QUANTUM NONLOCALITY AND REALITY

50 Years of Bell's Theorem

Combining twenty-six original essays written by an impressive line-up of distinguished physicists and philosophers of physics, this anthology reflects some of the latest thoughts by leading experts on the influence of Bell's Theorem on quantum physics.

Essays progress from John Bell's character and background, through studies of his main work, on to more speculative ideas, addressing the controversies surrounding the theorem, investigating the theorem's meaning and its deep implications for the nature of physical reality. Combined, they present a powerful comment on the undeniable significance of Bell's Theorem for the development of ideas in quantum physics over the past 50 years.

Questions surrounding the assumptions and significance of Bell's work still inspire discussion in field of quantum physics. Adding to this with a theoretical and philosophical perspective, this balanced anthology is an indispensable volume for students and researchers interested in the philosophy of physics and the foundations of quantum mechanics.

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Preface

I am very pleased to see, in this volume, the papers written in John's memory. He had many interests and it is good to see such a variety of authors. I thank all of them for their work. I am sure that John would have enjoyed the book.

Mary Bell

Preface

In 1964, John Stewart Bell published an important result that was later called Bell's theorem [1]. It states that certain predictions of quantum mechanics cannot be accounted for by any local realistic theory. Bell's theorem has been called "the most profound discovery of science" [2]. By introducing a notion of quantum nonlocality, it not only transforms the study of the foundations of quantum mechanics, but also paves the way to many quantum technologies that have been developed in the last decades. It can be expected that Bell's work will play a more important role in the physics of the future. Admittedly, there are still controversies on the underlying assumptions and deep implications of Bell's theorem. This also poses a challenge to us in understanding quantum theory, as well as the physical world at the most fundamental level.

This book is an anthology celebrating the 50th anniversary of Bell's theorem. It contains 26 original essays written by physicists and philosophers of physics, reflecting the latest thoughts of leading experts on the subject. The content includes recollections of John Bell, an introduction to Bell's nonlocality theorem, a review of its experimental tests, analyses of its meaning and implications, investigations of the nature of quantum nonlocality, discussions of possible ways to avoid nonlocality, and last but not least, analyses of various nonlocal realistic theories. The book is accessible to graduate students in physics. It will be of value to students and researchers with an interest in the philosophy of physics and especially to physicists and philosophers working on the foundations of quantum mechanics.

This book is arranged in four parts. The first part introduces John Bell, the great Northern Irish physicist, and it also contains a few physicists' treasured recollections of him. In Chapter 1, Andrew Whitaker introduces the Irish tradition of physics, Bell's Belfast background, and his studies of physics at Queen's University Belfast. Whitaker argues that there may exist a connection between Bell's work and the Irish tradition, especially concerning his views on the apparent incompatibility between quantum nonlocality and special relativity. In Chapter 2, Michael Nauenberg, who coauthored with Bell the paper "The moral aspect of quantum mechanics," recollects his encounters with Bell at SLAC during 1964–5 when Bell discovered the theorem, as well as his later interactions with Bell. In Chapter 3, GianCarlo Ghirardi recalls his repeated interactions with Bell in the last four years of Bell's life, including their deep discussions about the elaboration and interpretation of collapse theories, Bell's contributions to the development of this approach, and Bell's clearcut views on the locality issue. These discussions of Bell's character and background, as well as the recollections of him from other physicists, will help readers understand better the background and significance of Bell's theorem.

The second part of this book then introduces Bell's theorem, its later developments, and its experimental tests. In Chapter 4, Jean Bricmont first gives a pedagogical introduction to Bell's original theorem, in particular to how it establishes the existence of nonlocal effects. He also discusses several misunderstandings of Bell's result and explains how Bohm's theory allows people to understand what nonlocality is. In Chapter 5, Roderich Tumulka further analyzes the various statements that have been claimed to be assumed in the derivation of Bell's inequality. He gives reasons that some assumptions such as realism and determinism are not made in the derivation, and others such as locality are indeed refuted by experimental violations of Bell's inequality. Moreover, he also briefly analyzes the relationship between nonlocality and relativity. He argues that the GRW flash theory demonstrates that it is possible to retain relativity and give up locality, and to have nonlocal influence without direction.

