Einstein, Bohr and the Quantum Dilemma

From Quantum Theory to Quantum Information
Second Edition

Quantum theory, the most successful physical theory of all time, provoked intense debate between the twentieth century's two greatest physicists, Niels Bohr and Albert Einstein. Quantum information theory has emerged from intensive study of the structure and interpretation of quantum theory to become one of the fastest growing areas of twenty-first-century science. This study was stimulated by the seminal analysis of John Bell in the 1960s, but behind Bell lay the intensive debate between Niels Bohr and Albert Einstein which raged in the 1920s and 1930s. The debate concerned the nature of quantum theory, and the major contradictions and conceptual problems at its heart.

This second edition contains sympathetic accounts of the views of both Bohr and Einstein, and a thorough study of the argument between them. It includes non-technical and non-mathematical accounts of the development of quantum theory and relativity, and also the work of David Bohm and John Bell that restored interest in Einstein's views. It has been extensively revised and updated to cover recent developments, and the account of ongoing work has been brought up to date. A new chapter is devoted to describing the whole area of quantum information theory, from the work of Richard Feynman and David Deutsch that initiated the study of quantum computation to the theoretical and experimental approach to quantum cryptography.

This book provides a fascinating account of the development of quantum theory, which will appeal to anyone with an interest in the fundamental questions of physics, its philosophy and its history.

ANDREW WHITAKER is Professor of Physics at the Queen's University of Belfast, where he has worked since 1988. His main research has focussed on the foundations of quantum theory, particularly interpretations of quantum theory and the quantum Zeno effect. He also has a keen interest in the history and philosophy of quantum theory, and in particular the life and works of John Bell, on whom he has written several articles. He is co-editor with Mark McCartney of the book *Physicists of Ireland: Passion and Precision*.

Einstein, Bohr and the Quantum Dilemma

From Quantum Theory to Quantum Information

Second Edition

Andrew Whitaker
Department of Pure and Applied Physics
Queen's University Belfast

CAMBRIDGE UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 2RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521671026

First published 1996; second edition 2006

Printed in the United Kingdom at the University Press, Cambridge

A catalogue record for this publication is available from the British Library

ISBN-13 978-0-521-67102-6 paperback
ISBN-10 0-521-67102-7 paperback

for Joan

Contents

Preface

At the beginning of the twenty-first century, quantum information theory is an exceptionally lively area of scientific research. Quantum computation and quantum cryptography promise powerful and efficient methods way beyond the scope of classical physics for solving practical problems. Quantum teleportation suggests the even more exciting possibility of achievements that would not even be dreamed of classically, and as minds adapt to new ways of thinking we must expect many other examples.

Quantum information theory emerged from a rich brew of scientific ideas that developed particularly in the 1980s and early 1990s. The ideas centred around the idea of quantum entanglement – the fact that, when two quantum particles have once interacted, even after separation their properties will be mutually dependent in a totally non-classical way. Crucially important were the theoretical analysis and experimental testing of the so-called Bell inequalities, the brain-child of John Bell, a physicist from Ireland.

Bell's main work and the initial experiments were performed in the 1960s and 1970s, respectively, and behind him was the famous Bohr–Einstein debate of the 1920s and 1930s. The Bohr–Einstein debate occurred at a critical point in the intellectual history of the twentieth century. By 1926, the 'new' quantum theory of Heisenberg and Schrödinger promised to provide the exact theoretical basis for the physics of atoms, but important questions remained about fundamental aspects of the theory.

Niels Bohr's approach implied the abandonment of *determinism*; in absolute contrast to Newtonian physics, complete knowledge of the present may provide only statistical information about the future. Also abandoned would be *realism*, at least in the form of *naive realism*, according to which any physical quantity – position, speed and so on – had a precise value at all times. Einstein was not prepared to go along with these revolutionary changes, so the great debate ensued during the next decade.

