's encounter with a polarization filter"[29] but concludes, "for the remainder of the chapter we will assume, in accord with property definiteness, that each photon carries with it a distinct and definite polarization value for each possible polarization measurement even before any measurement occurs."[30] As Wegter-McNelly points out, given that the whole point of Bell-type inequalities is to encode classical assumptions, the experiments that test them have to be capable of being conceptualized in classical terms. Wegter-McNelly moves on to explore what state separability and cause locality mean in this experimental context. With

[22] p.48
[23] p.48-9
[24] p.48
[25] p.48
[26] p.48
[27] pp.124-151
[28] p.50 Photons are not a classical concept however.
[29] p.51
[30] p.53

regard to state separability, he writes, "Let us consider a physical system composed of two photons, A and B. In a fully separable world one can always say that photon A over here has its own α-polarization state A.... and that photon B over there has its own β-polarization state....,"[31] while cause locality, he sums up thus: "if a photon traveling 1 billion kilometers per hour cannot span the distance in space and time between two spatiotemporal events, then nothing can. The two events are said to be "space-like" separated from one another. From the relativistic point of view, space-like separated events are causally isolated from one another—neither can have any effect on the other."[32]

Having established what these three principles mean in the context of a classical description of light conceived as photons, Wegter-MecNelly gives the background to Bell 1964 by outlining the Bohr and Einstein debates of the 1930s and EPR. Wegter-McNelly's summing up of EPR is subtly very misleading: "EPR showed that the idea of property definiteness led to entangled behaviour."[33] EPR, rather argues that, within the logic of the formalism of quantum theory, a contradiction can be demonstrated when the generally held assumption that quantum theory is a complete theory is taken together with a simple definition of how physically reality is represented within the theory. EPR hold that this demonstrated contradiction undermines the claim that quantum mechanics is a complete theory. To recap, according to EPR, a complete theory is one where "every element of the physical reality must have a counterpart in the physical theory."[34] What it means for something to be "an element of the physical reality" is also defined, "If, without in any way disturbing a system, we can predict with certainty (i.e. with a probability equal to 1) the value of a physical quantity, then there exists an objective element of physical reality

[31] p.54
[32] p.57
[33] p.60
[34] EPR p.777

corresponding to this physical quantity."[35] Using these definitions, the writers first show that when the momentum of a particle is known, the position of that particle cannot be predicted with a certainty equal to one and that the "usual conclusion from this in quantum mechanics is that *when the momentum of a particle is known, its coordinate has no physical reality*."[36] The writers show that this feature of the quantum mechanical description follows in all cases where the operators do not commute: "if the operators corresponding to two physical quantities, say A and B, do not commute, that is, if AB ≠BA, then the precise knowledge of one of them precludes such an knowledge of the other. Furthermore, any attempt to determine the latter experimentally will alter the state of the system in such a way as to destroy the knowledge of the first."[37] The writers conclude, "From this follows that either (1) *the quantum mechanical description of reality given by the wave function is not complete* or (2) *when the operators corresponding to two physical quantities do not commute the two qualities cannot have simultaneous reality*. For if both of them had simultaneous reality—and thus definite values—these values would enter into the complete description, according to the criterion of completeness. If then the wave function provided such a complete description of reality, it would contain these values; these would then be predictable. This not being the case, we are left with the alternatives stated."[38] The writers note that the completeness of quantum theory is usually assumed thus implying that noncommuting operators cannot represent quantities that are simultaneously real. In the next stage in their argument, the writers go on to describe a thought experiment that contradicts this conclusion. It can be briefly summarized: two systems have interacted for a specific time after which there is no interaction between them but because of their interaction, after the end of the specific time during which their interaction had taken place, the two systems can no longer

[35] EPR p.777
[36] EPR p.778.
[37] EPR p.778
[38] EPR p.778 Italics original.

be described separately.[39] They can only be described by a common wave function. Values for properties of the individual systems can therefore only be known by being measured but nevertheless, the result of any measurement that could take place can be predicted with a probability equal to one. This means that, according to their earlier definition of reality, all of these properties are elements of physical reality. The writers go on to demonstrate that this is true even if the measurements are represented by noncommuting operators. This generates a contradiction with the writers' earlier conclusion that, if it is assumed that the quantum mechanical description is complete, it follows that "*when the operators corresponding to two physical quantities do not commute the two qualities cannot have simultaneous reality*."[40] Thus demonstrating to the writers' satisfaction that the quantum mechanical description cannot be complete. This is the EPR contradiction.

This is not at all how Wegter-McNelly describes EPR. At the beginning of the section in which he considers it, Wegter-McNelly rightly notes "Einstein refused to accept that quantum theory was a conceptually complete account of the processes it described"[41] but he quickly states that EPR was "aimed more directly at the apparent entanglement of objects implied by the theory."[42] Wegter-McNelly's use of the word "apparent" to qualify "entanglement" here means he is remaining true to what he knows is at the heart of Einstein's disquiet, namely the mathematics of the theory. However, Wegter-McNelly is subtly giving the message that demonstrating "entanglement" rather than incompleteness was the point of the paper whereas in point of fact the nonfactorisability of the wave function of two systems, which had

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[39] This is the entanglement about which Schrödinger speaks Schrödinger. "Discussion of Probability Relations Between Separated Systems."p.555
[40] EPR p.778 Italics original.
[41] p.57
[42] p.58

previously interacted, is assumed in the paper and used to demonstrate quantum theory's incompleteness. What in the paper is a highlighted feature of quantum theory used as a stage in the argument to demonstrate the incompleteness of quantum theory, becomes in Wegter-McNelly's account of the paper, its main point. Wegter-McNelly's strategy is subtle. The theme of his book is entanglement. He uses his own derivation of a Bell inequality together with the results of the experiments testing other Bell inequalities as proof that entanglement exists as an ontological feature of the world. Knowing that EPR was the context for Bell's 1964 paper,[43] and knowing that Einstein did discuss entanglement, Wegter-McNelly conflates the EPR argument with other remarks by Einstein,[44] Schrödinger[45] and Ehrenfest[46] so as to give the impression that demonstrating the existence of entanglement was the end result of Bell 1964. Much of Wegter-McNelly's treatment of Bell 1964 is clear and correct but because he has given the impression that the end result of Bell's work has been the demonstration of ontological entanglement, his treatment of Bell 1964 and the experiments done to test Bell's inequality is told as part of "the story of entanglement."[47] McNelly rightly says "The point of Bell's article was to develop a prediction based on classical presuppositions and then to point out that this prediction cannot be reconciled with the prediction generated by quantum theory."[48] However, this statement is preceded by the inaccurate statement, that Bell "called attention to a previously unnoticed result - a mathematical inequality - buried within the details of the EPR argument, as later simplified by David Bohm."[49] It contains some truth, Bell did home in on a feature of David Bohm's scheme, nonlocality, and Bell did pick up

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[43] Bell 1964
[44] e.g. Einstein's arguments at the Solvay Conferences in 1927 and in 1933, see pp.58-9
[45] p.58
[46] p.58
[47] p.2
[48] p.60
[49] p.60

Bohm and Aharonov's specific example of an experiment of the sort that the EPR paper noted as a stage in their argument about the completeness or otherwise of quantum mechanics but Bell's inequality was certainly not "buried within the details of the EPR argument." However, it is true, that, as Wegter-McNelly says a few lines later: "What Bell discovered through his particular thought experiment was a novel implication of the classical world view."[50] This intermingling of accurate description with the narrative implying one specific interpretation without clarifying the distinction between the two means that Wegter-McNelly's detailed treatment of Bell's work does not so much provide a basis for the theological use to which it is put as the theological use determines the lens through which Bell's work is laid out.

We see this throughout Wegter-McNelly's discussion of Bell's paper. He gives Bell's argument the best and most detailed discussion of any theologian before or since but because he comes to Bell's work believing that he knows what it demonstrates, he frames his discussion of the paper from the perspective not of Bell's own conclusion but from his own perspective of what he believes Bell's paper demonstrates. However, what he believes Bell's conclusion to demonstrate needs more than just maths or science to undergird it, it needs philosophy. Wegter-McNelly knows this and ultimately expresses and defends it[51] but because he does not make that clear at the outset, as he describes Bell's work in this chapter three, he is fitting Bell's work into his own wider "story"[52] rather than opening up to his theological audience the complexities that interpretation of Bell's work entails. While Wegter-McNelly's grasp of Bell's maths and the clarity of his description of it is second to none, he feeds into his description

[50] p.60
[51] p.103
[52] p.2

words like entanglement,[53] used with one particular understanding of it,[54] which implies the inevitability of a certain interpretation of Bell's work.

In the climax to chapter three,[55] Wegter-McNelly describes the set up of a Bell-type experiment using photons and then derives his own[56] version of the CHSH inequality.[57] He notes that Bell's inequalities have been consistently violated and concludes from this: "Bell's inequality led to the discovery of something radically new about the world,"[58] which may be true but there is no consensus as to what that radically new something might be. In chapter four, Wegter-McNelly discusses the experiments that have been carried out to test Bell-type inequalities in more detail. He continues the framing of the narrative by entitling the chapter "Entanglement in Quantum Physics."[59] His stated aim in this chapter, having shown the classical prediction for a Bell-type experiment and demonstrated the rationale behind it in the previous one, is to "construct[] the quantum prediction for Bell type experiments."[60] Firstly, Wegter-McNelly gives a history of the development of the design of the experiments that have tested Bell-type inequalities up until 2008[61] and then explains what superposition is. He acknowledges that although the mathematics of quantum theory is universally accepted, interpretation of what it means is not. Wegter-McNelly chooses to review this through the lens of "the principle of superposition,"[62] which he calls, "ontologically ambiguous." He notes

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[53] e.g. p.61
[54] It is clear that Wegter-McNelly knows that for Schrödinger and Einstein "entanglement" is a description of the mathematics and not the underlying reality. p.20
[55] pp.62-67
[56] pp.67-73.
[57] pp.67-73.
[58] p.73
[59] p.74
[60] p.74
[61] p.75-77.
[62] p.78

that "entanglement is a special kind of superposition involving multiple objects."[63] While earlier he correctly called superposition "a principle" rather than an ontological occurrence, this statement about entanglement being a superposition of a number of objects imports the implication that superposition, just like entanglement, is a thing, an ambiguous thing, but a thing. This smuggling in of ontology can also be seen in the way Wegter-McNelly uses phrases like "When a physicist sets out to measure the v-polarization state of a photon she regards to be in the Tv + Sv polarization state."[64] It might seem innocuous but it assumes the prior existence of a discrete photon, which would have been consonant with his discussion of photon experiments seen through a classical lens but in the context of a discussion seen through a quantum lens, as he is doing here, a more appropriate term would be "prepare" instead of "measure." Having explained how photon polarization is conceptualized from the perspective of quantum theory, Wegter-McNelly concludes the chapter by deriving and explaining the quantum mechanical prediction for an experiment testing a Bell theorem using photons. Having noted that all the experiments done have violated the equality, he concludes accurately that this implies that one of the assumptions upon which the inequality is based is flawed. He reminds his readers of the three assumptions he made, property definiteness, state separability and cause locality and concludes, inaccurately, that because there is agreement amongst all commentators that the experimental set ups that produce the violations of Bell inequalities cannot be used to send supraluminal signals, therefore either the assumption of property definiteness or of state separability rather than cause locality is responsible for the violations.

In chapter five, "Philosophical Perspectives," Wegter-McNelly lays out three philosophical stances from within which to interpret the

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[63] p.78
[64] p.81

experimental violations: realism within the existing formalism, citing the de Broglie-Bohm pilot wave, John Cramer's transactional interpretation, a scheme that involves backward causation within individual quantum events and the Everett interpretation, in both the Many Worlds and Many Minds versions; realism with a modified formalism, citing the Ghirardi, Rimini and Weber collapse interpretation; and finally antirealism[65] for which he doesn't specify any interpretation but against which he argues because "to deny the possibility of drawing ontological inferences from scientific theories on the grounds that they cannot be expected to bear the burden of guiding our interpretation of the world is to undercut the central motivation animating most scientists' pursuit of knowledge: to know the world better. When an antirealist caution is elevated to the level of a philosophical program, it gets an undeserving free ride on the backs of the vast majority of scientists whose realist convictions push science forward."[66] Here Wegter-McNelly is conflating the indeterminism that is peculiar to quantum physics, i.e. what is measured doesn't have attributes until it is measured, with a wider philosophical antirealism. It is possible to hold to realism in the macroworld thereby being in Wegter-McNelly's terms, a realist, while still interpreting the violation of Bell's inequalities as meaning, "to concur with the late Asher Peres, unperformed experiments have no results."[67] Christopher Fuchs, one of the founders of Qbism and a leader in the field of quantum information, makes this point very strongly in his paper, "On Participatory Realism."[68] Conversely, it is possible to think that entanglement is ontological while being a philosophical antirealist.[69] While Wegter-McNelly acknowledges that many quantum physicists or philosophers of science do not think that the quantum correlations

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[65] see pp.105-110.
[66] p.106
[67] Anthony Leggett in Schlosshauer, *Elegance and Enigma. The Quantum Interviews*. p.176
[68] Fuchs. "On Participatory Realism."
[69] Antirealism is not solipsism, see Merold Westphal. "In Defense of the Thing in Itself," *Kant-Studien* 59 (1968):118-41.

evidenced in the experimental violation of Bell inequalities need to be explained,[70] because of his own commitment to realism, he presses on to find an interpretation for the correlations he calls entanglement and takes to be an ontological feature of the world. This he finds within a relational holist interpretation of reality, or more specifically, a "nonemergent, nonsupervenient holism."[71] The chapter ends with an interesting discussion of what this sort of relational holism does and doesn't mean and what entangled does and doesn't mean from this interpretative perspective. Wegter-McNelly follows Paul Teller "in thinking that entangled states can be understood as holistic inasmuch as they have definite properties that do not supervene on the definite properties of the subsystems…… and in thinking of these properties as collective, as 'relations.'"[72] Wegter-McNelly describes how an entangled property is seen to be nonemergent if it is a property that can equally well be held by one of the entangled systems alone. He uses the examples of wetness and weight. Wetness is an emergent property of water that is not a property of the individual hydrogen molecules of which water is made up whereas the weight of water being entirely composed by the weight of the hydrogen molecules that comprise it is not emergent.[73] Wegter-McNelly explains what he means thus, "A system of two entangled photons, for example, can have a definite value of polarization only because each individual electron [sic] has the capacity to carry the same property. This is what makes the polarization a nonemergent property. At the same time, the two-photon system can have a definite polarization value as a whole without implying that either individual photon must also be carrying a

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[70] p.110-1
[71] p.117
[72] pp.116-7. Cf the Ithaca Interpretation of David N. Mermin. N David Mermin. "The Ithaca Interpretation of Quantum Mechanics," *Pramana* 51, no. 5 (1998)pp.549-65. Mermin later adopted the QBist interpretation of quantum mechanics, (see N David Mermin. "Qbism Puts the Scientist Back Into Science," *Nature* 507, no. March (2014):421-23.) but this was after Wegter-McNelly wrote *KW-M*
[73] p.117

definite polarization value. This is what I refer to as the 'nonemergent, nonsupervenient holism' of quantum mechanics."[74] It seems to be a somewhat circular argument. Entanglement as an ontological feature of the world is evidence for relational holism while assuming relational holism enables the correlated statistics resulting from a Bell experiment to be interpreted as entanglement.

