The New Quantum Universe

Quantum mechanics gives an understanding of not only atoms and nuclei, but also all the elements and even the stars. It makes possible the silicon chip and the myriad of laser applications, it explains the structure of Jupiter and provides an understanding of the mechanism of energy generation in our Sun and other stars. Quantum mechanics has given us great insights into the nature of the universe, promising an unlimited supply of energy from nuclear power and unlocking the awesome capability for self-destruction through nuclear weapons.

Following the success of *The Quantum Universe*, first published in 1987, a host of exciting new discoveries has been made in the field of quantum mechanics. *The New Quantum Universe* provides an accessible introduction to the essential ideas of quantum physics, and demonstrates how it affects our everyday life. Quantum paradoxes and the eventful life of Schrödinger's cat are explained, along with the Einstein–Podolsky–Rosen paradox and the Bell inequality. The book looks ahead to the coming nanotechnology revolution, describing quantum cryptography, quantum computing and quantum teleportation, and ends with an account of quantum mechanics and science fiction.

Explaining quantum mechanics in a simple non-mathematical way, this book is a fascinating and accessible introduction to one of the most important scientific disciplines of the twenty-first century. It is suitable for final-year school students, science undergraduates, and anyone wishing to appreciate how physics has made possible the new technologies that are changing our lives.

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The New Quantum Universe

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Preface

The popularization of science is now an established business for booksellers and publishers. The traditional formula for a 'trade' book on popular science is a text of about 100 000 words or so (around 200 pages) with relatively few diagrams or pictures. The target audience is the educated reader with a general interest in science. At the other end of the scale we have popular science reference books such as encyclopedias and atlases. Our target audience lies in between these two extremes. We wish to write a book that will not only interest the 'educated reader' as above but, more importantly, capture the interest and imagination of young people. We believe that it is vitally important to give young people a glimpse of the excitement of physics so that they may be motivated to take up the challenge themselves. Nowadays, there are many more alternatives for young people and there is a general perception that science and mathematics are 'hard' subjects. It is certainly true that understanding in these subjects does not come without effort and real mastery may indeed take years. So we cannot promise instant gratification. What we can promise is that the study of science and mathematics will provide a gateway to a deeper understanding of a fascinating universe – our universe, a quantum universe. And paradoxically, as our world becomes more and more dependent on science and technology, it has also become increasingly technologically fragile in that fewer people understand the technology on which we all depend. Civilization requires us to inspire and motivate young people to take up the challenge of science. This is the true target audience for this book. But we hope that our text and our extensive use of diagrams, colour photographs and biographies of great scientists will also be interesting and entertaining to the 'educated reader'!

Our first book on quantum mechanics, *The Quantum Universe*, was published in 1987. At the time, it seemed to us that there was a clear need to communicate the strange ideas of quantum mechanics to a wider audience, since this is the theory that underpins the operation of many 'high tech' objects in daily use. So, after a look at the fundamentals, we concentrated on explaining how quantum mechanics gives us an understanding of not only atoms and nuclei, but also all the elements and even the stars. Quantum mechanics makes possible the incredible silicon chip as well as all the myriad of applications of lasers that we see today. It explains not only the structure of Jupiter but also provides us with an understanding of the mechanism of energy generation in our Sun and other stars. Because of the bizarreness of quantum theory at a fundamental level, we deliberately avoided all philosophical issues and followed Richard Feynman's advice in adopting a very pragmatic stance. We therefore concerned ourselves with demonstrating that the theory, no matter how strange it may seem, clearly works in practice. Since quantum theory was developed in the 1920s by Niels Bohr, Erwin Schroedinger, Werner Heisenberg, Paul Dirac and others, it seemed that, apart from more applications, there was little new to be discovered.