The debate was not so much about the contents of any theory, as about what a scientific theory ought to be; it was not *just* about the nature of the Universe, but about what kind of description of the Universe should be regarded as meaningful. It may not be over-dramatic to call it a battle for the *soul* of physics.

The practically universal view at the time that Bohr won the debate played a large part in Einstein, perhaps the most famous scientist ever, becoming practically a scientific recluse for the last quarter of a century of his life. Yet 50 years after Einstein's death, and thanks largely to the work of David Bohm and Bell himself, Einstein's views are being taken very seriously. Questions that seemed to have been settled 70 or 80 years ago are back under very serious consideration, and experimental techniques that Bohr would never have dreamed of have been perfected, many working with individual atomic particles. The Bohr–Einstein debate is very much alive!

In this book, after a brief discussion of Einstein and Bohr in Chapter 1, I give rather a full account of classical physics – physics before relativity and quantum theory – in Chapter 2; practically every part of classical physics plays a role in understanding quantum theory. Chapter 3 contains a brief account of relativity, which has a two-fold importance in the rest of the book. Relativity is at the heart of the crucial experiments suggested by Bell to test important aspects of quantum theory. More fundamentally, though, I argue that the mathematical sophistication of Einstein's theory of general relativity, coupled with its enormous importance, led to Einstein developing his view that quantum theory itself could progress only as a special case of a new highly mathematical and complex theory, a theory he was never able to produce.

Chapter 4 gives an account of the development of quantum theory, together with some idea of its basic structure and its many successes. It also introduces the initial conceptual difficulties brought up by the theories of Heisenberg and Schrödinger.

Chapters 5 and 6 describe Bohr's solution to these difficulties – his framework of *complementarity*, and Einstein's arguments against Bohr in the debate itself. They include the famous Einstein–Podolsky–Rosen argument. These chapters form the centre-piece of the book. Chapter 7 discusses the work of Bohm and Bell, which re-invigorated and extended the original debate, and played a major part in the creation of quantum information theory. Chapter 8 gives a brief account of some recent developments, theoretical and experimental, in the fundamental aspects of quantum theory, paying special attention to their relevance for the Bohr–Einstein debate.

Throughout the earlier part of the book I stress the manner in which the intellectual struggles over quantum theory led on to quantum information theory, and in Chapter 9 I reach the theory itself. Following a broad overview of the classical information theory and theory of computation, I study the work centred on Richard Feynman that introduced many of the ideas and developments required for quantum information theory, but did not quite manage to put them together in a coherent way. In particular I explain the idea of the reversible computer.

I then reach the work of David Deutsch, whom I consider to be the real father of quantum computation, the person who realised that the classical foundations of computer theory given by Alan Turing had to be rewritten from scratch to produce the new field of quantum computing. I sketch some of the algorithms that show clearly that quantum computation can achieve more than classical computation, the Deutsch and Grover algorithms, and in particular the all-important Shor algorithm.

Many ways of implementing the quantum computer have been studied; I briefly describe two of the most important, nuclear magnetic resonance and the ion trap. I then sketch the two most important areas of quantum information theory apart from quantum computation, namely quantum cryptography (or quantum key distribution) and quantum teleportation.

Lastly, in Chapter 10 I give a brief assessment of the work of Bohr and Einstein, particularly studying to what extent their particular perspectives encouraged Bell's own developments and the emergence of quantum information theory.

In the early chapters, references are given mainly to books, and wherever possible they are chosen to be non-technical. For the later chapters, though, and in particular Chapters 7 and 8 where current developments are being discussed, inevitably the references are nearly all to recent papers, often fairly technical, in the scientific literature. I might mention that I have perhaps over-represented papers by myself and collaborators. I make no apology for this since it may help to draw the attention of readers to accounts that may be more technical than those in the book, but are similar in approach, and so may serve as useful bridges to the more general literature.

The style of the book is as non-mathematical as possible; there are few actual equations, but there is a little reasonably simple mathematics at some points in the text; the only alternative would have been to paraphrase it, which would have been contrived, and probably harder to get to grips with. I have made every effort to avoid including too many technicalities, and the book should be accessible to anybody who is, or wishes to become, interested in quantum theory and its interpretation.

