Quantum Concepts in Physics

Written for advanced undergraduates, physicists, and historians and philosophers of physics, this book tells the story of the development of our understanding of quantum phenomena through the extraordinary years of the first three decades of the twentieth century.

Rather than following the standard axiomatic approach, this book adopts a historical perspective, explaining clearly and authoritatively how pioneers such as Heisenberg, Schrödinger, Pauli and Dirac developed the fundamentals of quantum mechanics and merged them into a coherent theory, and why the mathematical infrastructure of quantum mechanics has to be as complex as it is. The author creates a compelling narrative, providing a remarkable example of how physics and mathematics work in practice. The book encourages an enhanced appreciation of the interactions between mathematics, theory and experiment, helping the reader gain a deeper understanding of the development and content of quantum mechanics than with any other text at this level.

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An Alternative Approach to the Understanding of Quantum Mechanics

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CAMBRIDGE UNIVERSITY PRESS

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University Printing House, Cambridge CB2 8BS, United Kingdom

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www.cambridge.org
Information on this title: www.cambridge.org/9781107017092

First published 2013
Reprinted 2014

Printed in the United Kingdom by TJ International Ltd, Padstow, Cornwall

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

ISBN 978-1-107-01709-2 Hardback

For Deborah

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Preface

How this book came about

This book is the outcome of a long cherished ambition to write a follow-up to my book *Theoretical Concepts in Physics* (*TCP2*) (Longair, 2003). In that book, I took the story of the development of theoretical concepts in physics up to the discovery of quanta and the acceptance by the physics community that quanta and quantisation are essential features of the new physics of the early twentieth century. There was neither space nor scope to take that story further – it was just too complicated and would have required more advanced mathematics than I wished to include in that volume.

This book is my attempt to do for quantum mechanics what I did for classical physics and relativity in *TCP2*. The objective is to try to reconstruct as closely as possible the way in which quantum mechanics was created out of a mass of diverse experimental data and mathematical analyses through the period from about 1900 to 1930. In my view, quantisation and quanta are the greatest discoveries in the physics of the twentieth century. The phenomena of quantum mechanics have no direct impact upon our consciousness which to all intents and purposes is a world dominated by classical physics. But quantum mechanics underlies all the phenomena of matter and radiation and is the basis of essentially all aspects of civilisation in the twenty-first century.

There is no lack of excellent books on quantum mechanics which is one of the staples of all courses in undergraduate physics. Most of the successful texts adopt an axiomatic approach in which quantum mechanics is derived from a set of basic axioms, the consequences of which are elucidated in the subsequent mathematical elaboration. The first complete exposition of this approach was Dirac's classic book *Principles of Quantum Mechanics* of 1930 which may be thought of as the ultimate goal of this book (Dirac, 1930a). But how did it all come about? Can we understand why the theory has to be as complex as it is and how did the interpretation of the formalism come about?

Just as the core of *TCP2* was inspired by the essays of Martin J. Klein (1967), so this book was inspired long ago by the book *Sources of Quantum Mechanics* edited by B. L. van der Waerden (1967). I had an ambition to use van der Waerden's book as the basis of the equivalent of *TCP2* for the development of quantum mechanics. This was reinforced by the appearance of the massive six-volume series *The Historical Development of Quantum Theory* by Jagdish Mehra and Helmut Rechenberg which provides a very thorough, authoritative survey of the history of quantum mechanics and which were published between 1982 and 2001 (Mehra and Rechenberg, 1982a,b,c,d, 1987, 2000, 2001). Equally inspiring was *The Conceptual Development of Quantum Mechanics* by Max Jammer which covers similar ground in a single volume (Jammer, 1989). Another inspiration was the book *Inward Bound* by Abraham Pais (1985) which sets the development of quantum mechanics and quantum phenomena in a much longer time-frame. In my view, these truly excellent books are quite hard work and can only be readily appreciated by those who already have a strong foundation in classical and quantum physics. They are quite a challenge for those seeking more readily accessible enlightenment.

The historical approach and level of presentation

The experience of teaching and writing a number of books convinced me of the value of rethinking the foundations of physics from a somewhat historical perspective, at the same time making as few assumptions as is reasonable about the mathematical sophistication of the reader. As in *TCP2*, I assume some fluency in physics and mathematics, but nothing that would be beyond the first couple of years of the typical course in physics. It is useful to restate some of the objectives of *TCP2* which apply equally to the approach adopted in this book, in contrast to the standard way in which the subject is tackled.

The origin of *TCP2* can be traced to discussions in the Cavendish Laboratory in the mid-1970s among those of us who were involved in teaching theoretically biased undergraduate courses. There was a feeling that the syllabuses lacked coherence from the theoretical perspective and that the students were not quite clear about the scope of *physics* as opposed to *theoretical physics*. As our ideas evolved, it became apparent that a discussion of these ideas would be of value for all final-year students. The course entitled *Theoretical Concepts in Physics* was therefore designed to be given in the summer term in July and August to undergraduates entering their final year. It was to be strictly non-examinable and entirely optional. Students obtained no credit from having attended the course beyond an increased appreciation of physics and theoretical physics. I was invited to give this course of lectures for the first time, with the considerable challenge of attracting students to 9.00 am lectures on Mondays, Wednesdays and Fridays during the most glorious summer months in Cambridge.