Despite his reading ontology in so as to get ontology out, Wegter-McNelly is careful to avoid the romantic excess of some theologians or popular science writers, stressing that "[p]hysicists have never observed entanglement "in the wild" so to speak, but rather entangle and disentangle small numbers of particles in the highly controlled and artificial environments of their laboratories... To claim that two photons can become entangled is one thing, but to claim that the physical world as whole is ubiquitously entangled is quite another."[75] However this does not prevent him using entanglement as a metaphor with which to explore an even bigger theme, the theme of divine relationality, the subject of his final chapter.

Wegter-McNelly's detailed and careful exposition of Bell's inequality coupled with a derivation of a Bell-type inequality of his own is exceptionally impressive. *KW-M* is a fine example of interdisciplinary scholarship and provides the template that I have followed in being unashamed to include a detailed account of the science with which he is engaging within a theological work. Nevertheless, despite his careful exposition, Wegter-McNelly still expounds Bell's work through a particular lens. Entanglement is *KW-M*'s subject and therefore it is through this lens that Wegter-McNelly explores Bell's work. It is entanglement that he goes to Bell to find and find it he does. This is by no means a strained or illegitimate interpretation of the experimental violations of Bell's inequality, but given that all that Wegter-McNelly

[74] p.117
[75] p.121

requires is a metaphor, acknowledging the different ways in which quantum physicists and philosophers of science understand Bell's work might have been appropriate.

Wegter-McNelly's book has been cited on 19 occasions[76] but in only one of these works is Wegter-McNelly's systematic work on John Bell's paper and the experiments that followed discussed: in Ernest Simmons' *The Entangled Trinity. Quantum Physics and Theology*.[77] Catherine Keller mentions both Bell[78] and Wegter-McNelly[79] in her discussion of entanglement in *Cloud of the Impossible: Negative Theology and Planetary Entanglement* [80] but it is Louisa Gilder,[81] Brian Greene[82] and Shimon Malin[83] from whom she quotes as her authority on Bell's theorem and it's experimental testing. She cites *KW-M* solely for Wegter-McNelly's theology of divine entanglement.

7.2 After *KW-M*: 2011-2018

The next scholar to mention Bell was the late Saikat Guha. In an article on Aquinas, Guha references Bell to back up his stance that alternative deterministic theories to the Copenhagen Interpretation are possible,[84]

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[76] as of July 18th 2018
[77] Ernest L. Simmons. *The Entangled Trinity. Quantum Physics and Theology*, Theology and the Sciences Fortress Press, (2014).pp.138-9
[78] Keller. *Cloud of the Impossible: Negative Theology and Planetary Entanglement*.pp.133,146-148 & 154
[79] Keller. *Cloud of the Impossible: Negative Theology and Planetary Entanglement*.pp.152-3
[80] Keller. *Cloud of the Impossible: Negative Theology and Planetary Entanglement*.
[81] Louisa Gilder. *The Age of Entanglement: When Quantum Physics Was Reborn* Knopf, (2004).
[82] Brian Greene. *The Fabric of the Cosmos*, London: Penguin Books, (2005).
[83] Malin. *Nature Loves to Hide: Quantum Physics and the Nature of Reality, a Western Perpsective*.(Keller references the 2003 version.)
[84] Saikat Guha. "An Interpretation of Aquinas' First and Second Ways," in *After God, With Reason Alone*, Proceedings of the Society for Medieval Logic and Metaphysics, Newcastle upon Tyne: Cambridge Scholars Publishing, (2011).p.17

concluding that therefore, Aquinas' First and Second Ways still have traction today. There were two[85] mentions of Bell's work in a theistic context in 2012 in articles[86] by Marc Pugliese and Catherine Keller.[87] As with so much theological reflection on Bell's work, it is not that Keller does not tell a truthful story, rather she tells a story made of other stories, plaited and woven together. "Turns out in each case local realism has failed and spooky action at a distance has prevailed .... As Greenstein and Zajonc put it, 'the experimental tests of Bell's inequalities .... go so far as to change the very way we should think of physical existence at its most fundamental level ... we must think in terms of nonlocality, and/or we must renounce the very idea that individual objects possess discrete attributes.'"[88] So far so good, but Keller goes on, "as a recent article in Scientific American put it: 'the division between the quantum and classical worlds appears not to be fundamental'[89] then involves Heisenberg via Henry Stapp and Whitehead and arrives at an ontological entanglement that takes place because in Malin's view "events far apart 'seem to 'feel' each other."[90]

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[85] Malin's 2001 book (Malin. *Nature Loves to Hide: Quantum Physics and the Nature of Reality, a Western Perpsective*.) was revised and published, see Shimon Malin. *Nature Loves to Hide: Quantum Physics and the Nature of Reality. A Western Perspective (Revised Edition)* Singapore: World Scientific, (2012).
[86] Marc Pugliese. "Orthodoxy or Orthopraxy. Recent Developments in Physics and Joseph A. Bracken as Revisionist Whiteheadian," in *Seeking Common Ground: Evaluation and Critique of Joseph A. Bracken's Comprehensive World View*, ed. Marc Pugliese and Gloria Schaab, Marquette Studies in Theology Marquette University Press, (2012).; Catherine Keller. "The Entangled Cosmos: An Experiment in Physical Theopoetics," *Journal of Cosmology* 20 (2012):8648-66.
[87] Keller. "The Entangled Cosmos: An Experiment in Physical Theopoetics."
[88] Keller. "The Entangled Cosmos: An Experiment in Physical Theopoetics."pp.7-8 of online version http://journalofcosmology.com/JOC20/Keller_rev1.pdf
[89] Keller. "The Entangled Cosmos: An Experiment in Physical Theopoetics."(online version)p.8
[90] Keller. "The Entangled Cosmos: An Experiment in Physical Theopoetics."(online version)p.9

Keller specifically disavows the theology and science dialogue[91] but it is disappointing that Keller isn't a little more careful in her use of Bell's work. Once again, Bell's work undergirds and legitimizes a trajectory that leads from the experimental violations to ontological entanglement. This is not to say this is an indefensible position, simply that it should not be portrayed as the only position. Keller both cites and references Wegter-McNelly's book but, as in her later book, of which this becomes a chapter, while applauding him for his work on relationality, Keller does not reference his detailed work on Bell's inequality and its experimental violations. Neither does Keller refer to Bell's own original article. To back up her treatment of Bell's work, Keller mentions Henry Stapp's description of it as "the most profound discovery of science,"[92] then quotes from Brian Greene's *The Fabric of the Cosmos*[93] and Greenstein and Zajonc via Karen Barad's *Meeting the Universe Halfway*. Keller's article has been cited 8 times, once in a theology PhD thesis, in which Bell's work is also cited[94] but in none of these citations is Keller's work on Bell mentioned.

In the same year, Pugliese mentions Bell's work in an article[95] on Joseph Bracken's revision of Whitehead's philosophy. Pugliese's understanding of Bell's inequality, his theorem and the experiments is detailed but confused. He picks the same point that Hartshorne had made 35 years earlier, albeit without any reference to Hartshorne, "Empirical data that might disconfirm the causal independence of contemporary entities is the experimental invalidation of Bell's

[91] Keller. "The Entangled Cosmos: An Experiment in Physical Theopoetics."(online version)p.3
[92] Keller. "The Entangled Cosmos: An Experiment in Physical Theopoetics."(online version)p.7 Although Keller doesn't reference it, Stapp said this in Stapp. "Bell's Theorem and World Process."p.271
[93] Greene. *The Fabric of the Cosmos*.
[94] Konigsburg. "Relational Interreligious Dialogue: Interdisciplinary Arguments From Creator/Creature Theology and Quantum Entanglement."
[95] Pugliese. "Orthodoxy or Orthopraxy. Recent Developments in Physics and Joseph A. Bracken as Revisionist Whiteheadian."

Inequalities."[96] Making this point in 1977, Hartshorne relied heavily on Stapp. While Pugliese has an article and a book by Henry Stapp in his bibliography, he shows no awareness that Stapp has brought this very point to the fore 35 years before[97] and that Hartshorne, although spotting its relevance, finally changed his mind as to it significance. For his account of Bell's work, Pugliese references the original literature but does not reference or cite anyone's work to back up his interpretation. He begins with EPR, the aim of which he correctly sums up as "intending to prove that quantum mechanics is not a complete physical theory...."[98] This clarity does not extend to his very confused discussion of it, "The real state of affairs according to EPR... is that measuring B's momentum could yield a definite result that may not correspond to its momentum as predicted by quantum theory. This is called "The EPR Paradox."[99] This mixture of accuracy and confusion also marks his discussion of Bell 1964. The accurate statement, "The key is that Bell found that the predictions of quantum theory exceeded the upper-limits of the correlations predicted with local hidden variables"[100] is immediately followed by the absurd, "Due to their inequality with quantum predictions, the predictions with local hidden variables are called "Bell's Inequalities."[101] The remaining discussion of Bell 1964 is likewise a mixture of the accurate, the confused and the anachronistic. Like Wegter-McNelly, he dismisses physicists who

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[96] Pugliese,. "Orthodoxy or Orthopraxy. Recent Developments in Physics and Joseph A. Bracken as Revisionist Whiteheadian."p.102

[97] Pugliese references Stapps's 1977 paper (Henry P Stapp "Are Superluminal Connections Necessary," *Il Nuovo Cimento* 40B, no. 1 (1977):191-204.) in a discussion about superluminal connections but does not refer to Stapp's work or cite it with regard to Bell's relevance to this point.

[98] Pugliese."Orthodoxy or Orthopraxy. Recent Developments in Physics and Joseph A. Bracken as Revisionist Whiteheadian."p.102

[99] Pugliese. "Orthodoxy or Orthopraxy. Recent Developments in Physics and Joseph A. Bracken as Revisionist Whiteheadian."

[100] Pugliese. "Orthodoxy or Orthopraxy. Recent Developments in Physics and Joseph A. Bracken as Revisionist Whiteheadian."p.103

[101] Pugliese. "Orthodoxy or Orthopraxy. Recent Developments in Physics and Joseph A. Bracken as Revisionist Whiteheadian."p.103

speak only in terms of macro experiments rather than attempting to give an account of what lies behind them[102] but acknowledges that giving a definite account of microprocesses in Bell experiments requires the assumption of some form of nonlocality. He references Teller's "relational holism" and like Russell and Barbour he speaks of the need to abandon local realism without realizing that retaining realism was the point of Bohm's interpretation of quantum theory, which came at the cost of nonlocality, the feature Bell derived his inequality to test.[103] His account of the assumptions that lie behind Bell's derivation is also confused. Pugliese's article has been cited four times, three times by himself and once by a theologian, [104] who does not mention his work on Bell.

As we have seen, the vast majority of those who mention Bell's work in a theological or theistic context do so assuming some form of nonlocality or ontological entanglement. One of the mentions of Bell in 2014 joins Placher and Hodgson as an exception. In *Chance and the Sovereignty of God*[105] Venn Poythress cites Bell's theorem and the experimental violations as theoretical and experimental evidence that there is no such thing as physical determinism.[106] While his short account of Bell's thought is clear and correct, it is misleading because he writes as if indeterminism is the only possible interpretation of both Bell's theorem and its experimental validation. Thus far, his book has not been cited for his work on Bell.

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[102] Pugliese. "Orthodoxy or Orthopraxy. Recent Developments in Physics and Joseph A. Bracken as Revisionist Whiteheadian."p.102
[103] Pugliese. "Orthodoxy or Orthopraxy. Recent Developments in Physics and Joseph A. Bracken as Revisionist Whiteheadian."p.103
[104] Karen Baker-Fletcher. *Dancing With God. The Trinity From a Womanist Perspective*, Chalice Press, (2006).
[105] Vern Poythress. *Chance and the Sovereignty of God* Wheaton, Illinois: Crossway, (2014).
[106] Poythress, *Chance and the Sovereignty of God*.p.83

Simmons, the next theologian to mention Bell, clearly thinks that entanglement is an ontological feature of reality but signals himself as a believer in both "quantum indeterminacy and nonlocal relational holism, "[107] which he says have been "experimentally verified" citing the Aspect experiments as evidence, [108] with Wegter-McNelly to back up this point.[109] He writes, "Entanglement is real and a part of the nature of the quantum world."[110] The section "Experimental Evidence"[111] in *KW-M* is Simmons' main source for his work on Bell. He references it four times and twice refers to a personal email from Wegter-McNelly, which he quotes.[112] He also cites Polkinghorne's popular science book.[113] Simmons' description of what Bell's inequality achieves is succinct and accurate, "Bell's inequality very ingeniously sets up the conditions that would have to be met if a theory were strictly local in its character. The conditions would apply only if there were no nonlocal correlations."[114] However, this is immediately followed by the incorrect statement, "In effect, what Bell did was to show what would be needed to be observed if EPR was correct."[115] Despite Simmon's clear statements about both Bell's inequality and EPR, neither of the original papers are either cited or in his bibliography. To be fair to Simmons, he does quote from

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[107] Simmons. *The Entangled Trinity. Quantum Physics and Theology*.p.138
[108] Simmons. *The Entangled Trinity. Quantum Physics and Theology*.p.138
[109] Simmons. *The Entangled Trinity. Quantum Physics and Theology*.p.138 citing *KW-M.*pp.75-77
[110] Simmons. *The Entangled Trinity. Quantum Physics and Theology*. p.138
[111] pp.75-77
[112] Simmons. *The Entangled Trinity. Quantum Physics and Theology*.p.139
[113] John Polkinghorne. *Quantum Theory: A Very Short Introduction* Oxford: Oxford University Press.(2002)., see Simmons. *The Entangled Trinity. Quantum Physics and Theology*.p.139n.41.
[114] Simmons. *The Entangled Trinity. Quantum Physics and Theology*.p.138.
[115] Simmons. *The Entangled Trinity. Quantum Physics and Theology*.p.138.

