

Quantum Physics

Quantum physics allows us to understand the nature of the physical phenomena which govern the behavior of solids, semiconductors, lasers, atoms, nuclei, subnuclear particles, and light. In *Quantum Physics*, Le Bellac provides a thoroughly modern approach to this fundamental theory.

Throughout the book, Le Bellac teaches the fundamentals of quantum physics using an original approach which relies primarily on an algebraic treatment and on the systematic use of symmetry principles. In addition to the standard topics such as one-dimensional potentials, angular momentum and scattering theory, the reader is introduced to more recent developments at an early stage. These include a detailed account of entangled states and their applications, the optical Bloch equations, the theory of laser cooling and of magneto-optical traps, vacuum Rabi oscillations, and an introduction to open quantum systems. This is a textbook for a modern course on quantum physics, written for advanced undergraduate and graduate students.

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Foreword

Quantum physics is now one hundred years old, and this description of physical phenomena, which has transformed our vision of the world, has never been found at fault, which is exceptional for a scientific theory. Its predictions have always been verified by experiment with impressive accuracy. The basic concepts of quantum physics such as probability amplitudes and linear superpositions of states, which seem so strange to our intuition when encountered for the first time, remain fundamental. However, during the last few decades an important evolution has occurred. The spectacular progress made in observational techniques and methods of manipulating atoms now makes it possible to perform experiments so delicate that they were once considered as only “thought experiments” by the founders of quantum mechanics. The existence of “nonseparable” quantum correlations, which forms the basis of the Einstein–Podolsky–Rosen “paradox” and which violates the famous Bell inequalities, has been confirmed experimentally with high precision. “Entangled” states of two systems which manifest such quantum correlations are now better understood and even used in practical applications such as quantum cryptography. The entanglement of a measuring device with its environment reveals an interesting new pathway to better understanding of the measurement process.

In parallel with these conceptual advances, our everyday world is being invaded by devices which function on the basis of quantum phenomena. The laser sources used to read compact disks, in ophthalmology, and in optical telecommunications are based on light amplification by atomic systems with population inversion. Nuclear magnetic resonance is widely used in hospitals to obtain ever more detailed images of the organs of the human body. Millions of transistors are incorporated in the chips which allow our computers to perform operations at phenomenal speeds.

It is therefore clear that any modern course in quantum physics must cover these recent developments in order to give the student or researcher a more accurate idea of the progress that has been made and to motivate the better understanding of physical phenomena whose conceptual and practical importance is increasingly obvious. This is the goal that Michel Le Bellac has successfully accomplished in the present work.

Each of the fifteen chapters of this book contains not only a clear and concise description of the basic ideas, but also numerous discussions of the most recent conceptual and experimental developments which give the reader an accurate idea of the advances in

the field and the general trends in its evolution. Chapter 6 on entangled states is typical of this method of presentation. Instead of stressing the mathematical properties of the tensor product of two spaces of states, which is rather austere and forbidding, this chapter is oriented on discussion of the idea of entanglement, and introduces several examples of theoretical and experimental developments (some of them very new) such as the Bell inequalities, tests of these inequalities and in particular the most recent ones based on parametric conversion, GHZ (Greenberger, Horne, Zeilinger) states, the idea of decoherence illustrated by modern experiments in cavity quantum electrodynamics (discussed in more detail in an appendix), and teleportation. It is difficult to imagine a more complete immersion in one of the most active current areas of quantum physics. Numerous examples of this modern presentation can be found in other chapters, too: interference of de Broglie waves realized using slow neutrons or laser-cooled atoms; tunnel-effect microscopy; quantum field fluctuations and the Casimir effect; non-Abelian gauge transformations; the optical Bloch equations; radiative forces exerted by laser beams on atoms; magneto-optical traps; Rabi oscillations in a cavity vacuum, and so on.

I greatly admire the effort made by the author to give the reader such a modern and compelling view of quantum physics. Of course, not all subjects can be treated in great detail, and the reader must make some effort to obtain a deeper comprehension of the subject. This is aided by the detailed bibliography given in the form of both footnotes to the text and a list of suggested reading at the end of each chapter. I am sure that this text will lead to better comprehension of quantum physics and will stimulate greater interest in this absolutely central discipline. I would like to thank Michel Le Bellac for this important contribution which will certainly give physics a more exciting image.

Claude Cohen-Tannoudji

Preface

This book has grown out of a course given at the University of Nice over many years for advanced undergraduates and graduate students in physics. The first ten chapters correspond to a basic course in quantum mechanics for advanced undergraduates, and the last four could serve to complement a graduate course in, for example, atomic physics. The book contains about 130 exercises of varying length and difficulty, most of which have actually been used in homework or exams.