The expert may complain about *technical* simplification – about almost total restriction to the Schrödinger formalism, leading to discussion of a 'spin wave-function', and occasional use of the term 'state' in a non-technical manner.

However, I feel that there has been no requirement for watering-down the *conceptual* arguments. The reader should need no expertise in mathematics or previous knowledge of physics to obtain an understanding not only of the main conceptual factors involved in discussing quantum theory and quantum information theory, but also of the disagreements which still exist.

As is almost inevitable, much of the content of the book is stated in historical terms, and it is impossible to avoid certain philosophical allusions, but readers should be warned or promised that the book is fundamentally on physics, and in the end it is the *physical* arguments which I hope they come to appreciate. I have tried to give the main arguments as much as possible in the actual words of the various participants; I would like to thank all those who have given permission for their writings to be quoted and, in particular, those who have allowed reproduction of diagrams, and in some cases provided suitable copies.

For the benefit of those who have studied the previous edition of this book, *Einstein, Bohr and the Quantum Dilemma*, published in 1996, I will explain briefly the changes introduced in the current book. Foremost, of course, is the entire new chapter on quantum information theory, Chapter 9, though I have also tried throughout the previous chapters to indicate the sources for quantum information theory in the earlier work. In 1996 quantum information theory was less a lusty infant than a babe in arms, and it achieved only the briefest of mentions in the previous edition.

The other main area of progress in the last decade has been the large amount of theoretical and experimental work on the Bell inequalities, and a full account of this work has been included in Chapter 7.

All the various sections of Chapter 8 on modern developments have also been updated. Some of the main additions are the following: the work principally of David Deutsch and David Wallace on modern views of many-worlds interpretations; Kurt Gottfried's reply to Bell's criticisms concerning his approach to measurement; the move from the knowledge interpretation of quantum theory due principally to Rudolf Peierls to the information interpretation of Anton Zeilinger; the contributions of Guido Bacciagaluppi and others to the theory of stochastic interpretations; the passage of the quantum Zeno effect from an abstract and almost despised curiosity to a practically universal component of any description of change of quantum state; and the progress of Tony Leggett towards macroscopic quantum mechanics.

Other parts of book have been updated and revised where appropriate, in particular the discussion of the famous EPR argument in Chapter 6. Overall, of the 567 references in this second edition, about 340 are new to this edition, and of these 230 have been published since the publication of the first edition and 130 date from the year 2000 or later.

I would again like to give my thanks to those with whom I have performed and published work on quantum theory in the past – Dipankar Home, Ishwar Singh, Euan Squires, Lucien Hardy and John Dennison. I have learned much from them. I would like to thank Adrian Kent and Tchavdar Todorov for discussions on the consistent histories and stochastic interpretations of quantum theory, respectively; Martin Lamb for discussions on the Mach–Zehnder interferometer; and Reinhold Bertlmann and Anton Zeilinger for hospitality in Vienna during discussions on the life and work of John Bell, and attendance at the conference of reference [215]. I would like to thank Dipankar Home again, and the S. N. Bose Centre and the Bose Institute, both in Calcutta, for hospitality during the final stages of completing this edition.

I would like to thank Simon Capelin, Vince Higgs, Steve Holt, Wendy Phillips, and others at Cambridge University Press, for their helpfulness and efficiency in the production of this book.

Lastly I would like to renew my thanks to my immediate family – Joan, John and Peter, for their support and tolerance during the preparation of this second edition of the book.