Polkinghorne's writing on EPR, whom he naturally assumes can be relied upon for an accurate summing up of what both EPR and Bell's work means. However, Polkinghorne's description of the significance of Bell's inequality and it's experimental testing by Aspect, which Simmons' quotes[116] reflects Polkinghorne's own understanding of what they signify and while Polkinghorne clearly explains the philosophical standpoint which drives his interpretation, he does not explain adequately the alternative viewpoints available and how choosing a different alternative philosophical standpoint would alter what the experimental violations of Bell inequality can be said to show. Indeed, Polkinghorne, gives no indication that any other is interpretation is possible. Simmmons follows the philosophical choices of Polkinghorne[117] and Wegter-McNelly[118] and, quoting from Polkinghorne, concludes his assessment of the significance of the experimental violation of Bell's inequalities, "Putting it in learned language, the EPR effect is ontological and not simply epistemological."[119] However, without being aware of it, Simmons immediately contradicts himself with a final sentence, "Bohr and Heisenberg were right."[120] Simmons' confusion is a very good example of why it is vital for theologians in the theology and science debates to acquaint themselves with the complexities of the scientific findings upon which they rely.

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[116] Simmons. *The Entangled Trinity. Quantum Physics and Theology*.p.139 from Polkinghorne. *Quantum Theory: A Very Short Introduction*.p.79.
[117] Polkinghorne is more clearly aligned with those who intepret the experimental violations as establishing nonlocality rather than relational holism e.g. Polkinghorne. "The Quantum World."p.338
[118] p.102.
[119] Simmons. *The Entangled Trinity. Quantum Physics and Theology*.p. 140, citing from John Polkinghorne. *Quantum Theory. A Very Short Introduction*.p.79.
[120] Simmons. *The Entangled Trinity. Quantum Physics and Theology*. p.140

In 2015, four theologians discussed Bell's work: Keller,[121] Pugliese,[122] Heidi Russell[123] and Claudia E. Vanney.[124] Pugliese's article continues his discussion of Bracken's revision of Whitehead's process philosophy. We have seen how his discussion of Bell's work in his earlier article[125] was somewhat confused. This article is no less confused, combining uncontroversial statements about what John Bell achieved with some that are true only from a particular philosophical standpoint and still others that are simply inaccurate. Pugliese begins with the straightforward descriptive statement: "John S. Bell used a variant of the EPR experiment to show quantum theory is incompatible with any explanation assuming local hidden variables (Bell 1964).[[126]] To summarize, the probabilities of a correlation predicted by quantum theory exceeded the upper-limits of those predicted using locality and hidden variable assumptions."[127] Pugliese then notes the complexity of interpreting the significance of the experimental violations. However immediately after, noting "With respect to the experimental violations of Bell's Inequalities, ontological realism implies some sort of "real" connection between the two space-like separated but entangled particles,"[128] Pugliese adds in the very next sentence, as if ontological realism was the only interpretative choice on offer: "The experimental violation of Bell-type inequalities means that two space-like entangled particles are somehow

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[121] Keller. *Cloud of the Impossible: Negative Theology and Planetary Entanglement*.
[122] Marc Pugliese. "Revising Whitehead's Notion of Society in the Light of Contemporary Physics," *Open Theology* 1 (2015):301-15.
[123] Heidi Ann Russell. *Quantum Shift. Theological and Pastoral Implications of Contemporary Developments in Science*, Minnesota: Michael Glazier Liturgical Press, (2015).
[124] Claudia E. Vanney."Is Quantum Indeterminism Real? Theological Implications," *Zygon* 50, no. 3 (2015):736-56.
[125] Pugliese. "Orthodoxy or Orthopraxy. Recent Developments in Physics and Joseph A. Bracken as Revisionist Whiteheadian."
[126] Pugliese here cites Bell 1964
[127] Pugliese. "Revising Whitehead's Notion of Society in the Light of Contemporary Physics."p.304
[128] Pugliese. "Revising Whitehead's Notion of Society in the Light of Contemporary Physics."p.304

connected."[129] Next Pugliese discusses John von Neumann's famous discussion of how in scientific description, be it classical or quantum, it is possible to fix the boundary between the observed and the observing system at any point.[130] Pugliese uses this discussion to give credence to holism as an appropriate philosophical standpoint from which to view quantum mechanics in general and the experimental violations in particular and, after a discussion of Bohm's implicate order, notes, entirely inaccurately that, "This sort of "holism" is relevant to explanations of the violations of Bell's Inequalities because there are real particles and they are connected. Entangled particles comprise an irreducible fact that cannot be reduced to more fundamental nonrelational facts."[131] As with Wegter-McNelly, a description of the significance of the experimental violations of the inequalities that is true only given an assumption of nonlocality is used to prove the ontological nature of the entanglement it has assumed. Pugliese goes on to add that holism is gaining ground amongst physicist but of the four physicists he adduces to back up his claim, the most recent citation was dated a full 12 years before Pugliese's own article. Pugliese's citation of scientific literature about Bell's work is broad, but he doesn't cite any other theologian or theistic philosopher who has written on Bell's work, apart from his own.[132] Pugliese's 2015 paper, to date, has not been cited.[133]

In a wide ranging discussion of the various interpretations of quantum mechanics, Vanney does not mention either John Bell or his 1964

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[129] Pugliese. "Revising Whitehead's Notion of Society in the Light of Contemporary Physics."p.304

[130] Pugliese footnotes the English translation of von Neumann's seminal book, (von Neumann, *Mathematical Foundations of Quantum Mechanics*.) but does not cites the specific passage from which the discussion comes, namely pp.418-421.

[131] Pugliese. "Revising Whitehead's Notion of Society in the Light of Contemporary Physics."p.306

[132] Pugliese. "Orthodoxy or Orthopraxy. Recent Developments in Physics and Joseph A. Bracken as Revisionist Whiteheadian.";

[133] as of 30th July 2018.

paper. However, in a paragraph entitled, "Quantum holism and top down causation," the Aspect, Dalibard and Roger experiments, in which the CHSH version of Bell's inequality was tested with time varying analyzers,[134] are put forward as evidence that "the entanglement persists even when being separated across large distances ("nonlocality") (Aspect, Dalibard, and Roger 1982)."[135] Again, Bell's work is being cited as evidence for a position, which may be true, but can only be held on the basis of particular prior philosophical choices, with seemingly no awareness of the complexity or circularity involved. *Quantum Mechanics. Scientific Perspectives on Divine Action Volume 5*[136] as well as some of this volume's individual chapters that mention Bell's work[137] are Vanney's only references to work by theologians on Bell. Vanney's paper has been cited once.[138] In the same year, while discussing EPR, [139] John Bell's work was noted by Heidi Ann Russell. Her account is based on Brian Greene's *Fabric of the Cosmos.*[140] Russell's treatment of Bell is confused. "In 1964, John Bell came up with a possible experiment, albeit without the equipment to carry it out, that could conceivably test this theory. The experiment involved adding a third element that could not be determined prior to

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[134] Aspect, Dalibard and Roger. "Experimental Test of Bell Inequalities Using Time-Varying Analyzers."
[135] Vanney. "Is Quantum Indeterminism Real? Theological Implications."p.747
[136] Russell, et al. *Quantum Mechanics. Scientific Perspectives on Divine Action. Volume 5*.
[137] i.e. Stoeger S.J. "Epistemological and Ontological Issues Arising From Quantum Theory.";Redhead. "The Tangled Story of Nonlocality in Quantum Mechanics."; Clayton. "Tracing the Lines: Constraint and Freedom in the Movement From Quantum Physics to Theology."; Tracy. "Creation, Providence and Quantum Chance.".
[138] In Wilhelm B Drees. "Contingency in the Cosmos and Contingency of the Cosmos. Two Theological Approaches," *Philosophy, Theology and the Sciences* 2, no. 2 (2015):158-77..
[139] Russell. *Quantum Shift. Theological and Pastoral Implications of Contemporary Developments in Science*.pp.60-1
[140] Greene. *The Fabric of the Cosmos*.

measurement into the equation, the spin of the particle."[141] However, Russell goes on to quote Robert John Russell and correctly states one way of interpreting the experiment violations: "This experiment demonstrates a causality that is nonlocal,"[142] but with no sense of the complexity of the wider debate. As with Vanney, Bell's work is being rolled out to support a position but without careful attention being paid as to the extent to which Bell's work can be used in that way. Sources are taken on trust rather than checked. Bell's work has become totemic.

The final theologian to discuss Bell's in work in 2015 does so in some detail. In *Cloud of the Impossible. Negative Theology and Planetary Entanglement*, Keller draws on previous articles or book chapters.[143] The book is premised on the ontological reality of entanglement. She sets out on "certain layered explications —scientific, philosophical and poetic— by which our ontological entanglement comes to matter."[144] The insightful pun is typical of the way she writes theology. Part of the book's theme is the story of this "ontological entanglement." Ontology is centre stage. Keller begins the chapter exploring Bohm's attempts to restore to quantum physics the ability to speak about what is there rather than simply about the activity of physicists' interventions.[145] Keller's interest in Bohm is sparked by his vision of the

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[141] Russell. *Quantum Shift. Theological and Pastoral Implications of Contemporary Developments in Science*.p.60
[142] Russell. *Quantum Shift. Theological and Pastoral Implications of Contemporary Developments in Science*.p.61
[143] Catherine Keller. "The Cloud of the Impossible: Embodiment and Apophasis," in *Apophatic Bodies: Negative Theology, Incarnation and Relationality*, eds. Chris Boesel and Catherine Keller, New York: Fordham University Press, (2009).; Keller. "The Entangled Cosmos: An Experiment in Physical Theopoetics."; Catherine Keller. "A Democracy of Fellow Creatures. Feminist Theology and Planetary Entanglement," *Studia Theologica - Nordic Journal of Theology* 69, no. 1 (2015):3-18.
[144] Keller. *Cloud of the Impossible: Negative Theology and Planetary Entanglement*.p.9
[145] Keller. *Cloud of the Impossible: Negative Theology and Planetary Entanglement*. pp.153-162.

interconnectivity of all that is, his implicit order. In the book she "entangles" his work with that of Nicholas of Cusa, who draws on the early apophatic theology of the Eastern Church. Keller is drawn to the possibility of relationship that his thinking opens up, the relation of subject and object, God and cosmos. She links this with Bohm, in whose work she sees a commensurate sense of the entanglement of being. However, she fails to see that while Cusa is opening up and freeing the doctrine of God from a theological desire to see it grasped and pinned down, much like Victorian butterfly collectors, for all the delightful entangling of his implicate order, Bohm's desire is quite the opposite. At the human scale, Bohm seeks a physics of causality and determinism. There is an irony in Keller's placement of Bohm as a Pied Piper-esque figure leading us to creative relationship from restrictive certainties, given that, as Abner Shimony noted, it was "from the standpoint of a conservative metaphysician" that a hidden variables programme, such as Bohm's, that violates Bell's locality condition, "might be attractive."[146] Keller comes to Bell through her work on Bohm and so the role of Bell's work in the story is already set. As we have seen before, if ontological entanglement is what you want, ontological entanglement is what the experimental violations of Bell's inequalities will deliver. In Keller's wonderful and insightful book, Bell has been put to use rather than explored. While Keller quotes from KW-M she does so to explore her work on superposition.[147] Like Heidi Ann Russell, Keller's discussion of Bell's work comes from Brian Greene[148] and begins, with the circularity we have noted so often in theological commentary on Bell, "Bell proved that even if you cannot measure features obscured by quantum uncertainty, their existence

[146] Abner Shimony. "Search for a Worldview Which Can Accomodate Our Knowledge of Microphysics," in *The Philosophical Consequences of Quantum Theory*, Notre Dame, Indiana: University of Notre Dame, (1989).p.30
[147] Keller. *Cloud of the Impossible: Negative Theology and Planetary Entanglement*.p.151-2
[148] Greene. *The Fabric of the Cosmos*. see Keller. *Cloud of the Impossible: Negative Theology and Planetary Entanglement*.p.147

does make a difference, 'a difference that can be checked experimentally.'[149] It is this difference that, when tested, would confirm in one fell swoop Einstein's haunting fear: the universe is spooky."[150] Keller asserts from the start, with no reference whatsoever to the complexities of the debate that the experimental violation of Bell's mathematics leads to demonstration of ontological entanglement: "when two particles originally linked and then experimentally separated fly off in opposition directions, they remain immediately responsive to one another—*no matter what the distance*. They remain 'entangled.'"[151] Keller backs up Greene's account of what the experimental violations of Bell's inequalities mean from Malin's *Nature loves to hide*,[152] which is also an account of Bell tailored to ensure ontological outcomes. The quotes from Greene and Malin, Keller links with words she says are from Bell himself about the measurement problem in quantum physics, but which are quoted from another book which coopts Bell into its own narrative, *Quantum Enigma: Physics Encounters Consciousness*[153] "Observations not only disturb what is to be measured they produce it"[154] (a phrase, actually said by Pascual Jordan). While the quote allies with the sense of

[149] Keller quotes and references, Greene,.*The Fabric of the Cosmos*. p.112
[150] Keller. *Cloud of the Impossible: Negative Theology and Planetary Entanglement*.p.147
[151] Keller. *Cloud of the Impossible: Negative Theology and Planetary Entanglement*.p.147
[152] Malin. *Nature Loves to Hide: Quantum Physics and the Nature of Reality, a Western Perpsective*. on Keller. *Cloud of the Impossible: Negative Theology and Planetary Entanglement*. p.149
[153] Bruce Rosenblum and Fred Kuttner. *Quantum Enigma: Physics Encounters Consciousness*, London: Gerald Duckworth & Co, (2007).
[154] Keller. *Cloud of the Impossible: Negative Theology and Planetary Entanglement*.p.149. For this quote from Bell, Keller cites Rosenblum, and Kuttner. *Quantum Enigma: Physics Encounters Consciousness*.p.227f. However, there isn't a page 227. Rosenblum and Kuttner do include this quote, which is from Pascual Jordan, Rosenblum, and Kuttner, *Quantum Enigma: Physics Encounters Consciousness*.p.103.

"spooky" in the Einstein phrase[155] for which Keller's chapter is named, Keller is seemingly unaware that Bohm developed his theory to remove the spookiness from quantum physics. As Bell wrote, "Bohm showed explicitly how parameters could indeed be introduced, into non-relativistic wave mechanics, with the help of which the indeterministic description could be transformed into a deterministic one. More importantly, in my opinion, the subjectivity of the orthodox version, the necessary reference to the 'observer' could be eliminated."[156] Keller's evocative and thought provoking writing, as interesting and stimulating as it is, underlines the need for theologians to ensure that they do justice to the thought of the scientists with whose work they riff. Theology can be jazz[157] but as Bruce Benson Ellis reminds us, "jazz improvisation provides a model of something at least *approximating* a 'hermeneutical justice.'"[158] Keller's work is both moving and inspiring but she does not take care in understanding and exploring the complexity of the scientists from whose work she draws.

