Preface

There have been two revolutions in the way we view the physical world in the twentieth century: relativity and quantum mechanics. In quantum mechanics the revolution has been both profound—requiring a dramatic revision in the structure of the laws of mechanics that govern the behavior of all particles, be they electrons or photons—and far-reaching in its impact—determining the stability of matter itself, shaping the interactions of particles on the atomic, nuclear, and particle physics level, and leading to macroscopic quantum effects ranging from lasers and superconductivity to neutron stars and radiation from black holes. Moreover, in a triumph for twentieth-century physics, special relativity and quantum mechanics have been joined together in the form of quantum field theory. Field theories such as quantum electrodynamics have been tested with an extremely high precision, with agreement between theory and experiment verified to better than nine significant figures. It should be emphasized that while our understanding of the laws of physics is continually evolving, always being subjected to experimental scrutiny, so far no confirmed discrepancy between theory and experiment for quantum mechanics has been detected.

This book is intended for an upper-division course in quantum mechanics. The most likely audience for the book consists of students who have completed a course in modern physics that includes an introduction to quantum mechanics that emphasizes wave mechanics. Rather than continue with a similar approach in a second course, I have chosen to introduce the fundamentals of quantum mechanics through a detailed discussion of the physics of intrinsic spin. Such an approach has a number of significant advantages. First, students find starting a course with something "new" such as intrinsic spin both interesting and exciting, and they enjoy making the connections with what they have seen before. Second, spin systems provide us with many beautiful but straightforward illustrations of the essential structure of quantum mechanics, a structure that is not obscured by the mathematics of wave mechanics. Quantum mechanics can be presented through concrete examples. I believe that most physicists learn through specific examples and then find it easy to generalize. By

Townsend third pages 2012/1/3 8:59 p. xi (front) Windfall Software, PCA ZzTEX 14.3

starting with spin, students are given plenty of time to assimilate this novel and striking material. I have found that they seem to learn this key introductory material easily and well—material that was often perceived to be difficult when I came to it midway through a course that began with wave mechanics. Third, when we do come to wave mechanics, students see that wave mechanics is only one aspect of quantum mechanics, not the fundamental core of the subject. They see at an early stage that wave mechanics and matrix mechanics are just different ways of calculating based on the same underlying quantum mechanics and that the approach they use depends on the particular problem they are addressing.

I have been inspired by two sources, an "introductory" treatment in Volume III of *The Feynman Lectures on Physics* and an advanced exposition in J. J. Sakurai's *Modern Quantum Mechanics*. Overall, I believe that wave mechanics is probably the best way to *introduce* students to quantum mechanics. Wave mechanics makes the largest overlap with what students know from classical mechanics and shows them the strange behavior of quantum mechanics in a familiar environment. This is probably why students find their first introduction to quantum mechanics so stimulating. However, starting a second course with wave mechanics runs the risk of diminishing much of the excitement and enthusiasm for the entirely new way of viewing nature that is demanded by quantum mechanics. It becomes sort of old hat, material the students has seen before, repeated in more depth. It is, I believe, with the second exposure to quantum mechanics that something like Feynman's approach has its best chance to be effective. But to be effective, a quantum mechanics text needs to make lots of contact with the way most physicists think and calculate in quantum mechanics using the language of kets and operators. This is Sakurai's approach in his graduate-level textbook. In a sense, the approach that I am presenting here can be viewed as a superposition of these two approaches, but at the junior-senior level.

Chapter 1 introduces the concepts of the quantum state vector, complex probability amplitudes, and the probabilistic interpretation of quantum mechanics in the context of analyzing a number of Stern–Gerlach experiments carried out with spin-$\frac{1}{2}$ particles. By introducing ket vectors at the beginning, we have the framework for thinking about states as having an existence quite apart from the way we happen to choose to represent them, whether it be with matrix mechanics, which is discussed at length in Chapter 2, or, where appropriate, with wave mechanics, which is introduced in Chapter 6. Moreover, there is a natural role for operators; in Chapter 2 they rotate spin states so that the spin "points" in a different direction. I do not follow a postulatory approach, but rather I allow the basic physics of this spin system to drive the introduction of concepts such as Hermitian operators, eigenvalues, and eigenstates.