Acknowledgements

I am very grateful to the following publishers for granting me permission to reprint copyright material. Elsevier Science B. V., Amsterdam, the Netherlands and The Boulevard, Langford Lane, Kidlington OX5 1GB, UK (*Studies in the History and Philosophy of Science* (reference [47]) © 1990, *The Framework of Complementarity* (H. J. Folse) [55] © 1985, *Niels Bohr: His Life and Work As Seen by Friends and Colleagues* (S. Rozental, ed.) [74] © 1968, *Niels Bohr – Collected Works*, Vol. 6 (J. Kalchar, ed.) [66] © 1985, *The Lesson of Quantum Theory* (J. de Boer, E. Dal and O. Ulfbeck, eds.) [77] © 1986). Macmillan Press Ltd (*The Born–Einstein Letters* (M. Born, ed.) [5]. Macmillan Magazines Ltd (*Nature*, N. Bohr, Supplement, 14 April 1928, pages 148–58) © 1928). Kluwer Academic Publishers (*The Physicist's Conception of Nature* (J. Mehra, ed., 1973), *Quantum Paradoxes and Physical Reality* (F. Selleri) [140]). Oxford University Press (*Subtle Is the Lord* (A. Pais) [1], J. S. Bell in *Quantum Gravity 2* (C. Isham, R. Penrose and D. Sciama, eds., 1981, pp. 611–37)). Les Editions de Physique (J. S. Bell in *Journal de Physique*, Colloque C2, Supplément au numéro 3, Tôme 42, 1981, pages 41–61). Plenum Publishing Corporation (J. S. Bell in *Sixty-Two Years of Uncertainty* (A. I. Miller, ed., 1990). *Journal of Statistical Physics* [295]). The Nobel Foundation (J. S. Bell in *Proceedings of the Nobel Symposium 65: Possible Worlds in Arts and Science* (S. Allen, ed.) © 1986). John Wiley and Sons Inc. (*The Philosophy of Quantum Mechanics* (M. Jammer) [67] © 1974, *The Conceptual Development of Quantum Mechanics* (M. Jammer) [39] © 1966, *Atomic Physics and Human Knowledge* (N. Bohr) [68] © 1958). McGraw-Hill, Inc., (*Quantum Mechanics* (L. Schiff) [54] © 1955). Faber and Faber (*The Whitsun Weddings* (P. Larkin, 1964), *Larkin at Sixty* (A. Thwaite, ed.) [85]). Farrar, Straus and Giroux (*The Whitsun Weddings* (P. Larkin) (US rights)). Princeton University Press (*Quantum Profiles* (J. Bernstein) [78], *Mathematical Foundations of Quantum Mechanics* (J. von Neumann) [87]). University of Pittsburgh Press (*Frontiers of Science and Philosophy* (R. G. Colodny, ed.) [64] © 1962). University of Chicago Press (*The Shaky Game* (A. Fine) [94] © 1986 by the University of Chicago). American Philosophical Society (*Proceedings of the American*

Philosophical Society **124**, 1980, 323–45 (translation by J. D. Trimmer) [100]). Open Court Publishing Company, Chicago and LaSalle, Illinois (*Library of the Living Philosophers*, Vol. VII, *Albert Einstein, Philosopher-Scientist* (P. A. Schilpp, ed.) pp. 85, 89, 668, 674, 681 [73]). International Thomson Publishing Services Ltd (*Quantum Implications* (B. J. Hiley and D. Peat, eds.) [127]). World Scientific Publishing Co. Pte. Ltd (*Symposium on the Foundations of Modern Physics* 1985 (P. Lahti and P. Mittelstaedt, eds.) [104], *Symposia on the Foundations of Modern Physics* 1993 (K. V. Laurikainen and C. Montonen, eds.) [271], *Stochastic Evolution of Quantum States in Open Systems and Measurement Processes* (L. Diósi and B. Lukács, eds.) [304]). Societa Italiana di Fisica (*Il Nuovo Cimento* [227]). American Institute of Physics (B. de Witt in *Physics Today*, September 1970; also *Physics Today* [166, 293]). Institute of Physics (*Journal of Physics A* [314, 315]). University of Bristol (*Observation and Interpretation in the Philosophy of Physics* (S. Körner, ed.) [52]). Niels Bohr archive (F. Aaserud, Director) (published writings of Niels Bohr).