In Robert John Russell's 2016 review[159] of *The Entangled God,* Bell's theorem and the experimental test of the inequalities[160] are mentioned

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[155] Einstein used the phrase in a letter to Max Born in 1947 Born. *The Born-Einstein Letters 1916-55 Friendship, Politics and Physics in Uncertain Times*.p.155
[156] John S Bell. "On the Impossible Pilot Wave," in *Speakable and Unspeakable in Quantum Mechanics*, Cambridge: Cambridge University Press, (2004).p.160 Bell is talking about Bohm's 152 papers: Bohm. "A Suggested Interpretation of Quantum Theory in Terms of "Hidden Variables" I." & Bohm. "A Suggested Interpretation of Quantum Theory in Terms of "Hidden" Variables II.".
[157] Robert Gelinas. *Finding the Groove: Composing a Jazz-Shaped Faith* Grand Rapids, Michigan: Zondervan, (2009).p.14; Robert Barron. "Considering the Systematic Theology of James William Mcclendon, Jnr," *Modern Theology* 18, no. 2 (2002):267-76.p.275
[158] Bruce Ellis Benson. "The Improvisation of Hermeneutics. Jazz Lessons for Interpreters," in *Hermeneutics At the Crossroads*, ed. Kevin Vanhoozer, James K.A. Smith, and Bruce Ellis Benson, Bloomington and Indianapolis: Indiana University Press, (2006).p.194 (italics original).
[159] Robert John Russell. "The Entangled God: Divine Relationality and Quantum Physics, By Kirk Wegter-McNelly," *Theology and Science* 14, no. 1 (2016):121-27.

briefly but in Wegter-McNelly's response,[161] he acknowledges the difficulty that beset his earlier handling of Bell's work, namely that "the nature and power that enables (drives?) quantum entanglement"[162] has not yet fully been grasped. It is clear that because Wegter-McNelly is still working within a realist metaphysic, he thinks that entanglement is a thing to be understood and holds out a hope of developing a better metaphor for exploring God's relationship with the world once the specifics of entanglement are better delineated. In 2017, we have two further examples of Bell's work being a trope, to be trotted out to give credence to particular view of the world or a theological statement. In *Quantum Shift*,[163] we noted Heidi Ann Russell's confused account of the significance of the experimental violations of Bell's inequalities.[164] In *The Source of All Love: Catholicity and the Trinity*"[165] Russell quotes from a 1998 article by Timothy Murphy and simply mentions Bell as someone who has tried, unlike the proponents of the Copenhagen interpretation, to "treat[] quantum mechanical occurences as actual occurences rather than probabilities." [166] The second time in 2017 Bell is simply dropped into the text is in Thomas Hosinski's, *The Image of the Unseen God.*[167] He writes, "But in later years actual experiments (the John Bell and

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[160] Russell. "The Entangled God: Divine Relationality and Quantum Physics, By Kirk Wegter-Mcnelly."pp.123
[161] Kirk Wegter-McNelly."Response to Robert John Russell's Review of Entangled God," *Theology and Science* 14, no. 1 (2016):128-29.
[162] Wegter-McNelly. "Response to Robert John Russell's Review of Entangled God."p.129
[163] Russell. *Quantum Shift. Theological and Pastoral Implications of Contemporary Developments in Science*.
[164] Russell.*Quantum Shift. Theological and Pastoral Implications of Contemporary Developments in Science*.p.60
[165] Russell. *The Source of All Love: Catholicity and the Trinity*.p.12
[166] Timothy S. Murphy."Quantum Ontology: A Virtual Mechanics of Becoming," in *Deleuze and Guattari: New Mappings in Politics, Philosophy and Culture*, ed. Eleanor Kaufmann and Kevin Jon Heller (1998).p.213
[167] Thomas E. Hosinski. *The Image of the Unseen God. Catholicity, Science and Our Evolving Understanding of God.*, New York: Orbis Books, (2017).

Alain Aspect experiments) have shown that quantum entanglement appears to be a fact."[168] Hosinski's book is predicated on this even though entanglement may or may not be an ontological fact. Given that John Bell's paper and the experiments done to test Bell-type inequalities have been repeatedly discussed, it is easy for theologians to think that interpreting what these experiments do and don't mean has been settled. Bell's intentions, his theorem, his inequality and the experiments have been accessed in these later works through other scholars' discussion of them and without a degree of comparative research, it is easy to compose a seemingly credible paragraph explaining them without exposing the complexity that surrounds them. In recent dogmatic theology, the experimental violations of Bell inequalities have been reduced to that which demonstrates the existence of ontological entanglement in the quantum world with no hint of the wide range of different views held by experts in the field. Furthermore, opposing strands are woven together as if telling a coherent and agreed story. In Joyce Ann Konigsburg's 2017 PhD thesis, she begins with EPR, noting correctly that the crux of the issue in the paper, is whether or not quantum mechanics can be said to be a complete theory.[169] However, her summing is anachronistic and inaccurate: "the EPR paper establishes the following paradox, either each entangled quantum particle possesses local, separate, realities or the entangled wave function is not complete."[170] As Konigsburg explains Einstein's thinking and then Bell's, words of later scholars are interpreted as if they were the words of Bell and Einstein

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[168] Hosinski. *The Image of the Unseen God. Catholicity, Science and Our Evolving Understanding of God*., in Chapter 4, in the section on Quantum Theory. The online book is not paginated.

[169] Konigsburg. "Relational Interreligious Dialogue: Interdisciplinary Arguments From Creator/Creature Theology and Quantum Entanglement."p.120

[170] Konigsburg,. "Relational Interreligious Dialogue: Interdisciplinary Arguments From Creator/Creature Theology and Quantum Entanglement."p.120

themselves.[171] In everything Konigsburg says there are elements that represent Bell or Einstein's position, but the overall tenor of her explanations is less than clear. *The Entangled God* is in her bibliography but Wegter-McNelly is not referred to in her account of EPR or Bell's work. The final reference to Bell's work in a theological or theistic context that we shall look at occurs in an essay published in a collection of essays questioning Christian theology's recent hesitancy with regard to the traditional idea of body and soul.[172] In his essay, "The Incompatibility of Physicalism with Physics,"[173] like so many other writers before him, Bruce L. Gordon marshalls Bell in support of his own argument. Gordon avers that to be cogent, the physicalist argument must be able to demonstrate that the macroworld must depend upon or emerge from the microphysical realm. Gordon claims that John Bell's "work on the EPR argument and missing elements of reality, along with subsequent experimental tests, have shown that Bohr was essentially correct and Einstein wrong about the completeness of quantum mechanics"[174] and furthermore: "What John Bell showed is that, if quantum theory is correct, no hidden variables (empirically undetectable elements of reality) can be added to the description of quantum systems exhibiting nonlocal behaviour that would explain these instantaneous correlations on the basis on local considerations." Gordon continues however, "As indicated, subsequent experiment showed that quantum theory is correct and complete as it stands. But since all *physical* cause-and-effect relations are local, the completeness of quantum theory implies the physical incompleteness

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[171] Konigsburg. "Relational Interreligious Dialogue: Interdisciplinary Arguments From Creator/Creature Theology and Quantum Entanglement." see p.121

[172] R. Keith Loftin and Joshua R. Farris. (eds) *Christian Physicalism? Philosophical Theological Criticisms*, Lanham, Bolder, Lexington, New York: Lexington Books, (2018).

[173] Bruce L. Gordon. "The Incompatibility of Physicalism With Physics," in *Christian Physicalism? Philosophical Theological Criticism*, ed. R. Keith Loftin, and Joshua R. Farris, Lanham, Boulder, Lexington, New York: Lexington Books, (2018).:371-402

[174] Gordon. "The Incompatibility of Physicalism With Physics."p.375

of reality: the universe is shot through with mathematically predictable nonlocal correlations that, on pain of experimental contradiction, have *no* physical cause."[175] Gordon backs this up by citing a paper by Hans Halvorson and Robert Clifton. [176] A closer look at this paper reveals Halvorson and Clifton's claim is somewhat less melodramatic. Rather than declaring the physical unreality of the universe, they are concurring with David Malament's statement in his 1996 book chapter that "in the attempt to reconcile quantum mechanics with relativity theory ..... one is driven to a field theory; all talk of "particles" has to be understood, at least in principle, as talk about the properties of, and interactions among, quantized fields."[177] This simply concurs with a footnote in Clauser and Horne's 1974 article, "We use the word "particle" in the conventional way to identify experimental phenomena exemplifying the general situation studied. We do not assume here the existence of a microscopic entity with a "particle-like" structure."[178]

In this survey, we have seen how, despite Wegter-McNelly's careful and detailed analysis of the experimental violations of Bell-type inequalities, where Bell's work is subsequently mentioned, it is usually rolled out to demonstrate the entanged nature of the world which is then used to highlight something about God or God's relationship to all that is. Quite often, statements to which the experimental violations of a Bell-type inequality are adduced as confirmation are, at least in part, anachronistic or misleading. Bell's work is used to provide legitimacy to a theological position rather than explored theologically in its own

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[175] Gordon. "The Incompatibility of Physicalism With Physics."p.376
[176] Hans Halvorsen and R Clifton, "No Place for Particles in Relativistic Quantum Theories?" *Philosophy of Science* 69, no. 1 (2002):1-28.
[177] Halvorsen, and Clifton. "No Place for Particles in Relativistic Quantum Theories?"p.27 quoting from David Malament. "In Defence of Dogma: Why There Cannot be a Relativistic Quantum Mechanics of (Localizable) Particles," in *Perspectives on Quantum Reality*, ed. R Clifton, Dodrecht: Kluwer, (1996).p.12
[178] Clauser, and Horne. "Experimental Consequences of Objective Local Theories."p.534n.8.

right. In the next chapter, I draw attention to two significant findings from my paying attention to the "paradoxical book of Bell"[179] and suggest avenues for theological reflection that might "bring.. out from Christian belief some of the possibilities which have not yet been realized."[180]

[179] Żukowski, "On the Paradoxical Book of Bell."
[180] Pope John Paul II, "To the Reverend George V. Coyne."m.10

Chapter Eight: Perspectives on Immanence and Creaturehood

Thus far, I have paid attention to "the paradoxical book of Bell,"[1] presenting a both a commentary on and a reception history of the paper. I have shown how Bell-type experiments became realizable, showing the complexity of testing contentions drawn from one theory base in experimental set ups that are undergirded by quite others. I have described the first generation of experimental tests as well as the most recent and indicated new areas of research that Bell's work has opened up. I have surveyed how experimental and theoretical physicists, philosophers of science, theologians and theistic philosophers have interpreted Bell 1964 and the work done in response to it. This paying attention is part of what it means to "test their value."[2] In this chapter I note two things that have emerged from this study and suggest the potential that paying attention to these has for "bringing out from Christian belief some of the possibilities which have not yet been realized."[3]

Firstly, we are no nearer than Einstein was in 1935 of having a quantum theory that offers more information than we need. The world shows no signs of yielding to our desire to pin it down but this strangely enhances rather than restricts our ability to interact with it fruitfully. Secondly, not only is there no consensus on what the experimental violations of Bell-type inequalities mean 48 years after the first experimental test, there is no sign of how consensus might be reached. Deciding between which interpretation of Bell's inequalities to espouse all comes down to the choice of the espouser. Amongst those who accept Bell's inequalities have been violated, there remains

[1] Żukowski. "On the Paradoxical Book of Bell."
[2] Pope John II. "To the Reverend George V. Coyne."m10 [sic]
[3] Pope John II. "To the Reverend George V. Coyne."m10 [sic]

no logical or rational way to decide definitively between the competing explanations. Any or none of the interpretations as to the implications of the violations of Bell's inequalities might be true. The choice as to which of the interpretations of experimental violations of Bell's inequality to accept is not logically or rationally mandated. It is decided on rational or logical grounds but this decision remains a choice, a choice determined by prior commitments about the nature of the world, the nature of philosophy, the nature of science, for example. This multiplicity of interpretations of what Bell 1964 means is rationally and logically irreducible and inescapable. This is not to make any statement about the ontology of the world within which we are set, it is simply to note that any decision made about the nature of the world derived on the basis of reflection upon the experimental violations of Bell's inequalities is not mandated by the science but chosen by the scientist, philosopher or theologian on extra scientific grounds. That quantum theory offers no more information than we need to act and also that the plurality of possible explanations as to what the experimental violations of Bell's inequalities mean is irreducible are both epistemologically significant facts. I suggest they can be seen as intimations of our creaturehood and I offer theological resources by which they may be explored further.

8.1 Fruitfulness rather than meaning

As Bell drew on EPR and theorists and experimentalists on Bell 1964, we have seen how past research has been put to use fruitfully in new ways. Einstein noted that to pursue his research objectives, he had to be epistemologically unscrupulous.[4] This unscrupulousness is something that emerged as we charted the history of Bell 1964 from its roots in the discussions about quantum theory in the 1920s to the present day and it is something of which theologians of science must be aware. We have seen this unscrupulousness evident at a number of

[4] Einstein. "Reply to Criticisms."p.684

points and as we draw attention to them, it is important to note that the word unscrupulous here has no moral or critical connotations whatsoever. What Einstein was drawing attention to in his use of the word is the rightful reluctance of the scientist to try to force the world into her own metaphysical system. It is worth reading Einstein's comment in full, "Science without epistemology is — insofar as it is thinkable at all — primitive and muddled. However no sooner has the epistemologist, who is seeking a clear system, fought his way through to such a system, than he is inclined to interpret the thought content of science in the sense of his system and to reject whatever does not fit into his system. The scientist however cannot afford to carry his striving for epistemological systematic that far. He accepts gratefully the epistemological conceptual analysis; but the external conditions, which are set for him by the facts of experience, do not permit him to let himself be too much restricted in the construction of his conceptual world by the adherence to an epistemological system."[5]

While Bell 1964 ultimately sprang from Einstein's desire to have an all encompassing complete theory, Einstein nevertheless draws attention to the importance of the flexible use of conceptual systems to aid in the scientist's construction of "his conceptual world." We have seen this incremental, flexible and responsive change throughout the prehistory and history of Bell 1964. Einstein referred to the scientist's freedom to use whatever conceptual tools are relevant to the task at hand. The unscrupulous opportunism we see evidenced in the trajectory of work surrounding Bell 1964 is the taking of something proffered by a paper in the past and putting it to use in a slightly but perceptively differently way, taking some of what it brings with it but angling it towards a perceptively different but "analogous"[6] purpose.

