
Preface

This book is divided into two parts: Part I deals with nonrelativistic quantum mechanics, from bound states of a single particle (harmonic oscillator, hydrogen atom) to fermionic many-body systems. Part II is devoted to the theory of quantized fields and ranges from canonical quantization to quantum electrodynamics and some elements of electroweak interactions.

Quantum mechanics provides both the conceptual and the practical basis for almost all branches of modern physics, atomic and molecular physics, condensed matter physics, nuclear and elementary particle physics. By itself it is a fascinating, though difficult, part of theoretical physics whose physical interpretation gives rise, till today, to surprises in novel applications, and to controversies regarding its foundations. The mathematical framework, in principle, ranges from ordinary and partial differential equations to the theory of Lie groups, of Hilbert spaces and linear operators, to functional analysis, more generally. He or she who wants to learn quantum mechanics and is not familiar with these topics, may introduce much of the necessary mathematics in a heuristic manner, by invoking analogies to linear algebra and to classical mechanics. (Although this is not a prerequisite it is certainly very helpful to know a good deal of canonical mechanics!)

Quantum field theory deals with quantum systems with an infinite number of degrees of freedom and generalizes the principles of quantum theory to *fields*, instead of finitely many point particles. As Sergio Doplicher once remarked, quantum field theory is, after all, the *real* theory of matter and radiation. So, in spite of its technical difficulties, every physicist should learn, at least to some extent, concepts and methods of quantum field theory.

Chapter 1 starts with examples for failures of classical mechanics and classical electrodynamics in describing quantum systems and develops what might be called elementary quantum mechanics. The particle-wave dualism, together with certain analogies to Hamilton–Jacobi mechanics are shown to lead to the Schrödinger equation in a rather natural way, leaving open, however, the question of interpretation of the wave function. This problem is solved in a convincing way by Born’s statistical interpretation which, in turn, is corroborated by the concept of expectation value and by Ehrenfest’s theorem. Having learned how to describe observables of quantum systems one then solves single-particle problems such as

the harmonic oscillator in one dimension, the spherical oscillator in three dimensions, and the hydrogen atom.

Chapter 2 develops scattering theory for particles scattered on a given potential. Partial wave analysis of the scattering amplitude as an example for an exact solution, as well as Born approximation for an approximate description are worked out and are illustrated by examples. The chapter also discusses briefly the analytical properties of partial wave amplitudes and the extension of the formalism to inelastic scattering.

Chapter 3 formalizes the general principles of quantum theory, on the basis of the empirical approach adopted in the first chapter. It starts with representation theory for quantum states, moves on to the concept of Hilbert space, and describes classes of linear operators acting on this space. With these tools at hand, it then develops the description and preparation of quantum states by means of the density matrix.

Chapter 4 discusses space–time symmetries in quantum physics, a first tour through the rotation group in nonrelativistic quantum mechanics and its representations, space reflection, and time reversal. It also addresses symmetry and antisymmetry of systems of a finite number of identical particles.

Chapter 5 which concludes Part I, is devoted to important practical applications of quantum mechanics, ranging from quantum information to time-independent as well as time-dependent perturbation theory, and to the description of many-body systems of identical fermions.

Chapter 6, the first of Part II, begins with an extended analysis of symmetries and symmetry groups in quantum physics. Wigner’s theorem on the unitary or antiunitary realization of symmetry transformations is in focus here. There follows more material on the rotation group and its use in quantum mechanics, as well as a brief excursion to internal symmetries. The analysis of the Lorentz and Poincaré groups is taken up from the perspective of particle properties, and some of their unitary representations are worked out.

Chapter 7 describes the principles of canonical quantization of Lorentz covariant field theories and illustrates them with examples of the real and complex scalar fields, and the Maxwell field. A section on the interaction of quantum Maxwell fields with nonrelativistic matter illustrates the use of second quantization by a number of physically interesting examples. The specific problems related to quantized Maxwell theory are analyzed and solved in its covariant quantization and in an investigation of the state space of quantum electrodynamics.

Chapter 8 takes up scattering theory in a more general framework by defining the S -matrix and by deriving its properties. The optical theorem is proved for the general case of elastic and inelastic final states and formulae for cross sections and decay widths are worked out in terms of the scattering matrix.

Chapter 9 deals exclusively with the Dirac equation and with quantized fields describing spin-1/2 particles. After the construction of the quantized Dirac field and a first analysis of its interactions we also explore the question to which extent the Dirac equation may be useful as an approximate single-particle theory.

Chapter 10 describes covariant perturbation theory and develops the technique of Feynman diagrams and their translation to analytic amplitudes. A number of physically relevant tree processes of quantum electrodynamics are worked out in detail. Higher order terms and the specific problems they raise serve to introduce and to motivate the concepts of regularization and renormalization in a heuristic manner. Some prominent examples of radiative corrections serve to illustrate their relevance for atomic and particle physics as well as their physical interpretation. The chapter concludes with a short excursion into weak interactions, placing these in the framework of electroweak interactions.

The book covers material (more than) sufficient for two full courses and, thus, may serve as an accompanying textbook for courses on quantum mechanics and introductory quantum field theory. However, as the main text is largely self-contained and contains a considerable number of worked-out examples, it may also be useful for independent individual study. The choice of topics and their presentation closely follows a two-volume German text well established at German speaking universities. Much of the material was tested and fine-tuned in lectures I gave at Johannes Gutenberg University in Mainz. The book contains many exercises for some of which I included complete solutions or gave some hints. In addition, there are a number of appendices collecting or explaining more technical aspects. Finally, I included some historical remarks about the people who pioneered quantum mechanics and quantum field theory, or helped to shape our present understanding of quantum theory.¹

I am grateful to the students who followed my courses and to my collaborators in research for their questions and critical comments some of which helped to clarify matters and to improve the presentation. Among the many colleagues and friends from whom I learnt a lot about the quantum world I owe special thanks to Martin Reuter who also read large parts of the original German manuscript, to Wolfgang Bulla who made constructive remarks on formal aspects of quantum mechanics, and to the late Othmar Steinmann from whom I learnt a good deal of quantum field theory during my years at ETH and PSI in Zurich.

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Florian Scheck

¹ I will keep track of possible errata on an Internet page attached to my home page. The latter can be accessed via <http://www.thep.uni-mainz.de/site>. I will be grateful for hints at misprints or errors.

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