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Jochen Pade

Quantum Mechanics for Pedestrians 2

Applications and Extensions

Second Edition

 Springer

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Preface to the Second Edition, Volume 2

In this second edition of Volume 2, a short introduction to the basics of quantum field theory has been added. The material is placed in the Appendix. It is not a comprehensive and complete presentation of the topic, but, in the sense of a primer, a concise account of some of the essential ideas.

Fundamentals from other areas can be found in Volume 1, i.e., outlines of special relativity, classical field theory, electrodynamics and relativistic quantum mechanics.

Oldenburg, Germany
February 2018

Jochen Pade

Preface to the First Edition, Volume 2

In the first volume of *Quantum Mechanics for Pedestrians*, we worked out the basic structure of quantum mechanics (QM) and summarized it in the form of postulates that provided its framework.

In this second volume, we want to fill that framework with life. To this end, in eight of the 14 chapters we will discuss some key applications, what might be called the ‘traditional’ subjects of quantum mechanics: simple potentials, angular momentum, perturbation theory, symmetries, identical particles, and scattering.

At the same time, we want to prudently broaden the scope of our treatment, in order to be able to discuss modern developments such as entanglement and decoherence. We begin this theme in Chap. 20 with the question of whether quantum mechanics is a local-realistic theory. In Chap. 22, we introduce the density operator in order to discuss the phenomenon of decoherence and its importance for the measurement process in Chap. 24. In Chap. 27, we address again the realism debate and examine the question as to what extent quantum mechanics can be considered to be a complete theory. Modern applications in the field of quantum information can be found in Chap. 26.

Finally, we outline in Chap. 28 the most common current interpretations of quantum mechanics. Apart from one chapter, what was said in Volume I applies generally: An introduction to quantum mechanics has to take a definite stand on the interpretation question, although (or perhaps because) the question as to which one of the current interpretations (if any) is the ‘correct’ one it is still quite controversial. We have taken as our basis what is often called the ‘standard interpretation.’

In order to formulate the postulates, we worked in the first volume with very simple models, essentially toy models. This is of course not possible for some of the ‘real’ systems presented in the present volume, and accordingly, these chapters are formally more complex. However, here also, we have kept the mathematical level as simple as possible. Moreover, we always choose that particular presentation which is best adapted to the question at hand, and we maintain the relaxed approach to mathematics which is usual in physics.

This volume is also accompanied by an extensive appendix. It contains some information on mathematical issues, but its principal focus is on physical topics whose consideration or detailed discussion would be beyond the scope of the main text in Chaps. 15–28.

In addition, there is for nearly every chapter a variety of exercises; solutions to most of them are given in the appendix.

Contents

Part II Applications and Extensions

| | | |
|-----------|---|----|
| 15 | One-Dimensional Piecewise-Constant Potentials | 3 |
| 15.1 | General Remarks | 4 |
| 15.2 | Potential Steps | 6 |
| 15.2.1 | Potential Step, $E < V_0$ | 7 |
| 15.2.2 | Potential Step, $E > V_0$ | 8 |
| 15.3 | Finite Potential Well | 11 |
| 15.3.1 | Potential Well, $E < 0$ | 12 |
| 15.3.2 | Potential Well, $E > 0$ | 15 |
| 15.4 | Potential Barrier, Tunnel Effect | 17 |
| 15.5 | From the Finite to the Infinite Potential Well | 20 |
| 15.6 | Wave Packets | 22 |
| 15.7 | Exercises | 25 |
| 16 | Angular Momentum | 29 |
| 16.1 | Orbital Angular Momentum Operator | 29 |
| 16.2 | Generalized Angular Momentum, Spectrum | 30 |
| 16.3 | Matrix Representation of Angular Momentum Operators | 34 |
| 16.4 | Orbital Angular Momentum: Spatial Representation of the Eigenfunctions | 35 |
| 16.5 | Addition of Angular Momenta | 37 |
| 16.6 | Exercises | 40 |
| 17 | The Hydrogen Atom | 43 |
| 17.1 | Central Potential | 44 |
| 17.2 | The Hydrogen Atom | 47 |
| 17.3 | Complete System of Commuting Observables | 52 |
| 17.4 | On Modelling | 53 |
| 17.5 | Exercises | 54 |