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5 Einstein."Reply to Criticisms."p.684
6 Wheeler. "Polyelectrons."p.235

I shall draw attention to three examples of this practice evident in this overview of Bell 1964, its background and the uses to which it has been put. The first example concerns the thought experiments outlined in EPR. A thought experiment was put forward in EPR as part of an argument demonstrating the incompleteness of quantum theory from within the strictures of the theory itself. Without any reference to EPR and accepting quantum theory as complete, WS perform an experiment suggested by Wheeler to test a prediction of pair theory about the linear polarization of photons emitted in the annihilation of a positron and electron pair. Assuming that quantum mechanics is an incomplete theory, Bohm outlines a theory that completes it while matching all the predictions of quantum theory. On the assumption that quantum theory is an incomplete theory, Bohm and BA scrupulously suggest performing the thought experiment contained in EPR to determine whether or not the prediction of quantum mechanics it enshrines would occur in practice. They unscrupulously marshall the WS experiment as an example of an experiment that does just that. Bell notes that Bohm's theory includes instantaneous connections between the settings of one measuring device and the outcome at the other. John Bell, also assuming the incompleteness of quantum theory, refers to BA's first version of the EPR thought experiment, the one conducted on spin half particles which has not been conducted. While BA suggests it as a test to see whether the feature of quantum mechanics assumed in the EPR experiment will occur in practice, Bell assumes that it would occur. However, assuming this, Bell suggests the experiment be conducted, not as a test of whether the EPR thought experiment is realized but as a test of whether or not the instantaneous connections of Bohm's theory will or will not occur in practice. Thus a thought experiment that was originally proposed as part of an argument to prove that quantum theory is incomplete becomes, unscrupulously, a proposed real experiment to test whether the world includes nonlocal connections via an actual experiment conducted for a completely different purpose.

The second set of examples of this unscrupulousness can be seen in the process by which CHSH outlined an experiment capable of testing a version of Bell 1964's ideal experiment. In suggesting a practical experiment that could be a realization of the thought experiment that they had outlined, BA had turned to the experiment of WS conducted in 1950 even though WS had nothing to do with EPR or the arguments it makes with regard to the completeness or otherwise of quantum theory. WS had designed their experiment, suggested by John Wheeler, to test a prediction of an entirely different theory, Dirac's pair theory, that in the annihilation of a positron-electron pair, two photons will be emitted simultaneously, the linear polarizations of which will be orthogonal to each other. BA saw in this prediction, instantiated by the WS experiment, an example of the feature of the mathematics of quantum theory, which EPR had evidenced of its incompleteness. Despite being quite different from the spin of electrons, the linear polarization of photons had been deemed "analogous" to the singlet state of electrons by John Wheeler for the purposes of testing a prediction of pair theory. CHSH turn to it as a possible means by which to test their version of Bell's inequality. However, they have realized that not only does WS not test at the required angles at which an experimental test might reveal whether or not the data collected violated their Bell-type inequality, they also realize that given the restrictions of realizable as opposed to thought experiments, it could not do so.[7] Therefore CHSH turn to another recently conducted experiment, KC, that also claims to be an example of the thought experiment noted by EPR in their argument demonstrating the incompleteness of quantum theory. KC specifically reference EPR and Bohr's reply to the paper.[8] They do not reference Bohm but they do

[7] Kasday outlined further assumptions that had to be made to enable it to do so: Kasday. "Experimental Test of Quantum Predictions for Widely Separated Photons."p.198

[8] Bohr. "Can Quantum-Mechanical Desciption of Physical Reality be Considered Complete?"

reference WS and two of the papers upon the theory or calculations of which WS rely,[9] despite KC's methodology being entirely different from that of WS. KC performed an experiment in which the photons the polarization of which is tested are emitted successively in an atomic cascade rather than simultaneously in an annihilation experiment as in WS. Since the linear polarization of the photons emitted in their cascade experiment can be directly tested because the rays given out are in the optical range unlike the gamma rays of the annihilation which have to be tested by Compton-scattering, this offers a more practical experimental methodology for CHSH who therefore accept the link that KC have presumed with the underlying theory of the WS experiment, an experiment that Bohm and Aharonov declared to be consonant with the case in point. Set out like this it seems somewhat tortuous. I am not suggesting that there is a sleight of hand or that the link that KC make with EPR and then CHSH make with the KC is in anyway illegitimate but I am suggesting that when metaphysical statements about the nature of reality as opposed to statements about the nature of a theory are being made, it is as well both for physicists, philosophers of science and theologians to be entirely clear about the stages of the argument being made.

The third set of examples by which experimental effects or the theory behind them produced to elucidate one set of problems is taken over by another is somewhat less subtle. It begins in Ekert's 1991 paper[10] in which he proposes using the experimental methodology of Bell-type experiments to produce effects that can make realizable Bennett and Brassard's suggestions for securing communication by quantum encryption. Ekert took the effects produced in experiments designed to test whether not Bell-type inequalities would be violated in practice. The thought experiment EPR put forward, assuming that quantum

[9] i.e., Yang. "Selection Rules for the Dematerialization of a Particle Into Two Photons."; Bleuler and Bradt. "Correlation Between the States of Polarization of the Two Quanta of Annihilation Radiation."
[10] Ekert. "Quantum Cryptography Based on Bell's Theorem."

mechanical effects would occur, was part of the EPR argument that quantum mechanics was an incomplete theory. Ekert on the other hand takes those experimental effects and puts them to use for an entirely different purpose the success of which depends upon the theoretical assumption that quantum mechanics is a complete theory.[11] It is this conceptual clash that runs through the later field of theory and experiment stemming from Bell 1964. Experiments are being performed, ostensibly so as to become loophole free, as part of what began in Bell's mind as testing whether any theory proposed as a means of completing quantum theory would have to have the same nonlocal feature as Bohm's proposed interpretation. The same experiments are being performed, on the assumption that quantum mechanics is complete, so as to produce effects that can be used to ensure the security of encrypted communications. As we noted while surveying the myriad of ways in which physicists, philosopher and mathematicians interpret Bell's work, there are those, particularly in the quantum information community that very definitely deny that the effects first noted in Bell-type experiments spring from the entangled, or nonlocal state of the underlying reality[12] while there are those working in the area who very definitely do.[13] It is an irreconcilable theoretical difference and yet the experimental and technological basis is the same.

These examples have not been adduced to show that there is a huge flaw in the theoretical and experimental research fields that have derived from Bell 1964 but to underline the importance of spotting the particular assumptions and theory bases that are used in any particular part of this wide research field so as to ensure that, when theologians extrapolate from the field they are clear as to the nature of

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[11] Ekert. "Quantum Cryptography Based on Bell's Theorem."p.661
[12] E.g., Schlosshauer. *Eleganace and Enigma.The Quantum Interviews,*p.171
[13] E.g., Schlosshauer. *Eleganace and Enigma.The Quantum Interviews,*p.173

what is being claimed, on what basis it is being claimed and why. It is important to note that effects produced by human interaction can be put to work by physicists in many different and sometimes contradictory ways entirely successfully which is an indication that the particular tranche of theory used to explain or justify a particular usage may not have any justification outside its particular sphere of use. This is one of the important points for theologians to understand in any attempt to see whether this area of physics can help them bring out "from Christian belief some of the possibilities which have not yet been realized."[14] Firstly to ensure that their own accounts of Bell 1964 are accurate but also because it demonstrates the fruitfulness of what the late Bernard d'Espagnat, who was the first to reference Bell 1964,[15] called a "fabricated ontology."[16] Quite often, to proceed, some questions simply have to be bracketed out. This is not in the least illegitimate. Indeed as Shapin and Shaffer show, the necessity of proceeding in this way when trust in the ultimacy of metaphysics had been shown to be misplaced, was the very thing that gave rise to the scientific methodology as developed by Boyle and the Royal Society and still practised today.[17] I suggest this is an intimation of our creaturehood.

In chapter five we saw a vast range of opinions about what the experimental violations of Bell's inequalities mean amongst mathematicians, philosophers of science and physicists, both experimental and theoretical, while in chapters six and seven, we saw the almost complete adherence to the idea that the experimental violations of Bell-type inequalities indicate that reality is nonlocal. While theologians have by and large chosen only one option out of all

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[14] Pope John Paul II. "To the Reverend George V. Coyne."m.10 [sic]
[15] d'Espagnat. *Conceptions De La Physique Contemporaine*.p.149
[16] d'Espagnat. *On Physics and Philosophy*.p.281
[17] Shapin, and Schaffer. *Leviathan and the Air Pump: Hobbes, Boyle and the Experimental Life*.

the variety of options of interpretation on offer, it is vital that theologians who study Bell 1964 acknowledge both the reality and the irreducibility of the multiplicity of interpretations as to what the experimental violations of Bell's inequalities mean. Thus the second area of learning from paying attention to Bell 1964 is that debate amongst scientists, philosophers of science and interested mathematicians shows no sign of reaching unanimity in seemingly stark contrast to the evidenced replicability of the experimental results that have been reproduced time after time and year after year. There is not only no unanimity as to what they mean, there is no sign that unanimity is possible. This I contend is the only uncontentious learning that theologians can take from this area of scientific research.

This is not to deny legitimacy to the work of theologians like Wegter-McNelly who espouse a particular way of interpreting Bell's work and mine it for its theological potential. Like the scientists in the field to which d'Espagnat draws attention, they assume a starting point, espouse a particular fabricated ontology and explore what can be said on that basis. In the evocative words of the title of Philip Clayton's 2001 article[18], they are "tracing a line." The plural "lines" in Clayton's title is especially helpful in providing a methodology for theologically reflecting on Bell 1964 where there is no convergence in the scientific community as to what the experimental violations of Bell-type inequalities mean, if indeed they mean anything at all. The interdisciplinary methodology of "Tracing the Lines"[19] could be adapted fruitfully as a theological equivalent of what d'Espagnat refers to as "fabricated ontology."[20] As long as theologians remember that the line they trace, the metaphysical starting point they espouse is set within the wider context of the irreducible plurality of understandings

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[18] Clayton. "Tracing the Lines: Constraint and Freedom in the Movement From Quantum Physics to Theology."
[19] Clayton. "Tracing the Lines: Constraint and Freedom in the Movement From Quantum Physics to Theology."
[20] d'Espagnat. *On Physics and Philosophy*. p.281

as to what Bell 1964 mean, that they are tracing one out of a number of possible lines, that they are offering a specific perspective rather than a final account of the whole, then following a particular trajectory, as Wegter-McNelly did will be theologically fruitful. However, ignoring the reality of the continuing inability of scientists and philosophers of science to agree in this area and putting forward a line traced as the only line that can or should be traced, as Wegter-McNelly also did,[21] is misleading. In the context of letting go of metaphysical certainty, as Boyle and the Royal Society did when they began the development of what has become the modern scientific method and acknowledging the irreducible plurality of interpretations as to what the experimental violations of Bell-type inequalities mean, then tracing a line, as Clayton suggests, is a fruitful way of exploring the wealth of Bell 1964 theologically and is comparable with the espousal of a fabricated ontology for theoretical and experimental physicists.

This is not only perfectly legitimate; it is absolutely necessary. Without starting assumptions, nothing can be said about anything. What is mistaken is a refusal to acknowledge that there are other equally legitimate ways of interpreting what Bell 1964 has achieved, other starting places, other sets of assumptions that can be made and that these may be equally enlightening. Wegter-McNelly's quite firmly stated unwillingness, not to say his dismissal,[22] a dismissal that is verging on the strident, of any other way of looking at Bell 1964 may be necessary for a scientist who is pursing particular research aims but it is unhelpful for someone mining Bell's work for the metaphorical potential it offers for a particular way of expressing something about the nature of the relationship between God and the world. Furthermore in pursuing only one particular avenue of interpretation, Wegter-McNelly has missed the theological pearl beyond price of this area of scientific research, a pearl of which our seventeenth century

[21] KW-M p.102
[22] KW-M p.102

contemporaries took hold and thereby invented what has become the modern scientific method. Certainty is not available for us. Even in physics, we walk by faith and not by sight. What this epistemological multiplicity confirms for us is that we cannot escape our situatedness.

One thing stands out from this study: the efficiency and fruitfulness of continued experimental actions not only does not require a clear and singular understanding of the ontology of what is being acted upon and what results from actions taken but rather requires sitting light to it. We have seen this in the ways that experimental effects produced out of one tranche of theory are fruitfully put to work in the service of another and we see this writ large in the vast range of ways in which the experimental violations of Bell's inequality are interpreted by scientists and philosophers of science, not only with no resolution of this debate in sight but also not even the outline of a means of coming to a common mind as to what they mean but without this in anyway affecting the possibility of putting the experimental effects to productive use.

Pope John Paul II stressed the importance of gaining a proper understanding of new discoveries of science so that theologians might better test their worth in drawing out new insights from the Christian faith. Heeding this stricture, means taking note of what scientists do and with what result as well as paying attention to what account is given of what has been done. What seems clear in the particular small slice of quantum physics to which we have been paying attention is both the precariousness of what is known with the precision and usefulness of what can be done. The experiments testing Bell's inequalities done so as to increase our understanding of what the quantum world is like, have, on that regard, signally failed. There remains, after 48 years of experiments all producing the expected results, no scientific consensus as to how to interpret them. However, not despite this, but because of this, not only have the experiments become increasingly sophisticated, enlarging our technological abilities to act but new fields of research such quantum cryptography and quantum computing have opened up. The technical capabilities that have been produced have sprung from the attempts to produce more and more sophisticated experiments that close the experimental loopholes so as to bear out Bell's contention that any theory designed to complete quantum theory cannot circumvent the nonlocality of Bohm's theory. However, the new fields, that have sprung from these research endeavours, precipitated out of Einstein's sense that quantum theory was incomplete, use those experimental effects thereby produced, in the service of research posited on the polar opposite assumption that quantum theory is complete. Thus, while we are unable to pin down what the experimental violations of Bell's inequalities mean, or even if they mean anything at all, in pursuing this line of work, physicists have increased vastly what it is possible to do. Indeed we see that different sets of research endeavours posited on contradictory premises can all bear fruit.