To our surprise, the last fifteen years have been years of great advances in quantum technology. Although no new results have arisen to challenge the supremacy of the underlying quantum theory, there have been many exciting new discoveries. In the main, these developments all demonstrate our increasing control of quantum systems. So much so that we believe that we are seeing the emergence of a new field of scientific endeavour – 'quantum engineering'. This term signifies our belief that this new century will see our increasing mastery over manipulating matter at the quantum level leading to new and spectacular applications of such 'nanotechnology'. There will certainly be significant implications for the semiconductor industry. We will see the end of 'Moore's Law' – the prediction that the number of transistors on computer chips, and hence their computational speed and memory capacity, doubles every eighteen months. In ten years or so, the dimensions of features on a silicon chip will have shrunk to such a size that the properties of individual atoms and electrons will play a determining role. Such quantum objects do not behave in a classically describable way. Unless quantum engineers are able to come up with some competitive new technology, Moore's Law will come to an end – along with the necessity to upgrade PCs every 18 months! One possible new technology on the horizon is 'quantum computing'. Instead of bits of information restricted to be either '1' or '0', as in present-day 'classical' computers, a quantum computer would allow the possibility of algorithms using quantum bits – 'qubits' – that are somehow simultaneously '1' and '0'! This observation has led to the development of a whole new area of research – 'quantum information theory' – and there are already possibilities of its practical application in cryptography. Although we retain our original approach to quantum mechanics in this book, the chapters on quantum applications have been extensively re-written and updated. In addition, a new chapter on 'quantum engineering' introduces the ideas and technologies of nanotechnology and quantum information.

As we have said, in our earlier book on quantum mechanics, we followed Feynman and avoided asking the question 'But how can it be like that?'. However, the last fifteen years have seen an upsurge of interest in understanding what quantum mechanics implies about the physical reality of the world in which we live. We have therefore included a chapter on 'quantum paradoxes' in which we introduce the reader to the unfinished debate between Niels Bohr and Albert Einstein. It was Bohr who formulated the orthodox 'Copenhagen' view of quantum mechanics and who was its most robust defender. According to Bohr's interpretation, uncertainty and unpredictability are intrinsic features of quantum theory, and the actual physical reality of quantum objects is debatable. Against such orthodoxy, Albert Einstein, Bohr's long-term friend and colleague, fought for the remainder of his life. He summed up his opposition to the Copenhagen interpretation in the memorable phrase 'God does not play dice!' After a lengthy but ultimately inconclusive debate, Einstein died still a non-believer in quantum theory. Soon after his death, the Irish physicist John Bell came up with a way to distinguish between the orthodox quantum mechanics of Bohr and the deterministic approach favoured by Einstein. Experiments to test 'Bell's Inequality' have now come down in favour of quantum mechanics and Einstein would have to think again! Bell's result is of such importance for quantum mechanics that we include an intuitive explanation of the Bell Inequality. Our presentation closely follows one given by John Bell himself in a meeting in Geneva. The other essential creature in any discussion of the interpretation of quantum mechanics is Schrödinger's Cat. The paradox of the cat graphically illustrates the so-called 'measurement problem' in quantum mechanics. We discuss how this problem is resolved – to a greater or lesser degree – by the ever popular 'Many Worlds' interpretation of quantum mechanics of Hugh Everett or by the 'Decoherence' mechanism favoured by Wojtek Zurek and others.

Finally, as a light-hearted 'afterword', we look at the treatment of quantum mechanics in Science Fiction. H.G. Wells led the way with his account of an atomic-bomb-induced Armageddon in his book *The World Set Free*. In the early years of quantum mechanics, SF writers struggled to incorporate the new understanding of the atom into a fictional context. Modern SF has now moved on to include multiple universes and nanotechnology as part of its standard technology base. Finally, in Michael Crichton's recent book, *Timeline*, quantum computers, teleportation and time travel are woven together to create yet another new dimension for Science Fiction to explore.

The distinguished theoretical physicist and author Paul Davies has made the following prediction:

> The nineteenth century was known as the machine age, the
> twentieth century will go down in history as the information age.
> I believe the twenty-first century will be the quantum age.

In the course of the next decades we will see how far this vision will be realized. Certainly, we believe that the influence on our society of this coming nanotechnology revolution, underpinned by quantum mechanics, will be at least as substantial as the fall-out from the present bio-informatics explosion. We hope that this book will assist in stimulating the imagination of a new generation of quantum engineers.

Some acknowledgements are in order. Once again we wish to thank our families for their invaluable support and forbearance – Marie Walters, and Jessie, Nancy, Jonathan and Christopher Hey. We are also grateful to colleagues who have read and commented on draft chapters, especially Phil Charles, Malcolm Coe, Jeff Mandula and Steve King. In Southampton, we