This book should be interesting not only to students in physics and engineering, but also to a wider group of physicists: graduate students, researchers, and secondary-school teachers who wish to update their knowledge of quantum physics. It discusses recent developments not covered in the classic texts such as entangled states, quantum cryptography and quantum computing, decoherence, interactions of a laser with a two-level atom, quantum fluctuations of the electromagnetic field, laser manipulation of atoms, and so on, and it also includes a concise discussion of the current ideas about measurement in quantum mechanics as an appendix.

The organization of this book differs greatly from that of the classic texts, which typically begin with the Schrödinger equation and then proceed to study its solution in various situations. That approach makes it necessary to introduce the basic principles of quantum mechanics in a relatively complicated situation, and they end up being obscured by calculations which are often rather complex. Instead, I have striven to present the fundamentals of quantum mechanics using the simplest examples, and the Schrödinger equation appears only in Chapter 9. I follow the approach of pushing the logic adopted by Feynman (Feynman *et al.* [1965]) to its limit: developing the algebraic approach as far as possible and exploiting the symmetries, so as to present quantum mechanics within an autonomous framework without reference to classical physics. There are several advantages to this logic.

- The algebraic approach allows the solution of simple problems in finite-dimensional (for example, two-dimensional) spaces, such as photon polarization, spin $1/2$, two-level atoms, and so on.
- This approach leads to the clearest statement of the postulates of quantum mechanics, as the fundamental issues are separated from the less fundamental ones (for example, the correspondence principle is not a fundamental postulate).

- The use of the symmetry properties leads to the most general introduction to fundamental physical properties such as momentum, angular momentum, and so on as the infinitesimal generators of these symmetries, without resorting to the correspondence principle or classical analogies.

Another advantage of this approach is that the reader wishing to learn about the recent developments in quantum information theory need consult only the first six chapters. These are sufficient for comprehension of the basics of quantum information, without passing through the stages of expansion of the wave function in spherical harmonics and solving the Schrödinger equation in a central potential!

I have given special attention to the pedagogical aspects. The order of chapters was carefully chosen: the early ones use only finite-dimensional spaces, and only after the basic principles have been covered do I go on to the general case in Chapter 7. Chapters 11 to 14 and the appendices involve more advanced techniques which may be of interest to professional physicists. An effort has been made regarding the vocabulary, in order to avoid certain historically dated expressions which can obstruct the understanding of quantum mechanics. Following the modernization proposed by J.-M. Lévy-Leblond (*Quantum words for a quantum world*, in *Epistemological and Experimental Perspectives on Quantum Physics*, D. Greenberger, W. L. Reiter and A. Zeilinger (eds.) Dordrecht: Kluwer (1999)), I use “physical property” instead of “observable” and “Heisenberg inequality” instead of “uncertainty principle,” and I avoid expressions such as “complementarity” and “wave–particle duality.”

The key chapters of this book, that is, those which diverge most obviously from the traditional treatment, are Chapters 3, 4, 5, 6, and 8. Chapter 3 introduces the space of states for the example of photon polarization and shows how to go from a wave amplitude to a probability amplitude. Spin 1/2 takes the reader directly to a problem without a classical analog. The essential properties of spin 1/2, namely the algebra of the Pauli matrices, the rotation matrices, and so on, are obtained using only two hypotheses: (1) two-dimensionality of the space of states and (2) rotational invariance. The Larmor precession of the quantum spin allows us to introduce the evolution equation. This chapter prepares the reader for the statement of the postulates of quantum mechanics in the following chapter, and it is possible to illustrate each postulate in a concrete fashion by returning to the examples of Chapter 3. The distinction between the general conceptual framework of quantum mechanics and the modeling of a particular problem is carefully explained. In Chapter 5 quantum mechanics is applied to some simple and physically important systems with a finite number of levels, a particular case being the diagonalization of the Hamiltonian in the presence of a periodic symmetry. This chapter also uses the example of the ammonia molecule to introduce the interaction of a two-level atomic or molecular system with an electromagnetic field, and the fundamental concepts of emission and absorption.

Chapter 6 is devoted to entangled states. The practical importance of these states dates from the early 1980s, but they are often ignored by textbooks. This chapter also deals with fundamental applications such as the Bell inequalities, two-photon interference, and measurement theory, as well as potential applications such as quantum computing.

Chapter 8 is devoted to the study of symmetries using the Wigner theorem, which is generally ignored in textbooks despite its crucial importance. Rotational symmetry allows the angular momentum to be defined as an infinitesimal generator, and the commutation relations of \vec{J} can be demonstrated immediately with emphasis on their geometrical origin. The canonical commutation relations of X and P are derived from the identification of the momentum as the infinitesimal generator of translations. Finally, I obtain the most general form of the Hamiltonian compatible with Galilean invariance using a hypothesis about the velocity transformation law. This Hamiltonian will be reinterpreted later on within the framework of local gauge invariance.