I will suggest that the irreducible plurality of interpretations of what this one small paper means, in concert with the learned "unscrupulousness" of scientists as they put previous research to use in new ways, signals something of what our human limitations are. However the fact that there is a vast number of possibilities open to them has not stopped physicists nor philosophers of science pursuing their own specific research endeavours within the wider breath of the field. This indicates how human beings can act fruitfully within the bounds of human limitation. The existence of a plurality of possible and even contradictory meanings does not preclude the possibility of acting, learning and increasing our ability to act. Indeed the possibility of acting and learning within a vast plethora of different and contradictory possibilities requires the exercising of choice. Working creatively within a research area that resists closure and offers an irreducible plurality of contradictory options means that accepting rather than resisting choice as choice rather than necessity is inevitable. In theological terms, this perhaps expresses something of what follows from our status as creatures. In this chapter, I will suggest some philosophical and theological resources that can help us explore what it means to be created as evidenced in this research field both as the impossibility of evading the irreducible plurality of possible interpretations of the experimental interpretations of Bell's inequality and embracing the fruitfulness that comes nevertheless from choosing to follow one partincular line of research.

What philosophical and theological resources are available? With a gap of seventeen centuries and from entirely diverse perspectives, St Gregory of Nyssa, James K. A. Smith and Deleuze and Guattari, offer fruitful means by which to conceptualize and make sense of the continuing inability of those working in the field to hit upon the one right answer to the question of what the experimental violations of Bell's inequality mean and to reflect upon the slipperiness of meaning as evidenced by an experimental effect or theoretical paper designed for one purpose being used fruitfully for another. What I am looking to Deleuze and Guattari, Smith and Gregory each to provide here is not *the* answer as to why the multiplicity of interpretations is, in principle, irreducible and ontology shape-shifting but resources that enable an exploration of my conjecture that this multiplicity and slipperiness is neither surprising nor embarrassing. That this exploration draws on multiple resources that are contradictory coheres well with my conjecture that the irreducible multiplicity of interpretations of the experimental violations and the slipperiness of scientific thought and practice tells us something about our situatedness rather than the that within which we are situated. A plurality of varied resources can shed light upon our situation: we are released from the necessity of finding the one right explanation, albeit never from the necessity of thinking one specific thought or taking one specific action at a time, which is the human condition.

8.2 Implications of Immanence

For Deleuze and Guattari, there is only the immanent flux in which we find ourselves and immanence is not immanent to anything but immanent only to itself.[23] Few philosophers or scientific thinkers have explored as thoroughly as Deleuze and Deleuze and Guattari the metaphysical implications of atheism for thought and speech, when God is "abducted:"[24] how can we conceive of the world as a whole when God can no longer be the place-holder for a thinking of the all? Deleuze and Deleuze and Guattari hold resolutely to thinking from within. They write from it, in it, demonstrating it rather than defending or explaining it. Without God, no God's eye view is possible, not even as a human conceptual strategy. Without God, even the notion of the whole no longer makes sense. Writing from within the flux, the chaos, the chaosmos,[25] a word Deleuze borrowed from Joyce, in the first two books[26] Deleuze and Guattari co-authored, they exemplifed rather than explained their methodological assumptions. They wrote, held within a simple recognition of the implications for human thinking and speaking of accepting Nietzsche's invitation "to remain earthly,"[27]exploring which philosophical and linguistic stances it makes possible and impossible. As Peter Gaffney writes, according to Deleuze, "We simply cannot know "what is" not because it is distorted by our senses, but because sensing and knowing take place alongside

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23 Gilles Deleuze and Félix Guattari. *What is Philosophy?,* trans. Graham Burchell and Hugh Tomlinson, London, New York: Verso, (1994).p.47
24 Sean Carroll. *The Big Picture: On the Origins of Life, Meaning and the Universe Itself*, London: Oneworld Publications,(2016).p.144
25 Deleuze, and Guattari. *What is Philosophy?*p.204
26 "Capitalism and Schizophrenia," their first book together, was published in two volumes, *L'anti-Oedipus* in 1972 & *Mille Plateaux* in 1980. Their second, *Kafka: Pour Une Littérature Mineure* published in 1975 and their final joint book was *Qu'est-que ce la philosophie?,* published in 1991.
27 Alain Beaulieu. "Introduction to Gilles Deleuze's Cosmological Sensibility," *Philosophy and Cosmology* 16 (2016):199-211.p.199

the process of actualization which produces "what is." This is the basis for Deleuze's characteristically ontological realism: to think, in this case, is to participate in the quasi-material process that produces, and never ceases to produce, the real. ("Ontology is the dice throw, the chaosmos from which the cosmos emerges.").”[28]

Deleuze and Deleuze and Guattari attempt to tread the tight-rope of giving an account of what is, without themselves seeming to give an account that is the account from a God’s eye view, from a transcendent outside, “there are no such things as universals, there's nothing transcendent, no Unity, subject (or object), Reason; there are only processes, sometimes unifying, subjectifying, rationalizing, but just processes all the same.” Deleuze and Deleuze and Guattari held themselves to a ruthless adherence to thinking within the boundaries of our situatedness and, as such, they can be said to exemplify the attentiveness that is one of Janz’s philosophical virtues.[29] They have ruthlessly explored what it is to think without God and have had the courage to speak and write without occupying a transcendent vantage point in God’s stead and without the locus of a discrete individual and this, seemingly paradoxically, is what makes their work so important for theologians. They write as atheists but their work is vital in exploring the reality of what it is to think, write and act as a creature. Their work gives a context to and makes philosophical sense of the ever receeding nature of the answer to the question of what the experimental violations of Bell’s inequality mean and, their account of what it is to think and particularly to do science immanently within immanence that is not immanent to anything, is particularly thought-provoking.

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[28] Peter Gaffney. “Science in the Gap,” in *The Force of the Virtual: Deleuze, Science and Philosophy* Minneapolis, London: University of Minnesota Press, (2010).p.15 Gaffney is quoting from Gilles Deleuze. *Difference and Repetition,* trans. Paul Patton, New York: Columbia University Press, (1994).p.199

[29] Janz. *God, the Mind’s Desire. Reference, Reason and Christian Thinking*. p.47

Deleuze and Guattari's final book, "What is Philosophy?"[30] includes an account of science as one of the three great forms of thought of which the other two are philosophy and art. This final book with its sense of giving an overview and prescriptions enraged many for whom it seemed a betrayal of what had gone before.[31] While there are commentators who deny that by "science," Deleuze and Guattari mean science as we ordinarily mean it,[32] the specificity of some their discussions in *What is Philosophy*? show more than a passing acquaintance with it. Indeed their discussion of Heisenberg's uncertainty principle is both profound and succinct, and in, this context, exceptionally helpful, "But perspective fixes a partial observer, like an eye, at the summit of the cone and so grasps contours without grasping reliefs or the quality of the surface that refer to another observer position. As a general rule, the observer is neither inadequate or subjective: even in quantum physics, Heisenberg's demon does not express the impossibility of measuring both the speed and the position of a particle on the grounds of subjective interference of the measure with the measured, but it measures exactly an objective state of affairs that leaves the respective positions of two of its particles outside of the field of its actualization, the number of independent variables being reduced and the values of the coordinates having the same probability. Subjectivist intepretations of thermodynamics, relativity, and quantum physics manifest the same inadequacies. Perspectivisim, or scientific relativism, is never relative to a subject: it constitutes not a relativity of truth but, on the contrary, a truth of the relative, that is to say, of variables whose cases it orders according to the values it extracts from

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[30] Deleuze, and Guattari. *What is Philosophy?*

[31] E.g., Isabelle Stengers. "Gilles Deleuze's Last Message," http://www.recalcitrance.com/deleuzelast.htm (accessed 27th August, 2017).

[32] Rex Butler. *Deleuze and Guattari's "What is Philosophy?"* London, New York, Sidney, Delhi: Bloomsbury, (2016).pp.112-3

them in its system of coordinates."[33] While Deleuze and Guattari are very definitely not talking here about the differences of opinions between individual groups of scientists, one side interpreting the violation of Bell's inequalities as indicating the nonlocality of the world, while others its randomness, they are bringing out the reality that all objective knowledge is still relative and perspectival. Thus, rather as seeing the variety of interpretations of the experimental violations of Bell-type inequalities, as an embarrassment to which the only response should be a continuing attempt to find and then espouse the cause of the correct one, Deleuze and Guattari offer the possibility of asking what does it look like from here? Given a specific set of starting assumptions what is possible? This is what Ekert had the insight to do. He did not get embroiled in pursuing the question of what the true interpretation might be, but asked what is possible if you stake a position and then see what the experimental observed effects can do rather than getting hung up on what they are. I suggest that as unlikely as it may seen, Deleuze and Guattari are companions well worth paying attention to in a theological reflection in the irreducibility of the interpretation of Bell 1964, but what about theology?

8.3 Boundedness

The work of Deleuze and Guattari offers philosophical resources indicating that finding the one right interpretation of Bell's work's from amongst the many is conceptually impossible and it resonates well, despite the gap of 1600 years, with the theology of St Gregory of Nyssa and with his concept of διάστημα, diastema. As unlikely as this pairing seems,[34] what unites them and makes them both relevant in this context, albeit, from completely different eras and perspectives, is

[33] Deleuze, and Guattari. *What is Philosophy?*pp.129-30
[34] As far as I am aware, this is the first attempt to show the commonalities between aspects of the thought of St Gregory of Nyssa with the work of Deleuze and Guattari.

their commitment to the situated and bounded nature of human thought:[35] Deleuze and Guattari because of their rigorous commitment to the implications of their atheistic monism and Gregory of Nyssa because of his resolute commitment to the maintenance of a clear distinction between creation and Creator such that no God's eye view of creation, of the world as a whole, is even in principle available to human beings. For Deleuze and Guattari, life is immanent only to itself and is the total context of human thought. For Gregory, an orthodox Christian, human thinking and the language by which it is enabled, are inescapably bound within a diastemic creation. St Gregory of Nyssa was born around 335. He became Bishop of Nyssa[36] and was the youngest of the Cappadocian Fathers[37] whose works, drawing on the Greek philosophers, contributed much to the further development of Christian doctrine. It is Gregory's fundamental and thoroughgoing appreciation of the bounded, situated and kinetic nature of human life and thought that is relevant to theological consideration of the brute fact of the irreducible multiplicity of interpretations of the experimental violations of Bell's inequality. Unlike Deleuze and Guattari, Gregory makes the assumption that all that is stems from the creative will of God. For Gregory, all that is, including human life and thought included, are bounded and situated within what he calls διάστημα (diastema), a word,[38] which, at root, means interval. It

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[35] As well as the resonances between Gregory's concept of διαστημα and Deleuze's concept of immanence, Gregory's understanding of κινησις and Deleuze's of difference also warrant further study.
[36] Thought to be near modern Harmandali, near Ortaköy in the Turkish province of Aksaray.
[37] The others are Gregory's elder brother Basil the Great and Basil's friend, Gregory of Nazianzus.
[38] For a review, see Basil Lourié. "Temporality and a Metric for Created Natures in Gregory of Nyssa," *Scrinium* 12 (2016):340-51.,pp344-349. I follow Alden A. Mosshammer's understanding of this concept in Gregory's works e.g. Alden A. Mosshammer. "Disclosing But Not Disclosed: Gregory of Nyssa as Deconstructionist," in *Studien Zu Gregor Von Nyssa Und Der Christlichen Spätanike*, ed. Hubertus R. Drobner, and C Klock, Leiden: Brill, (1990).; Alden A. Mosshammer. "Time for All and a Moment for Each. The Sixth Homily By Gregory of Nyssa on

literally means “a standing apart”.[39] As Paulos Mar Gregorios notes, in modern Greek, διάστημα simply means “space” in the sense of “space travel”[40] but in the earliest extant use of it, it refers to the interval between the notes on the musical scale.[41] Gregory of Nyssa’s theological use of the concept is rich and, according to Gregorius, original[42] and impossible to translate into English.[43] Translating it as “gap” or “interval” does not capture its sense of extendness or movement.[44] “For Gregory, διάστημα is intimately connected with movement or change. A translation like “standing apart” gives the impression of being static, while for Gregory it is impossible for creation to be static except in in death and non-being. All is in movement, all is changing—that is the very nature of creation.”[45] Διάστημα is the possibility of extension, the interval to be traversed

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Ecclesiastes,” in *Gregory of Nyssa. Homilies on Ecclesiastes. An English Version With Supporting Studies. Proceedings of the Seventh International Colloquium on Gregory of Nyssa, St Andrews, 5-10 September (1990)*, ed. Stuart G. Hall Berlin, New York: Walter de Gruyter, (1993). & Alden A. Mosshammer. “Gregory of Nyssa and Christian Hellenism,” in *Studia Patristica 32. Athanasius and His Opponents, Cappadocian Fathers, Other Greek Writers After Nicea*, ed. E. A. Livingstone, Peeters, (1997). Scot Douglas (Scot Douglass. *Theology of the Gap*, Peter Lang Publishing Inc, (2005).) and Tamsin Jones (Tamsin Jones. *A Genealogy of Marion’s Philosophy of Religion. Apparent Darkness*, Bloomington and Indianapolis: Indiana University Press, (2011).) both draw on Mosshammer’s work on διαστημα.

[39] Mosshammer. “Time for All and a Moment for Each. The Sixth Homily By Gregory of Nyssa on Ecclesiastes.”p.260

[40] Paulos Mar Gregorios. *Cosmic Man. The Divine Presence*, New York: Paragon House Publishers, (1988).p.68

[41] Gregorios. *Cosmic Man. The Divine Presence*.pp.67-99 referring to a fragment from a work of Archytas, a fourth century BCE philosopher, quoted by Porphory’s in his Commentary on Ptolemy’s Harmonics, and published in Hermann Diels, *Die Fragmente Der Vorsokratiker. Griechischund Und Deutsch*, Berlin: Weidmannsche Buchhandlung, (1903).p.272. The fragment from Archytas is translated in Monte Ransom Johnson. “Sources for the Philosophy of Archytas,” *Ancient Philosophy* 28 (2008):1-27.pp.5-6 and comes, according to Porphory, from Archytas’ *On Music*.

