# Quantum Mechanics with Basic Field Theory

Students and instructors alike will find this organized and detailed approach to quantum mechanics ideal for a two-semester graduate course on the subject.

This textbook covers, step-by-step, important topics in quantum mechanics, from traditional subjects like bound states, perturbation theory and scattering, to more current topics such as coherent states, quantum Hall effect, spontaneous symmetry breaking, superconductivity, and basic quantum electrodynamics with radiative corrections. The large number of diverse topics are covered in concise, highly focused chapters, and are explained in simple but mathematically rigorous ways. Derivations of results and formulas are carried out from beginning to end, without leaving students to complete them.

With over 200 exercises to aid understanding of the subject, this textbook provides a thorough grounding for students planning to enter research in physics. Several exercises are solved in the text, and password-protected solutions for remaining exercises are available to instructors at www.cambridge.org/9780521877602.

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*To Ba, Bapuji, and Blaire*

# Contents



 

# Preface

While writing this book I was reminded at times of what Professor Francis Low used to say when I took his class on undergraduate electromagnetism at the University of Illinois, Urbana-Champaign. “Be sure to understand the subject thoroughly,” he said, “otherwise, your only other chance will be when you have to teach it.” Knowing now what I know by having written this book, I would add that, if at that point one still does not understand the subject, there will be yet another opportunity when writing a book on it. That was certainly the case with me and this book.

For the last twenty years or so I have taught a one-year graduate course in quantum mechanics at the University of California, Riverside. I have used several books, including the text by Schiff which also happens to be the text I used when I was taking my graduate courses at the University of California, Berkeley (along with my class notes from Professor Eyvind Wichmann who taught the quantum electrodynamics course). However, it became clear to me that I would need to expand the subject matter considerably if I wanted the book not only to be as thorough and up-to-date as possible but also organized so that one subject followed the other in a logical sequence. I hope I have succeeded.

Traditionally, books on graduate quantum mechanics go up to relativity and in some cases even cover the Dirac equation. But relativistic equations lead to the troublesome negative-energy solutions. It would be unsatisfactory then to just stop there and not go to second quantization, to show how the negative-energy states are reinterpreted as positive-energy states of antiparticles. It was, therefore, logical to cover elementary second quantization, which in a sense is many-body quantum mechanics with quantization conditions. And once this topic was addressed it would be unfair not to cover the great successes of many-body systems in condensed matter, in particular, superconductivity and Bose–Einstein condensation. A logical concurrent step was to include also full relativistic quantum field theory, at least basic quantum electrodynamics (QED) and then finish on a triumphant note describing the stunning success of QED in explaining the anomalous magnetic moment and the Lamb shift. With the vast acreage that I wanted to cover, it seemed only appropriate to include as well the modern subject of spontaneous symmetry breaking, which has its applications both in condensed matter physics and in particle physics. This then was the rationale behind this book’s content and organization.

I have organized the book with small chapters in what I believe to be a logical order. One can think of the layout of the chapters in terms of the following blocks, each with a common thread, with chapters arranged in an increasing degree of complexity within each block

| | |
|---|---|
| Chs. 1, 2, 3 | Basic Formalism |
| Chs. 4, 5, 6, 7 | Free Particles |
| Chs. 8, 9, 10, 11, 12 | Exactly Solvable Bound State Problems |
| Chs. 13, 14, 15 | Two-Level Problems |
| Chs. 16, 17, 18 | Perturbation Theory |
| Ch. 24 | New approximation methods |
| Ch. 25 | Lagrangian and Feynman integral formalisms |
| Chs. 19, 20, 21, 22, 23 | Scattering Theory |
| Chs. 26, 27, 28, 29, 30 | Symmetry, Rotations, and Angular Momentum |
| Chs. 31, 32, 33, 34, 35, 36 | Relativistic theory with Klein–Gordon, Dirac, and Maxwell's equations |
| Chs. 37, 38, 39, 40 | Second Quantization, Condensed Matter Problems |
| Chs. 41, 42 | Classical Fields and Spontaneous Symmetry Breaking |
| Chs. 43, 44, 45 | Quantum Electrodynamics and Radiative Corrections |

In the chapters on scattering theory, one may find an extra coverage in this book on the properties of the *S*-matrix especially with reference to its analytical properties. This is thanks to my thesis advisor at Berkeley, Professor Geoffrey Chew who emphasized the importance of these properties to his students.

I believe it is feasible to complete the first 32 chapters in one year (two semesters or three quarters). The remaining chapters beginning with the Dirac equation could well be taught in the first semester or first quarter of an advanced quantum mechanics course. Since these topics cover quantum field theory applied to both particle physics and condensed matter physics, it could be taken by students specializing in either subject.

Except at the beginning of each chapter, this book does not have as much narrative or as many long descriptive paragraphs as one normally finds in other textbooks. I have instead spent extra space on deriving and solving the relevant equations. I feel that the extra narrative can always be supplemented by the person teaching the course.

There are an adequate number of problems in this book. They are fairly straightforward. I suppose I still have scars left from the days when I took graduate quantum mechanics from Professor Edward Teller at Berkeley, who gave very inspiring lectures full of interesting and topical episodes while on the blackboard he usually wrote down just the basic formulas. But then he turned around and gave, as homework, a huge number of some of the toughest problems this side of the Atlantic! Those assignments routinely took care of our entire weekends.

I have many people to thank, beginning with Dustin Urbaniec and Omar Moreno who did a good bit of the typing for me, and Barbara Simandl who did all the figures. I am also grateful to a number of graduate students from my Quantum Mechanics course for pointing out errors in my write-up; in particular, I am thankful to Eric Barbagiovanni, for suggesting a number of improvements. I must also thank Dr. Steve Foulkes, a former graduate student at UC Riverside, who read a number of chapters and, following my instructions not to show any mercy in criticizing what he read, did exactly that! I also wish to thank my colleagues who critically read parts of the manuscript: Professors Robert Clare (who also directed me to Cambridge University Press), Leonid Pryadkov, G. Rajasekaran and Utpal Sarkar.

At Cambridge University Press, my special thanks to Simon Mitton, with whom I corresponded in the early years, for his kind support and encouragement; to John Fowler and Lindsay Barnes for their constant help and, more importantly, for their patience with this long project.

There is one individual, Alex Vaucher, whom I must single out, without whose help this book would neither have been started nor completed. After finishing my graduate course on Quantum Mechanics at UC Riverside some years ago, he strongly encouraged me to write this book. He supplied the necessary software and, knowing how computer-ignorant I was, continued to provide me with technical instructions during all phases of this project. Initially the two of us were planning to collaborate on this book but, because of his full time position with the Physics and Astronomy department at the University of California, Los Angeles, he was not able to participate. My deepest gratitude to him.

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# Physical constants

| | | |
|---|---|---|
| Planck's constant | $\hbar$ | $6.581 \times 10^{-16}$ eV s |
| Velocity of light in vacuum | $c$ | $2.9979 \times 10^{10}$ cm/s |
| Fine structure constant | $\alpha = e^2/\hbar c$ | 1/137.04 |
| Rest mass of the electron | $mc^2$ | 0.511 MeV |
| Mass of the proton | $Mc^2$ | 938.28 MeV |
| Bohr radius | $\hbar^2/me^2$ | $5.2918 \times 10^{-9}$ cm |
| Bohr magneton | $e\hbar/2mc$ | $0.58 \times 10^{-8}$ eV/gauss |
| Boltzmann constant | $k$ | $8.62 \times 10^{-5}$ eV/K |
| 1 eV | | $1.6 \times 10^{-12}$ erg |