In Chapter 3 the commutation relations of the generators of rotations are determined from the behavior of ordinary vectors under rotations. Most of the material in this chapter is fairly conventional; what is not so conventional is the introduction of operator techniques for determining the angular momentum eigenstates and eigenvalue spectrum and the derivation of the uncertainty relations from the commutation relations at such an early stage. Since so much of our initial discussion of quantum mechanics revolves around intrinsic spin, it is important for students to see how quantum mechanics can be used to determine from first principles the spin states that have been introduced in Chapters 1 and 2, without having to appeal only to experimental results.

Chapter 4 is devoted to time evolution of states. The natural operation in time development is to translate states forward in time. The Hamiltonian enters as the generator of time translations, and the states are shown to obey the Schrödinger equation. Most of the chapter is devoted to physical examples. In Chapter 5 another physical system, the spin-spin interaction of an electron and proton in the ground state of hydrogen, is used to introduce the spin states of two spin-$\frac{1}{2}$ particles. The total-spin-0 state serves as the basis for a discussion of the Einstein–Podolsky–Rosen (EPR) paradox and the Bell inequalities.

The main theme of Chapter 6 is making contact with the usual formalism of wave mechanics. The special problems in dealing with states such as position and momentum states that have a continuous eigenvalue spectrum are analyzed. The momentum operator enters naturally as the generator of translations. Sections 6.8 through 6.10 include a general discussion with examples of solutions to the Schrödinger equation that can serve as a review for students with a good background in one-dimensional wave mechanics.

Chapter 7 is devoted to the one-dimensional simple harmonic oscillator, which merits a chapter all its own. Although the material in Chapter 8 on path integrals can be skipped without affecting subsequent chapters (with the exception of Section 14.1, on the Aharonov–Bohm effect), I believe that path integrals should be discussed, if possible, since this formalism provides real insight into quantum dynamics. However, I have found it difficult to fit this material into our one-semester course, which is taken by all physics majors as well as some students majoring in other disciplines. Rather, I have chosen to postpone path integrals to a second course and then to insert the material in Chapter 8 before Chapter 14. Incidentally, the material on path integrals is the only part of the book that may require students to have had an upper-division classical mechanics course, one in which the principle of least action is discussed.

Chapters 9 through 13 cover fully three-dimensional problems, including the two-body problem, orbital angular momentum, central potentials, time-independent perturbations, identical particles, and scattering. An effort has been made to include as many physical examples as possible.

Although this is a textbook on nonrelativistic quantum mechanics, I have chosen to include a discussion of the quantized radiation field in the final chapter, Chapter 14. The use of ket and bra vectors from the beginning and the discussion of solutions to problems such as angular momentum and the harmonic oscillator in terms of abstract raising and lowering operators should have helped to prepare the student for the exciting jump to a quantized electromagnetic field. By quantizing this field, we can really understand the properties of photons, we can calculate the lifetimes for spontaneous emission from first principles, and we can understand why a laser works. By looking at higher order processes such as photon-atom scattering, we can also see the essentials of Feynman diagrams. Although the atom is treated nonrelativistically, it is still possible to gain a sense of what quantum field theory is all about at this level without having to face the complications of the relativistic Dirac equation. For the instructor who wishes to cover time-dependent perturbation theory but does not have time for all of the chapter, Section 14.5 stands on its own.

Although SI units are the standard for undergraduate education in electricity and magnetism, I have chosen in the text to use Gaussian units, which are more commonly used to describe microscopic phenomena. However, with the possible exception of the last chapter, with its quantum treatment of the electromagnetic field, the choice of units has little impact. My own experience suggests that students who are generally at home with SI units are comfortable (as indicated in a number of footnotes through the text) replacing e^2 with $e^2/4\pi\epsilon_0$ or ignoring the factor of c in the Bohr magneton whenever they need to carry out numerical calculations. In addition, electromagnetic units are discussed in Appendix A.