In Chapter 6, Harvey Brown and Christopher Timpson analyze the change in the notion of nonlocality in Bell's papers between 1964 and 1990, and discuss the relevance of the modern Everettian stance on nonlocality. They argue that violating the 1964 locality condition gives rise to action at a distance, while violating the local causality of 1976 need not, and Bell came more and more to recognise that there need be no straightforward conflict between violation of either of his locality conditions and the demands of relativity. In their view, the significance of Bell's theorem can be fully understood by taking into account that a fully Lorentz-covariant version of quantum theory, free of action at a distance, can be articulated in the Everett interpretation. In Chapter 7, Marco Genovese presents the experimental progress in testing Bell's inequalities and discusses the remaining problems for a conclusive test of the inequalities, such as eliminating the detection loophole and spacelike loophole. In the Appendix added in proof, he also briefly introduces the latest loophole-free tests of Bell inequalities. One of the main theoretical developments that follow Bell's work is the Greenberger–Horne–Zeilinger (GHZ) theorem, also known as Bell's theorem without inequalities. In Chapter 8, Olival Freire Jr. and Osvaldo Pessoa Jr. introduce the history of the creation of this theorem and analyze its scope.

The third part of this book further investigates the nature of quantum nonlocality, as well as possible ways to avoid the nonlocality implication of Bell's theorem. In Chapter 9, Henry Stapp gives a new proof of Bell's inequality theorem, which avoids the hidden-variable assumption and the assumption of "outcome independence." The proof places no conditions on the underlying process, beyond the macroscopic predictions of quantum mechanics. In Chapter 10, Bernard d'Espagnat analyzes the nature of the premises assumed in Bell's proof, such as the nature of causality. Based on this analysis, he argues that a theory compatible with the quantum predictions is not necessarily nonlocal, and assuming realism is by far the safest way to establish nonlocality on truly firm grounds.

In Chapter 11, Richard Healey analyzes Bell's assumptions about probability in his formulations of local causality. He argues that probability does not conform to these assumptions when quantum mechanics is applied to account for the particular correlations that Bell argues are locally inexplicable. By assuming a pragmatist view of quantum mechanics, he also gives an explanation of nonlocalized quantum correlations. The explanation involves no superluminal action and there is even a sense in which it is local, but it is in tension with the requirement that the direct causes and effects of events be nearby. In Chapter 12, Lev Vaidman argues that the lesson we should learn from Bell's inequalities is not that quantum mechanics requires some kind of action at a distance, but that it leads us to believe in parallel worlds. In the many-worlds interpretation of quantum mechanics, Bell's proof of action at a distance fails, since it requires a single world to ensure that measurements have single outcomes. In his view, although there is no action at a distance in the many-worlds interpretation, it still has nonlocality, and the core of the nonlocality is entanglement, which is manifested in the connection between the local Everett worlds of the observers. In Chapter 13, Travis Norsen analyzes the many-worlds theory and the quantum Bayesian interpretation, which purport to avoid the nonlocality implication of Bell's theorem. By investigating each theory's grounds for claiming to explain the EPR–Bell correlations locally, he argues that the two theories share a common for-all-practical-purposes (FAPP) solipsistic character, and this undermines such theories' claims to provide a local explanation of the correlations. In Norsen's view, this analysis reinforces the assertion that nonlocality really is necessary to coherently explain the empirical data.

In Chapter 14, Wayne Myrvold investigates the possibility of the compatibility of nonlocality with relativity. He argues that the nonlocality required to violate the Bell inequalities need not involve action at a distance, and the distinction between forms of nonlocality makes a difference when it comes to compatibility with relativistic causal structure. Concretely speaking, although parameter dependence involves a departure from relativistic causal structure, nonlocal theories that satisfy parameter independence and exhibit only outcome dependence, such as collapse theories, can satisfy the compatibility with relativistic causal structure at a truly fundamental level. In Chapter 15, Gordon Fleming argues that in collapse theories the "elements of reality" can retain their Lorentz invariance or frame independence if the hyperplane dependence of their localization is recognized and the conflation of hyperplane dependence with frame dependence is avoided. He also criticizes a view of the nature of Lorentz transformations presented by Asher Peres and co-workers that conflicts with the view employed by him in the argument. In Chapter 16, Shan Gao presents a new analysis of quantum nonlocality and its apparent incompatibility with relativity. First, he gives a simpler proof of nonlocality in standard quantum mechanics, which also avoids the controversial assumption of counterfactual definiteness. Next, he argues that the new proof may imply the existence of a preferred Lorentz frame. After arguing for the detectability of the preferred frame, he further shows that the frame can be detected in a recently suggested model of energy-conserved wave function collapse. Moreover, he analyzes possible implications of quantum nonlocality for simultaneity of events. Last, he also discusses a possible mechanism of nonlinear quantum evolution and superluminal signaling.