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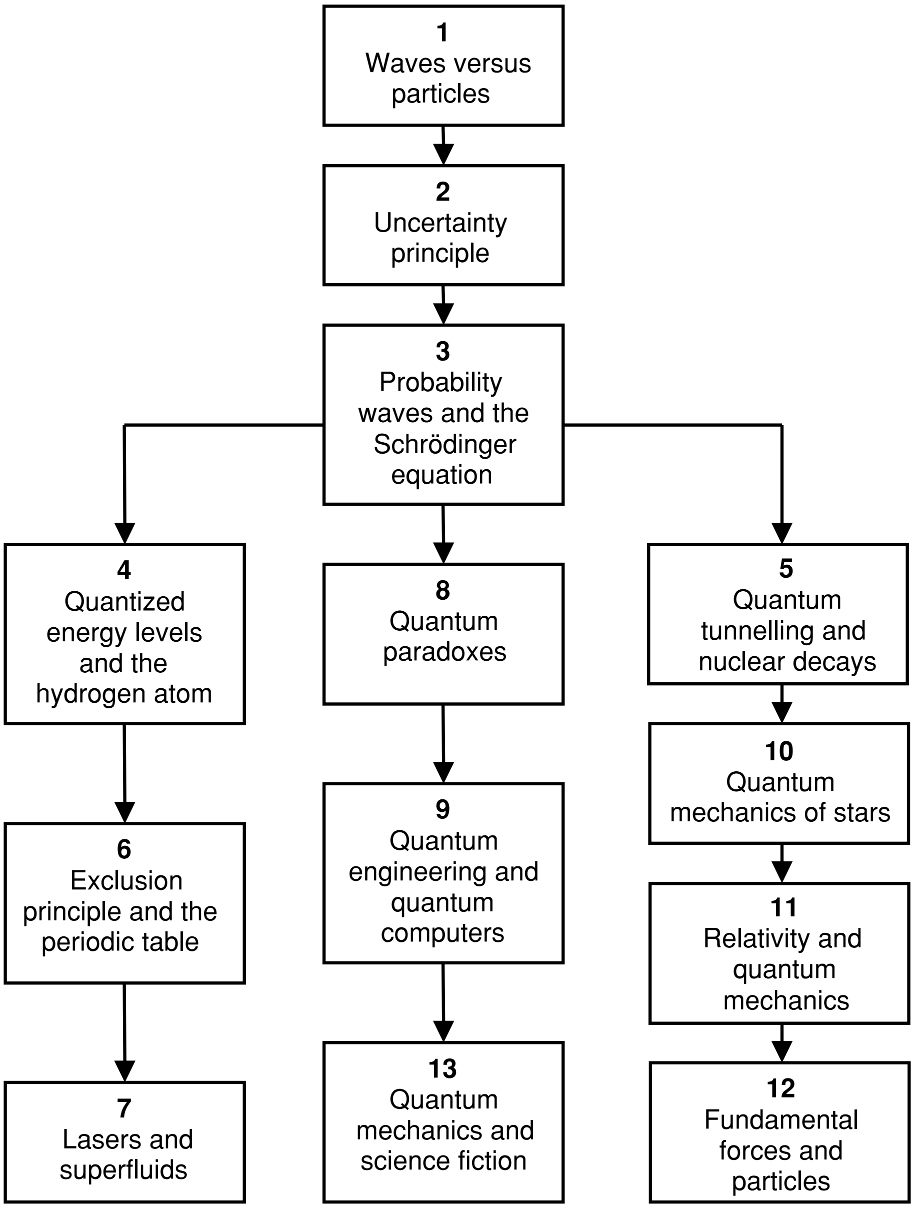
Prologue

Poets say science takes away from the beauty of the stars – mere globs of gas atoms. Nothing is 'mere'. I too can see the stars on a desert night, and feel them. But do I see less or more? The vastness of the heavens stretches my imagination – stuck on this carousel, my little eye can catch one-million-year- old light . . . Or see them [the stars] with the greater eye of Palomar, rushing all apart from some common starting point when they were perhaps all together. What is the pattern, or the meaning, or the why? It does not do harm to the mystery to know a little about it. For far more marvellous is the truth than any artists of the past imagined! Why do the poets of the present not speak of it?

Finally, may I add that the main purpose of my teaching has not been to prepare you for some examination – it was not even to prepare you to serve industry or the military. I wanted most to give you some appreciation of the wonderful world and the physicist's way of looking at it, which, I believe, is a major part of the true culture of modern times. (There are probably professors of other subjects who would object, but I believe they are completely wrong.) Perhaps you will not only have some appreciation of this culture; it is even possible that you may want to join in the greatest adventure that the human mind has ever begun.

Richard Feynman

Route map



The three major strands of interconnected topics through the book. Broadly speaking, the left-hand strand is concerned with the quantum mechanics of the solid state; the right-hand strand focuses on the quantum mechanics of stars and elementary particles; and the middle strand explores quantum paradoxes and quantum engineering, before looking at the fictional realization of these ideas.