[42] Gregorios. *Cosmic Man. The Divine Presence*.p.69

[43] Gregorios. *Cosmic Man. The Divine Presence*.p.75

[44] Gregorios. *Cosmic Man. The Divine Presence*.p.75

[45] Gregorios. *Cosmic Man. The Divine Presence*.p.75

temporally and spatially that enables movement, progression and change. It is its sense of movement in time as well as in space that lends the word its dynamism. It expresses the nature of creation which is a constant movement of change, diastemically, from moment to moment, “it is a movement from origin to perfection, from arche to telos, an hodos to traverse from begining to end.”[46]

Diastemic movement in time and space enables the life of all that has been created. Διάστημα is thus the mark of creation and is entirely absent in God who is all in all. It is διάστημα which, in thought, distinguishes the creation from the Creator. Διάστημα is the determining feature of the created order, extended in space and time, constantly in motion, moving from αρχη to τελος: creation is inherently diastemic.[47] “Diastemic existence, or created existence, is constant change—a sequence of unbroken change. Change is the ontological basis of the creation's existence, for it has come to be from that which is not.”[48] The creation that came to be was summoned ex nihilo and therefore change is literally its essence, its stamp. This, as Boersma stresses, for Gregory is positive; διάστημα is that which makes the life of creation possible, it makes “human growth in virtue”[49] possible and it is in this sense that Gregory sees it as that within which all creation is held, making possible creation’s eternal striving towards the goodness of God.[50] Thus to sum up, Gregory’s says , “the διάστημα is nothing other than creation”[51], it “is ...... the

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[46] Gregorios. *Cosmic Man. The Divine Presence*.p.75
[47] With its range of meanings, διάστημα resonates with Deleuze’s concept of difference.
[48] Gregorios. *Cosmic Man. The Divine Presence*.p.86
[49] Hans Boersma. *Embodiment and Virtue in Gregory of Nyssa*, Oxford: O.U.P., (2013).p.22
[50] For a discussion of this see Gregorios. *Cosmic Man. The Divine Presence*.p.88
[51] Mosshammer. “Disclosing But Not Disclosed: Gregory of Nyssa as Deconstructionist.” p107. In Greek, το διαστημα ουδεν αλλο η κτισις εστιν from Ecclesiastes 7.1.729 cited in Jones. *A Genealogy of Marion’s Philosophy of Religion. Apparent Darkness*.p.57.

common receptacle of all creation, intellectual as well as material. This διάστημα is both the chronological space of development from beginning to ending and the ontological space that distinguishes created becoming from uncreated being."[52] For created realities, there is no escaping the coming to be of which διάστημα both marks and enables.

The diastemic nature of the created has implications for Gregory's view of human thought and language and this is what makes it relevant when faced with the brute fact of the multiplicity of interpretations of the experimental violations. In the first place, positively, it is διάστημα that makes human language and thought possible; as Gregory writes in his Seventh Homily on Ecclesiastes, in the same way that "sensory perception is only possible only because of finite qualities of shape and size that define objects and separate one thing from another"[53] so "human intellection in general is possible only because the whole created order is defined and marked off by limiting qualities."[54] As Gregory explains, ""But the things which come under our comprehension (katalepsis) are such as can be understood only as extended in some diastematic manner (en diastematikei tini paratasei theoreisthai) or conceived as locally spaced, or appear to our perspective as enclosed within a beginning and an end, since the existence of each being is bounded on both sides by non-being."[55]

As well as making thought possible, διάστημα marks both thought and speech. Gregory goes beyond the then traditional acceptance that

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[52] Mosshammer. "Time for All and a Moment for Each. The Sixth Homily By Gregory of Nyssa on Ecclesiastes."p.274
[53] Mosshammer. "Time for All and a Moment for Each. The Sixth Homily By Gregory of Nyssa on Ecclesiastes."p.265
[54] Mosshammer. "Time for All and a Moment for Each. The Sixth Homily By Gregory of Nyssa on Ecclesiastes."p.265
[55] Gregorios. *Cosmic Man. The Divine Presence*.p.84 quoting from Gregory of Nyssa's Mediatations VII. 2. cited in Jean Danielou. *L'Être Et Le Temps Chez Grégoire De Nysse*, Leiden: Brill, (1970).p.98

human thought and langauge cannot not comprehend the divine to argue that human language cannot comprehend the essence of created things either. Gregory argues that language is a human construct. In later mediæval terms, Gregory was a nominalist. That humanity has the ability to create languages within which to think and to express thought is a God given gift but the languages themselves are a human product. As Tamsin Jones says, they are "a tool formed and welded by human communities for instrumental purposes and has no ontological relationship to objects of beings signified."[56] In this regard, the commonalities between Gregory of Nyssa's concept of language and that of modern philosophers has been variously noted.[57] As part of creation, language is "inherently diastemic. Language mediates between mind and body, between bodies separated in space, and between moments in time. The function of language (to attempt to bridge gaps that it can never traverse) results in its inherently transgressive and futile character: language strains to overcome the diastema between one's physical perception and one's thoughts, and between one person and another. This is a futile attempt because, itself belonging to the diastemic order, language 'depends for its efficacy on interval and separation.'"[58]

Gregory is clear: when human language attempts to speak of divine things, it is involved in "an endless pursuit of an ever elusive

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[56] Jones. *A Genealogy of Marion's Philosophy of Religion. Apparent Darkness*.p,52

[57] E.g. see Mosshammer."Disclosing But Not Disclosed: Gregory of Nyssa as Deconstructionist."; Scot Douglass. "A Critical Analysis of Gregory's Philosophy of Language: The Linguistic Reconstitution of Metadiastemic Intrusions," in *Gregory of Nyssa: Homilies on the Beatitudes: An English Version With Commentary and Supporting Studies. Proceedings of the Eight International Colloquium on Gregory of Nyssa*, ed. Hubertus R. Drobner, and Alberto Viciano, Leiden: Brill, (2000).; Douglass. *Theology of the Gap*. & Jones. *A Genealogy of Marion's Philosophy of Religion. Apparent Darkness*..

[58] Jones. *A Genealogy of Marion's Philosophy of Religion. Apparent Darkness*.p.145 quoting from Mosshammer. "Disclosing But Not Disclosed: Gregory of Nyssa as Deconstructionist."p.106

meaning."[59] Evidently, this doesn't stop Gregory speaking and writing theology or interpreting scripture. Furthermore he is clear that what he says or writes within and about created diastemic reality can also never be definitive and, in a point, relevant to the discussion of what the experimental violations of Bell's inequality might mean, Gregory is equally insistent that no confidence can therefore be placed in the ability of human language to express properly the essence of created things. As a human construct, language and the thought that it enables is both "arbitary and fallible"[60] albeit inescapable. "In the homilies on Ecclesiastes" Mosshammer writes "Gregory is moving towards something like the modern notion of the 'social construction of reality.'[61] If reality has any objective existence of its own, that objectivity can be known only to God, because only God can stand outside the διάστημα that contains it. Man shares the conditions of the reality that he seeks to know. He affects that reality in the very act of seeking to know it and to use it and is himself in turn affected by the effects he has caused."[62] This last sentence could have been written not about the thought of a fourth century C.E Church Father but by Heisenberg or Bohr about quantum theory. For Gregory, the human intellect operates within its own sphere and is unable to encompass the whole: a view that encompasses the whole is literally a view only available to God. Thus, despite his far distance from us in time, St Gregory of Nyssa, a church father of the fourth century C.E., offers us surprisingly modern theological resources with which to reflect upon and situate the irreducible multiplicity of interpretations of the significance of Bell's inequality and the experimental work that has

[59] Mosshammer. "Disclosing But Not Disclosed: Gregory of Nyssa as Deconstructionist."p.101
[60] Mosshammer. "Disclosing But Not Disclosed: Gregory of Nyssa as Deconstructionist."p.100
[61] Here Mosshammer cites Peter Berger and Thomas Luckmann. *The Social Construction of Reality*, Garden City, NY: Anchor Books, (1966). & Peter Berger. *The Sacred Canopy. Elements of a Sociological Theory of Religon*, New York: Doubleday, (1969).
[62] Mosshammer. "Time for All and a Moment for Each. The Sixth Homily By Gregory of Nyssa on Ecclesiastes."pp.275-6

sprung from it. Both Gregory's resolute commitment to the diastemic nature of human language and thought and of the creation from which they spring and Deleuze and Guattari's sense of immanence which is immanent only to itself, gives coherence to my contention that what the experimental violations mean is ultimately undecidable in principle.

8.4 Creaturehood: contingency, finitude and dependence

Gregory's sense of the constructed nature of human language and therefore thought is a theme taken up by James K. A. Smith, a self-confessedly conservative Christian. Like Gregory, that we are creatures, created by God in the midst of a total reality also created and upheld by God is a given for Smith and exploring the reality of this has meant him calling for a "a Christian appreciation of contingency, finitude, and dependence."[63] Like Gregory, he recognises that our thought and language cannot escape the limits of our creaturehood and that this has implications for what it is possible and indeed impossible for human beings to know. In the introduction to to the second edition of his first book, *The Fall of Interpretation* he describes the book as "a brief on behalf of particularity, an affirmation of difference and plurality as goods inherent in God's good creation. It is a celebration of the conditions of creaturehood——conditions that include and demand the inescapability of interpretation."[64] Just as Gregory sees the fact of διάστημα as the very condition that makes human cognition and language possible as well as the boundary beyond which they have no purchase, so Smith sees interpretation as not only inescapable but positive. Smith's work therefore holds out a promise. Taking the stance that interpretation is not a fault or a flaw,

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[63] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.14

[64] James K.A. Smith. *The Fall of Interpretation: Philosophical Foundations for a Creational Hermeneutics. 2nd Ed*, Grand Rapids: Baker Academic, (2012).p.2.

something from which to flee, something to be overcome, Smith therefore creates a space in which the plurality of interpretations of the experimental violations of Bell's inequality can be seen not simply as inevitable but good, a resource rather than a problem to be tackled.

Smith's work on twentieth century philosophy seasoned with his conservative Christian faith has resulted in deep reflection on what it is to think and speak as a contingent creature. Like Gregory of Nyssa (whom he does not cite and to whom he does not refer) and the philosophers upon whom he reflects, Smith argues that "the conditions of our knowledge ... are coincident with our status as finite, created, social beings."[65] He draws this out in both in *The Fall of Interpretation. Philosophical Foundations for a Creational Hermeneutic* [66] and in his *Whose afraid of Relativism: Community, Contingency and Creaturehood*.[67] He criticizes the pechant of theologians for staking a claim on absolute truth which he says "is a symptom of a deeper theological problem: an inability to honor the contingency and dependence of our creaturehood. There might even be something rather gnostic (and heretical) in this failure to own up to contingency; indeed one could argue that the claim to such "absoluteness" is a the heart of the first sin in the garden."[68] Like Gregory of Nyssa before him, Smith exposes the weakness of those who suppose and assume that the world is out their passively waiting for the human gaze and that our concepts and language are capable of rendering something as it is without us. "Meaning and knowledge are social accomplishments that *depend* on our relationships to communities of practice and an

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[65] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.30
[66] Smith. *The Fall of Interpretation: Philosophical Foundations for a Creational Hermeneutics. 2nd Ed*.
[67] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.
[68] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.30

environment with which we grapple."[69] In his first book, Smith draws on Heidegger and Derrida to set out the inevitability of interpretation and on St Augustine of Hippo so as to embrace this as constitutive of creation.[70] In *Whose Afraid of Relativism*[71] written thirteen years later, he explores Ludwig Wittgenstein,[72] Richard Rorty[73] and Robert Brandom[74] to show how our language about and knowledge of the world are the learned and inherited constructs of human societies. Thus, like Gregory, while believing passionately in the God and Father of our Lord Jesus Christ, he denies the possibility that human thinking can inhabit a God's eye view.[75]

James K. Smith doesn't use the word "immanence," nor refer to Deleuze or Deleuze and Guattari, but his work on contingency and creaturehood[76] is an exploration of doing and living theology from just that standpoint. His *Fall of Interpretation*[77] explores different philosophical and theological approaches to hermeneutics and, against theologians who think that interpretation is the result of the Fall from a creational immediacy, or philosophers who think interpretation,

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[69] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.105.
[70] Smith. *The Fall of Interpretation: Philosophical Foundations for a Creational Hermeneutics. 2nd Ed*.pp.24-6
[71] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.
[72] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.pp.39-72
[73] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.pp.73-114
[74] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.pp.115-150
[75] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.pp.180-181
[76] Smith. *The Fall of Interpretation: Philosophical Foundations for a Creational Hermeneutics. 2nd Ed*.; Smith, *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.
[77] Smith. *The Fall of Interpretation: Philosophical Foundations for a Creational Hermeneutics. 2nd Ed*.

while being necessary, is “structurally violent,”[78] drawing on Augustine, he develops a creational hermeneutic that “revalues embodiment and ultimately ends in an ethical respect for difference as the gift of a creating God who loves difference and who loves differently. The heart of a creational hermeneutic is also rather "Pentecostal," creating a space where there is room for a plurality of God's creatures to speak, sing, and dance in a multivalent chorus of tongues.”[79] Smith develops this further in *Who’s afraid of relativism: Community, Contingency and Creaturehood*.[80] “I'm arguing that relativism means everything depends—and that such a claim is a radically creational, radically Christian claim about the status of creaturehood, including creaturely knowing.” His appreciation of relativism neither springs from nor results in a denying of his reformed Christian orthodoxy. It is his work on Wittgenstein and Rorty which I suggest offers rich resources for a theological appreciation of the inevitability of multiple and plural intepretations of the experimental violations of Bell’s inequalities. Smith draws out aspects of pragmatism developing what he calls “a Christian philosophy of contingency,”[81] a central feature of which chimes in with what he notes is Hauerwas’ stricture that “the church is most faithful, when we “are content to live ‘out of control’..... , risk[ing] trusting in gifts, so [we] have no reason to deny the contingent character of our existence.”[82] For Hauerwas, as Smith points out, contingency “is a correlate of [our]

[78] Smith. *The Fall of Interpretation: Philosophical Foundations for a Creational Hermeneutics. 2nd Ed*.p.20
[79] Smith. *The Fall of Interpretation: Philosophical Foundations for a Creational Hermeneutics. 2nd Ed*.
[80] Smith.*Who’s Afraid of Relativism: Community, Contingency and Creaturehood*.
[81] Smith. *Who’s Afraid of Relativism: Community, Contingency and Creaturehood*.p.35
[82] Smith. *Who’s Afraid of Relativism: Community, Contingency and Creaturehood*. quoting Hauerwas. "Reforming Christian Social Ethics: Ten Theses,” *The Hauerwas Reader*, Durham, NC: Duke University Press, (2001)pp.111-115.p.113

status as creatures."[83] It is this acknowledgement of our status as contingent creatures, when as Hauerwas puts it, "we discover we are characters in a narrative we did not create,"[84] which, for Smith, resonates with pragmatism: the subtitle of the third chapter of *Who's Afraid of Relativism* is "Owning up to our Creaturehood with Rorty."[85]

Smith's book takes his readers on a journey to undermine their confidence in the necessity of holding tightly to a philosophy of realism and the correspondence theory of truth. It sheds doubt on Wegter-McNelly's stricture as to the necessity of holding onto some form of realism.[86] Smith begins with Wittgenstein's discussion of language in *Philosophical Investigations*[87] in which Wittgenstein draws out a theory of language based on a close examination on how human beings use it and the contexts in which and purposes for it is used. In contrast to a theory of language in which the base unit is the word which represents a thing, Wittgenstein explores how the suppposed correspondence between a word and a thing is always context dependent, communal and conventional. "Wittgenstein is pressing us to recognize that this communal situation is fundamental and precedes all of our meaning making as its condition of possibility. To be human is to be social, which is to be indebted, woven into a web of meaning making that is

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[83] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.36 quoting Hauerwas, "Preaching as though we had enemies," *First Things* May (1995)p.9

[84] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*. quoting Hauerwas, "Preaching as though we had enemies"p.9

[85] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.73.