The course was designed to contain the following elements:

(a) *The interaction between experiment and theory*. Particular stress would be laid upon the importance of experiment and, in particular, the role of advanced technology in leading to theoretical insights.
(b) The importance of having available the *appropriate mathematical tools for tackling theoretical problems*.
(c) *The theoretical background to the basic concepts of modern physics*, emphasising underlying themes such as *symmetry, conservation, invariance*, and so on.
(d) *The role of approximations and models in physics*.
(e) *The analysis of real scientific papers in theoretical physics*, providing insight into how professional physicists tackle real problems.

(f) *The consolidation and revision* of many of the basic physical concepts which all final-year undergraduates can reasonably be expected to have at their fingertips.
(g) Finally, *to convey my own personal enthusiasm for physics and theoretical physics*. My own research has been in high energy astrophysics and astrophysical cosmology, but I remain a physicist at heart. My own view is that astronomy, astrophysics and cosmology are no more than subsets of physics, but applied to the Universe on the large scale. I am one of the very lucky generation who began research in astrophysics in the early 1960s and who have witnessed the astonishing revolutions which have taken place in our understanding of all aspects of the physics of the Universe. But, the same can be said of all areas of physics. The subject is not a dead, pedagogic discipline, the only object of which is to provide examination questions for students. It is an active, extensive subject in a robust state of good health.

My objective in writing *Quantum Concepts in Physics* has been to adopt the same user-friendly approach as in *TCP2* but now applied to the discovery of quantum mechanics. I should emphasise that this is a *personal approach* to the understanding of quantum mechanics, but it has the great virtue of forcing the writer and reader to think hard about the issues at stake at each stage in the development through one of the most dramatic periods in the evolution of our understanding of fundamental processes in physics. One of the differences as compared with *TCP2* is that somewhat more advanced mathematical tools have to be introduced to appreciate the full essence of the story. I have tried to lay out the necessary mathematics in as simple a form as I could devise, without sacrificing rigour. In my view, final-year undergraduates and their teachers should have little trouble in coping with these requirements.

Let me also emphasise that this book is *not* a textbook on quantum mechanics. It is certainly *not* a substitute for the systematic development of these topics through the standard axiomatic approach to the discipline. You should regard this book as a supplement to the standard courses, but one which I hope will enhance your understanding, appreciation and enjoyment of the physics. Certainly, I have learned a huge amount about quantum mechanics through studying the works of genius of the pioneers of the subject.

The challenge

Let me make it clear at the outset that the amount of material which has to be condensed into a single manageable volume is immense. Some impression of the magnitude of the task can be appreciated from the almost 4500 pages of the magnificent series by Mehra and Rechenberg. In addition, the history of physics literature is vast. As a result, I have had to be selective, and although the course is tortuous, I have had to streamline the story to reach my goal in a finite space. For further enlightenment, which I thoroughly recommend, there is no alternative but to delve into the writings of Mehra, Rechenberg, Jammer, Pais and the many other authors cited in the text.

I should also confess that, although I have taught numerous courses on quantum physics, I do not regard myself as a 'black-belt' quantum physicist. This has the advantage that I am embarking on a voyage of personal intellectual discovery as well. I like very much the splendid remark of Fitzgerald,

> 'A Briton wants emotion in his science, something to raise enthusiasm, something with human interest.' (Fitzgerald, 1902)

I confess to belonging to that school. I hope you will enjoy this adventure as much as I do.

Malcolm Longair
Cambridge and Venice, 2012

Acknowledgements

I have greatly benefitted from interactions with many colleagues in the Cavendish Laboratory over the years while this project has been mulled over in my mind. These began in the 1970s when the hot debates in the Cavendish Teaching Committee, which I chaired for a number of years, gave fascinating insights into what my distinguished colleagues considered to be the central core of physical thinking. The stimulus of giving parallel courses in undergraduate physics with my colleagues undoubtedly influenced my understanding. These colleagues include John Waldram, David Green and Paul Alexander, whose insights I much appreciate. I also benefitted from the lecture notes in quantum mechanics prepared by Michael Payne and Howard Hughes, which I have used as reference points in my thinking to ensure that I was to end up in the right place by the end of the book. Once the writing was completed, I was most grateful to receive the advice of Malcolm Perry and Anna Żytkow, who generously scrutinised parts of the text where I felt deeper mathematical insights would improve the clarity of the exposition – I am most grateful to them for the changes they recommended and which I implemented.

As in my earlier books, I have greatly benefitted from the advice of David Green on the subtleties of *LaTeX* coding. His expert advice has greatly improved the appearance of the text and the mathematics. I am most grateful to the librarians in the Rayleigh Library, Nevenka Huntic and Helen Suddaby, who have been unfailingly helpful in tracking down many of the rarer books and papers referred to in the text. Similar thanks go to Mark Hurn, Librarian at the Institute of Astronomy, for uncovering various little-known treasures in that library.

I would emphasise that *Quantum Concepts in Physics* is a much more personal voyage of discovery than my previous books. I knew what I wanted to achieve at the outset, but the working out and research were carried out in parallel with the writing. As such, the usual disclaimers that I am solely responsible for errors of content and judgement are even more apposite than usual. This is a story which can be told in many different ways, with different emphases according to the inclination of the writer. It is all the more important that the reader should consult the many texts referenced in this book to obtain the fuller picture.

As in all my work, the love, support, encouragement and understanding of my family, Deborah, Mark and Sarah, means more to me than can ever be expressed in words.

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