In Chapter 17, Daniel Rohrlich shows that maximally nonlocal "superquantum" (or "PR-box") correlations, unlike quantum correlations, do not have a classical limit consistent with relativistic causality, and by deriving Tsirelson's bound from the three axioms of relativistic causality, nonlocality, and the existence of a classical limit, this result can be generalized to all stronger-than-quantum nonlocal correlations. Moreover, he argues that local retrocausality offers us an alternative to nonlocality. In Chapter 18, Yakir Aharonov and Eliahu Cohen analyze entanglement and nonlocality in the framework of pre-/postselected ensembles with the aid of weak measurements and the two-state-vector formalism that admits local retrocausality. In addition to the EPR–Bohm experiment, they revisit the Hardy and Cheshire Cat experiments, whose entangled pre- or postselected states give rise to curious phenomena. Moreover, they also analyze even more peculiar phenomena suggesting "emerging correlations" between independent pre- and postselected ensembles of particles, which can be viewed as a quantum violation of the classical "pigeonhole principle."

The last part of this book introduces and analyzes various nonlocal realistic theories, including Bohm's theory, collapse theories, and twistor theory. In Chapter 19, Tim Maudlin analyzes Bell's theory of local beables, which not only underpins all analyses of the significance of violations of Bell's inequalities, but also stands on its own as a contribution to the foundations of physics. In particular, he discusses Bohm's theory, GRW theory, and Bell's Everett(?) theory, which are different nonlocal realistic theories of local beables. In his view, the analysis of local beables also highlights a challenge for the orthodox Everettian position. In Chapter 20, H. Dieter Zeh compares and discusses various realistic interpretations of quantum mechanics, which were either favored or neglected by John Bell in the context of his nonlocality theorem.

In Chapter 21, Basil Hiley presents the background of Bohm's theory that led Bell to a study of quantum nonlocality from which Bell's inequalities emerged. He recalls the early experiments done at Birkbeck with the aim of exploring the possibility of "spontaneous collapse," a way suggested by Schrödinger to avoid the conclusion that quantum mechanics was grossly nonlocal. He also reviews some of the work that Bell did that directly impinged on his own investigations into the foundations of quantum mechanics, and reports some new investigations toward a more fundamental theory, such as the Clifford algebra approach to quantum mechanics. In Chapter 22, Sheldon Goldstein further analyzes Bell's supportive views on Bohm's theory in more detail. He points out that these views are not nearly as well appreciated as they should be. Moreover, he also briefly discusses nonlocality and the "big question" about Lorentz invariance.

In addition to Bohm's theory, Bell was also a staunch supporter of collapse theories. In Chapter 23, Philip Pearle reminisces on his handful of interactions with Bell on such theories through letters between them. He also discusses quantum nonlocality and some of its implications within the framework of the CSL (continuous spontaneous localization) model of dynamical collapse. In Chapter 24, Stephen Adler first recalls intersections of his research interests with those of Bell. He then argues that the noise needed in collapse theories most likely comes from a fluctuating complex part in the classical spacetime metric; that is, wave function collapse is driven by complex-number-valued "spacetime foam."

In Chapter 25, Roger Penrose argues that quantum nonlocality must be gravitationally related, as it comes about only with quantum state reduction, this being claimed to be a gravitational effect. He also outlines a new formalism for curved space–times, palatial twistor theory, which seems to be able to accommodate gravitation fully, providing a nonlocal description of the physical world. In Chapter 26, Gregg Jaeger considers Bell's critique of standard quantum measurement theory and some alternative treatments wherein Bell saw greater conceptual precision, such as collapse theories. He also makes further suggestions as to how to improve conceptual precision.

No doubt, the discussions about the significance and implications of Bell's theorem still have a long way to run. This anthology is a tribute to John Bell, and I hope it will arouse more researchers' interest in his profound work and its ramifications. I thank all contributors for taking the time to write the new essays in this anthology. I am particularly grateful to Martinus Veltman, Kurt Gottfried, and Mary Bell for their help and support. I also wish to express my warm thanks to all participants of the John Bell Workshop 2014, which was organized by the *International Journal of Quantum Foundations* and in which the drafts of the essays of this anthology were discussed [3]. I thank Simon Capelin of Cambridge University Press for his kind support as I worked on this project, and the referees who gave helpful suggestions on how the work could best serve its targeted audience. Finally, I am deeply indebted to my parents, QingFeng Gao and LiHua Zhao, my wife Huixia, and my daughter Ruiqi for their unflagging love and support.

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