[86] KW-M p.102

[87] Ludwig Wittgenstein. *Philosophical Investigations 3rd Edition,* trans. G.E.M Anscombe, New York: Macmillan, (1953).This conception of language was already held by the Cappadocian Fathers in the fourth century CE. For a discussion of Gregory of Nyssa's debate with Eunomius, see Jones. *A Genealogy of Marion's Philosophy of Religion. Apparent Darkness*.pp.52-53.

the product of social construction"[88] and this is, for Smith, "a feature of finitude, a characteristic of creaturehood,"[89] a concept he explores further through the work of Richard Rorty,[90] claiming that Rorty's pragmatism "might be more an ally than an enemy."[91] Smith means by this Rorty's sense that "the "problem" that perplexes philosopher-as-epistemologist— "How do we know there is a world outside our minds?"— is a pseudoproblem we have created."[92] Rorty's critique of philosophy "as a quest ….. for "justified true belief"[93] points to the inside/outside metaphor that is used to characterise the relationship between our minds and the world as the heart of the problem. ".. [P]hilosophy takes as "given" what is contingent. What epistemology takes as "given"—as what we "find" when we investigate our "experience"— is in fact *put* there by our training in the epistemology language game: what we "find" is what we've been trained to see."[94] Smith goes on, "And once you have been assimilated to this game, its no longer a game: it's just the way things are...... In other words, the social web of our knowing drops away, and instead we adopt a working picture of knowledge as an atomistic, isolated, interiorized "minds" who are confronted by an "external world."[95] This is exactly the working picture that undergirds the quest to find what the experimental violations of Bell's inequality mean. Rorty instead draws out the social and conversational character of our knowledge "to

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[88] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.53
[89] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.53
[90] Particularly drawing on Richard Rorty,.*Philosophy and the Mirror of Nature*, Princeton: Princeton University Press, (1979).
[91] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.74
[92] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.79
[93] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.81
[94] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.81
[95] Smith.*Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.81

recover and appreciate the significance of our contingency and dependence, our finitude and our sociality."[96] Rorty's appreciation of the constructed and social nature of human knowing is heavily criticised by those who think that this leads to a denial of the real world. It is this fear that lies behind Wegter-McNelly's emotive need to pin down the "ontological" implications of the experimental violations of Bell's inequality.[97] But, as Smith points out, Rorty is clear; "We do not give up the world, but re-establish unmediated touch with the familiar objects whose antics make our sentences and opinions true or false."[98] Recognising that our knowing is socially constructed, that we are part of a community of knowers, and unmasking the in/out picture of our minds relation to the world as a metaphor into which we have been inculcated does not thereby, "reject the antics of things."[99] While recognising that Rorty wouldn't put it this way, Smith sees Rorty's pragmatism as a helpful exploration of what it means for human beings to be both created and contingent as well as social.[100] For Smith, clinging to realism and a correspondence theory of truth, is part of our hubristic desire to be in control of rather than a part of the world in which we find ourselves, it is a strategy to escape the confines of our creaturehood and mutual interdependence. Drawing on the work of Deleuze and Guattari, we can see it is a strategy to escape immanence and on the work of St Gregory, betrays a failure to face up to the inevitable diastemic situatedness of our living, our thinking and our language.

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[96] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.81
[97] KW-M p.103
[98] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.pp.87-8 quoting Rorty. *Philosophy and the Mirror of Nature*.p.310
[99] Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.88
[100] Equally, Smith defends his position against those who see Rorty's pragmatism as incompatible with a Christian sense of sacramental ontology see Smith. *Who's Afraid of Relativism: Community, Contingency and Creaturehood*.p.106-114

Part of what inhibits the theologians who have worked on the experimental violations of Bell's inequalities from appreciating the huge breadth of the interpretative field available to them is their almost credal adherence to scientific or critical realism. For the majority, this is an unexplored assumption, but for Wegter-McNelly and Brown, it is a quasi moral requirement if we are wanting to retain our ability to speak about the world,[101] or to halt the inevitable slide to solipsism.[102] Smith explores the work of Wittgenstein and Rorty and contends that their appreciation of the constructed and social nature of human knowing is, in fact, more consonant with Christian belief in our status as creatures than the commitment to a correspondence theory of truth and philosophical realism. Furthermore, Smith reminds us that the philosophy of language, the theory of truth with which we work are all choices. The picture of a world out there that we look out at from in here is just that, a picture. Just as we have seen that how the experimental violations of Bell's inequalities are interpreted depends upon which of the assumptions upon which they rely are kept and which are excluded and that this is a matter of choice, equally the philosophical accounts of language and of truth with which we operate are also choices. There are alternatives available. For Smith, this is not a horrifying result of humanistic hubristic arrogance but a timely reminder of the contextualization that is the inevitable outworking of our creaturehood. It may even be part of the freedom that is the Creator's gift.

Smith points to the inevitability of choice. Wegter-McNelly adopts a philosophical realism and thereby finds nonlocality in the experimental violations. Depending on what they deem vital to the pursuance of science, physicists select which of the assumptions upon

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[101] KW-M p.103
[102] Brown. "Quantum Theology: Christianity and the New Physics."pp.482-3

which Bell's derivation has been deemed to rest to forgo. In theological terms, Wegter-McNelly is "tracing a line:"[103] in d'Espagnat's terms, the physicists are "fabricating an ontology."[104] Both strategies are inevitable and necessary if a specific research agenda is to be pursued or explored. For example, Artur Ekert[105] sidestepped what had become the sterile questioning of what the experimental violations of Bell-type inequalities mean in order to see what could be done and new areas of research and application became possible. If theologians of science can, with Deleuze and Guattari, St Gregory of Nyssa and James K Smith, amongst others[106] likewise step back from a hubristic, not to say blasphemous, quest for ultimate meaning and have the courage to "trace a line,"[107] the wealth of possible interpretations of what the experimental violations might mean[108] and how reflection on them might enable a deeper contemporary understanding of our Christian faith offers a fruitful field. I particularly suggest that what I take to be the irreducibility of the plurality of interpretations as to what the experimental violations might mean, the lack of the one right answer offers rich possibilities for theological reflection on what it means to be inescapably situated and specific. The fields of thinking, experimentation and technological development that have sprung and

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[103] Clayton. "Tracing the Lines: Constraint and Freedom in the Movement From Quantum Physics to Theology."

[104] d'Espagnat. *On Physics and Philosophy*.p.281

[105] Ekert. "Quantum Cryptography Based on Bell's Theorem."

[106] E.g., Philip Hefner's "created co-creator," Philip Hefner. *The Human Factor: Evolution, Culture and Religion,* Minneapolis: Fortress Press, (1993). This could fruitfully be explored alongside Fuch's sense that what quantum physics shows is that "With every quantum measurement set by an experimenter's free will, the world is shaped just a little as it participates in a moment of birth." Schlosshauer. *Elegance and Enigma. The Quantum Interviews*.p.172

[107] Clayton. "Tracing the Lines: Constraint and Freedom in the Movement From Quantum Physics to Theology."

[108] This does not assume that Joy Christian's critique of Bell's use of geometry and algebra is unfounded. As the quantum information theorists show, one does not have to accept that the experimental violations indicate anything about how the world is for them to be fruitful.

continue to spring from Bell's one short paper in a short lived journal, a paper about which there is still no agreement as to what it means nor any sign of how a unanimity of interpretation could be arrived at seems to me to be a lived expression of what it is to be creature.

Conclusion

"Theology is not to incorporate indifferently each new philosophical or scientific theory. As these findings become part of the intellectual culture of the time, however, theologians must understand them and test their value in bringing out from Christian belief some of the possibilities which have not yet been realized."[1]

We finish where we began with Pope John Paul II's call to theologians to bring their understanding to bear on the findings and insights of modern science so as to use them to draw more deeply on the resources of our faith as did the theologians of the past when faced with the new. Heeding Pope John Paul II's call, I have undertaken a detailed interdisciplinary study of Bell 1964. Following Wegter-McNelly, I have been unafraid to devote a substantial section of a theological thesis to a close reading of scientific work. To understand, I have taken up one of Janz's intellectual and therefore theological virtues[2] and paid attention. Paying attention means just that: looking at the specifics of something. I have chosen to pay attention to one of the most significant scientific papers of the twentieth century, Bell 1964. This paper has been an engine driving new fields in quantum theory and is becoming a cultural trope.

This thesis has three aims. My first aim was to pay close attention to Bell 1964, to outline what Bell said about what, to whom and why. Thus, in the first four chapters, I have described the context of Bell 1964, outlining what led Bell to write this paper, indicating upon whose work he built his own and why. In chapter one, I surveyed the

[1] Pope John Paul II. "To the Reverend George V. Coyne."m.10 [sic]
[2] Janz. *God, the Mind's Desire. Reference, Reason and Christian Thinking*.pp.48-9

EPR paper and gave a brief background about the discussions raging at the time about whether or not quantum mechanics was a complete theory. I gave an overview of Bell's thinking that led him to write the paper on his sabbatical from CERN in 1964. In chapter two, I wrote a commentary on Bell 1964. In chapter three, I charted the time between the publishing of Bell 1964 and the conducting of the first experiment in 1970 by Kasday, Ullman and Wu[3] giving an account of the variety of different theory bases upon which the experiments drew. Chapter three included a commentary on CHSH, the paper in which Clauser, Horne, Shimony and Holt outline a testable inequality derived from Bell's ideal inequality. In chapter four, I surveyed the first seven experiments testing a Bell-type inequality, outlined briefly the new fields of research Bell 1964 has opened up or impacted upon and ended by discussing five contemporary experiments to test a Bell-type inequality conducted. I outlined the shift in research questions that has animated this field over the almost forty years of experimentation and led to the development of completely new areas of research and application as a result. The second aim of this thesis was to provide a reception history of Bell 1964, to survey what physicists, both experimental and theoretical, mathematicians, philosophers of sciences, theistic philosophers and theologians have said about Bell 1964, to explore how they have interpreted it and put it to use. Chapter five was a synchronic snapshot of what some physicists, mathematicians and philosophers of science make of Bell 1964 today while chapters six and seven are a diachronic survey of how Bell's work has been interpreted by theologians and theistic philosophers since it was first mentioned in theistic contexts in 1977.[4] While I

[3] Kasday, Ullman & Wu. "The Einstein-Podolsky-Rosen Argument: Positron Annhilation Experiment."; Kasday, "Experimental Test of Quantum Predictions for Widely Separated Photons."; Kasday, Ullman & Wu. "Angular Correlation of Compton-Scattered Annihilation Photons and Hidden Variables."

[4] Heelan S.J. "Quantum Relativity and the Cosmic Observer."p.29; Hartshorne "The Neglect of Relative Predicates in Modern Philosophy."p.317

surveyed a small but representative corner of the writings of physicists, philosophers and mathematicians, my survey of references to Bell 1964 by theistic philosophers and theologians to Bell is comprehensive. I have brought together these references to Bell 1964 made in a theistic context for the first time. My third aim was to point to some learnings gained from this research and outline some philosophical and theological resources to aid further work, the subject of chapter eight. In order to pay attention to the specifics of Bell's paper, I have used a wealth of primary and secondly sources all of which are detailed fully in the footnotes. I have used the tools and skills of a historian of science, a biblical critic and a reception historian.

Having gained some understanding of Bell 1964, what provoked Bell to write it and to what it subsequently led, following Pope John Paul II's strictures to the theologians and scientists gathered at the Study Week at Castel Gandolpho to discuss "Our Knowledge of God and Nature: Physics, Philosophy and Theology," I suggested that our nature as creatures and how that is reflected in our knowing and interrelationship with the world is an area of the Christian faith from which I consider this thesis can "bring… out ……… some of the possibilities which have not yet been realized."[5] I noted the undoubted technological fruitfulness of Bell's work in leading to new areas of research alongside increased experimental sophistication being allied nevertheless to a complete inability to secure the metaphysical understanding for which Bell and many of the early experimentalists working in the area hoped. In my view this indicates both our competency to act within Deleuze and Guattari's immanence, St Gregory's διαστημα alongside our inability to secure a God's eye view of truth. I noted a number of ways in which following the narrative of what led up to Bell 1964 and of what has sprung from it exemplifies how scientists, whatever they espouse, are prepared to be flexible both as to the ontology of experimental existents needed in their pursuit of

[5] Pope John Paul II. "To the Reverend George V. Coyne."m.10 [sic]

their current research aims and also in the use they make of previous theory. They are, as Einstein noted, "unscrupulous."[6] Even those whose motivation in testing Bell inequalities was to understand how the world is rather than to extend what can be done, take on trust the theory behind experiments they choose to use so long as some kind of imprimatur can be demonstrated. This is a sensible strategy demonstrating espousal of what d'Espagnat's calls a fabricated ontology in action.[7] I suggest that this sense of our human ability to act, to experiment, to learn and to develop effective technology without being able to identify an ontology stable over time that we see played out in this research area exemplifies an aspect of what it means to be a creature and I suggested the work of Deleuze and Guattari, St Gregory of Nyssa and James K. Smith as providing resources to explore this further while noting Philip Clayton's "tracing the lines"[8] as offering a theological strategy that respects the limitations of creaturehood, comparable to a "fabricated ontology" to which d'Espagnat drew attention. While some scientists find the complete lack of unanimity as to what quantum theory tells us about the world "embarrassing"[9] and Bell 1964 "paradoxical,"[10] paying attention to this one small paper has shown it to be a scientific paper that is both profound and fascinating, fruitful and productive while offering something of a parable on what it is to be created.

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6 Einstein. "Reply to Criticisms."p.684
7 d'Espagnat. *On Physics and Philosophy*.p.281
8 Clayton. "Tracing the Lines: Constraint and Freedom in the Movement From Quantum Physics to Theology."
9 Carroll "The Most Embarassing Graph in Modern Physics."
10 Żukowski. "On the Paradoxical Book of Bell."