In writing the second edition, I have added two sections to Chapter 5, one on entanglement and quantum teleportation and the other on the density operator. Given the importance of entanglement in quantum mechanics, it may seem strange, as it does to me now, to have written a quantum mechanics textbook without explicit use of the word entanglement. The concept of entanglement is, of course, at the heart of the discussion of the EPR paradox, which focused on the entangled state of two spin-$\frac{1}{2}$ particles in a spin-singlet state. Nonetheless, it wasn't until the early 1990s, when topics such as quantum teleportation came to the fore, that the importance of entanglement as a fundamental resource that can be utilized in novel ways was fully appreciated and the term entanglement began to be widely used. I am also somewhat embarrassed not to have included a discussion of the density operator in the first edition. Unlike a textbook author, the experimentalist does not necessarily have the luxury of being able to focus on pure states. Thus there is good reason to introduce the density operator (and the density matrix) as a systematic way to deal with mixed states as well as pure states in quantum mechanics. I have added a section on coherent states of the harmonic oscillator to Chapter 7. Coherent states were first derived by Schrödinger in his efforts to find states that satisfy the correspondence principle. The real utility of these states is most apparent in Chapter 14, where it is seen that coherent states come closest to representing classical electromagnetic waves with a well-defined phase. I have also added a section to Chapter 14 on cavity quantum electrodynamics, showing how the interaction of the quantized electromagnetic field with atoms is modified by confinement in a reflective cavity. Like quantum teleportation, cavity quantum electrodynamics is a topic that really came to the fore in the 1990s. In addition to these new sections, I have added numerous worked example problems to the text, with the hope that these examples will help students in mastering quantum mechanics. I have also increased the end-of-chapter problems by 25 percent.

There is almost certainly enough material here for a full-year course. For a one-semester course, I have covered the material through Chapter 12, omitting Sections 6.7 through 6.10 and, as noted earlier, Chapter 8. The material in the latter half of Chapter 6 is covered thoroughly in our introductory course on quantum physics. See John S. Townsend, *Quantum Physics: A Fundamental Approach to Modern Physics,* University Science Books, 2010. In addition to Chapter 8, other sections that might be omitted in a one-semester course include parts of Chapter 5, Section 9.7, and Sections 11.5 through 11.9. Or one might choose to go as far as Chapter 10 and reserve the remaining material for a later course.

A comprehensive solutions manual for the instructor is available from the publisher, upon request of the instructor.

Finally, some grateful acknowledgments are certainly in order. Students in my quantum mechanics classes have given me useful feedback as I have taught from the book over the years. Colleagues at Harvey Mudd College who have offered valuable comments as well as encouragement include Bob Cave, Chih-Yung Chen, Tom Donnelly, Tom Helliwell, Theresa Lynn, and Peter Saeta. Art Weldon of West Virginia University suggested a number of ways to improve the accuracy and effectiveness of the first edition. This text was initially published in the McGraw-Hill International Series in Pure and Applied Physics. I have benefited from comments from the following reviewers: William Dalton, St. Cloud State University; Michael Grady, SUNY-Fredonia; Richard Hazeltine, University of Texas at Austin; Jack Mochel, University of Illinois at Urbana-Champaign; and Jae Y. Park, North Carolina State University. For the first edition, the Pew Science Program provided support for Doug Dunston and Doug Ridgway, two Harvey Mudd College students, who helped in the preparation of the text and figures, respectively, and Helen White helped in checking the galley proofs. A number of people have kindly given me feedback on the material for the second edition, including Rich Holman, Carnegie Mellon University; Randy Hulet, Rice University; Jim Napolitano, RPI; Tom Moore and David Tanenbaum, Pomona College; and John Taylor, University of Colorado.

I have been fortunate to have the production of the book carried out by a very capable group of individuals headed by Paul Anagnostopoulos, the project manager. In addition to Paul, I want to thank Lee Young for copyediting, Joe Snowden for entering the copyedits and laying out the pages, Tom Webster for the artwork, MaryEllen Oliver for her amazingly thorough job of proofreading, and Genette Itoko McGrew for her creative cover design. I also wish to thank Jane Ellis and Bruce

Armbruster of University Science Books not only for their assistance but also for the care and attention to detail they have taken in preparing this new edition of the book. And I especially want to thank my wife, Ellen, for cheerfully letting me devote so much time to this project.

Please do not hesitate to contact me if you find errors or have suggestions that might improve the book.

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