The other chapters can be summarized as follows. Chapter 1 has the triple goal of (1) introducing the basic notions of microscopic physics which will be used later on in the text; (2) introducing the behavior of quantum particles, conventionally called “wave–particle duality”; and (3) presenting a simple explanation, with the aid of the Bohr atom, of the notion of energy level and of level spectrum. Chapter 2 presents the essential ideas about Hilbert space in the case of finite dimension. Chapter 7 gives some information about Hilbert spaces of infinite dimension; the goal here is of course not to present a mathematically rigorous treatment, but rather to warn the reader of certain pitfalls in infinite dimension.

The final chapters are devoted to more classic applications. Chapter 9 presents wave mechanics and its usual applications (the tunnel effect, bound states in the square well, periodic potentials, and so on). The angular momentum commutation relations already presented in Chapter 8 reappear in Chapter 10 in the construction of eigenstates of \vec{J}^2 and J_z , and lead to the Wigner–Eckart theorem for vector operators. Chapter 11 develops the theory of the harmonic oscillator and motion in a constant magnetic field, which provides the occasion for explaining local gauge invariance. An important section in this chapter deals with quantized fields: the vibrational field and phonons, and the electromagnetic field and its quantum fluctuations. Chapters 12 and 13 are devoted to scattering and identical particles. In Chapter 14 I present a brief introduction to the physics of one-electron atoms, the main objective being to calculate the forces on a two-level atom placed in the field of a laser and to discuss applications such as Doppler cooling and magneto-optical traps.

The appendices deal with subjects which are a bit more technically demanding. The proof of the Wigner theorem and the time-reversal operation are explained in detail in Appendix A. Some complementary information about the theory and experiments on decoherence can be found in Appendix B along with a discussion of some current ideas about measurement. Finally, Appendix C contains a discussion of the method of Wigner and Weisskopf for unstable states.

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Fabrice Mortessagne, Jean-Pierre Romagnan, and François Rocca, who have read large parts or in some cases all of the manuscript. I also wish to thank David Wilkowski, who provided the inspiration for the text in some of the exercises of Chapter 14. Of course, I bear sole responsibility for the final text. The assistance of Karim Bernardet and Fabrice Mortessagne, who initiated me into XFIG and installed the software, was crucial for realizing the figures, and I also thank Christian Taggiasco for competently installing and maintaining all the necessary software. Finally, this book would never have seen the light of day were it not for the encouragement and unfailing support of Michèle Leduc, and I am very grateful to Claude Cohen-Tannoudji for writing the Preface.

Addendum for the English edition

In addition to minor corrections, I have included a few new exercises, partly rewritten Chapters 5 and 6, and added a new chapter on open quantum systems. I am grateful to Jean Dalibard and Christian Miniatura for their careful reading of this new chapter and for their useful comments. I would like to thank Simon Capelin and Vincent Higgs for their help in the publication and, above all, Patricia de Forcrand-Millard for her excellent translation and for her patience in our many email exchanges in order to find the right word.

Units and physical constants

The physical constants below are given with a relative precision of 10^{-3} which is sufficient for the numerical applications in this book.

Speed of light in vacuum	$c = 3.00 \times 10^8 \text{ m s}^{-1}$
Planck constant	$h = 6.63 \times 10^{-34} \text{ J s}$
Planck constant divided by 2π	$\hbar = 1.055 \times 10^{-34} \text{ J s}$
Electronic charge (absolute value)	$q_e = 1.602 \times 10^{-19} \text{ C}$
Fine structure constant	$\alpha = q_e^2 / (4\pi\epsilon_0 \hbar c) = e^2 / (\hbar c) = 1/137$
Electron mass	$m_e = 9.11 \times 10^{-31} \text{ kg} = 0.511 \text{ MeV } c^{-2}$
Proton mass	$m_p = 1.67 \times 10^{-27} \text{ kg} = 938 \text{ MeV } c^{-2}$
Bohr magneton	$\mu_B = q_e \hbar / (2m_e) = 5.79 \times 10^{-5} \text{ eV T}^{-1}$
Nuclear magneton	$\mu_N = q_e \hbar / (2m_p) = 3.15 \times 10^{-8} \text{ eV T}^{-1}$
Bohr radius	$a_0 = \hbar^2 / (m_e e^2) = 0.529 \times 10^{-8} \text{ m}$
Rydberg constant	$R_\infty = m_e e^4 / (2\hbar^2) = 13.61 \text{ eV}$
Boltzmann constant	$k_B = 1.38 \times 10^{-23} \text{ J K}^{-1}$
Electron volt and temperature	$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J} = k_B \times 11\,600 \text{ K}$
Gravitational constant	$G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$