| | | |
|-----------|---|-----|
| 18 | The Harmonic Oscillator | 55 |
| 18.1 | Algebraic Approach | 56 |
| 18.1.1 | Creation and Annihilation Operators | 56 |
| 18.1.2 | Properties of the Occupation-Number Operator | 58 |
| 18.1.3 | Derivation of the Spectrum | 58 |
| 18.1.4 | Spectrum of the Harmonic Oscillator | 61 |
| 18.2 | Analytic Approach (Position Representation) | 61 |
| 18.3 | Exercises | 63 |
| 19 | Perturbation Theory | 65 |
| 19.1 | Stationary Perturbation Theory, Nondegenerate | 66 |
| 19.1.1 | Calculation of the First-Order Energy Correction | 67 |
| 19.1.2 | Calculation of the First-Order State Correction | 68 |
| 19.2 | Stationary Perturbation Theory, Degenerate | 69 |
| 19.3 | Hydrogen: Fine Structure | 70 |
| 19.3.1 | Relativistic Corrections to the Hamiltonian | 70 |
| 19.3.2 | Results of Perturbation Theory | 72 |
| 19.3.3 | Comparison with the Results of the Dirac Equation | 73 |
| 19.4 | Hydrogen: Lamb Shift and Hyperfine Structure | 74 |
| 19.5 | Exercises | 76 |
| 20 | Entanglement, EPR, Bell | 79 |
| 20.1 | Product Space | 79 |
| 20.2 | Entangled States | 80 |
| 20.2.1 | Definition | 81 |
| 20.2.2 | Single Measurements on Entangled States | 83 |
| 20.2.3 | Schrödinger's Cat | 85 |
| 20.2.4 | A Misunderstanding | 87 |
| 20.3 | The EPR Paradox | 88 |
| 20.4 | Bell's Inequality | 91 |
| 20.4.1 | Derivation of Bell's Inequality | 91 |
| 20.4.2 | EPR Photon Pairs | 92 |
| 20.4.3 | EPR and Bell | 93 |
| 20.5 | Conclusions | 96 |
| 20.6 | Exercises | 97 |
| 21 | Symmetries and Conservation Laws | 99 |
| 21.1 | Continuous Symmetry Transformations | 101 |
| 21.1.1 | General: Symmetries and Conservation Laws | 101 |
| 21.1.2 | Time Translation | 103 |
| 21.1.3 | Spatial Translation | 104 |
| 21.1.4 | Spatial Rotation | 106 |
| 21.1.5 | Special Galilean Transformation | 109 |

- 21.2 Discrete Symmetry Transformations 109
 - 21.2.1 Parity 109
 - 21.2.2 Time Reversal 111
- 21.3 Exercises 114
- 22 The Density Operator 117**
 - 22.1 Pure States 117
 - 22.2 Mixed States 120
 - 22.3 Reduced Density Operator 123
 - 22.3.1 Example 125
 - 22.3.2 Comparison 126
 - 22.3.3 General Formulation 127
 - 22.4 Exercises 128
- 23 Identical Particles 131**
 - 23.1 Distinguishable Particles 132
 - 23.2 Identical Particles 133
 - 23.2.1 A Simple Example 133
 - 23.2.2 The General Case 134
 - 23.3 The Pauli Exclusion Principle 137
 - 23.4 The Helium Atom 138
 - 23.4.1 Spectrum Without $V_{1,2}$ 139
 - 23.4.2 Spectrum with $V_{1,2}$ (Perturbation Theory) 141
 - 23.5 The Ritz Method 143
 - 23.6 How Far does the Pauli Principle Reach? 145
 - 23.6.1 Distinguishable Quantum Objects 146
 - 23.6.2 Identical Quantum Objects 146
 - 23.7 Exercises 147
- 24 Decoherence 149**
 - 24.1 A Simple Example 150
 - 24.2 Decoherence 152
 - 24.2.1 The Effect of the Environment I 154
 - 24.2.2 Simplified Description 156
 - 24.2.3 The Effect of the Environment II 157
 - 24.2.4 Interim Review 159
 - 24.2.5 Formal Treatment 160
 - 24.3 Time Scales, Universality 161
 - 24.4 Decoherence-Free Subspaces, Basis 162
 - 24.5 Historical Side Note 163
 - 24.6 Conclusions 164
 - 24.7 Exercises 166

| | | |
|-----------|---|-----|
| 25 | Scattering | 169 |
| 25.1 | Basic Idea; Scattering Cross Section | 170 |
| 25.1.1 | Classical Mechanics | 170 |
| 25.1.2 | Quantum Mechanics | 171 |
| 25.2 | The Partial-Wave Method | 173 |
| 25.3 | Integral Equations, Born Approximation | 177 |
| 25.4 | Exercises | 180 |
| 26 | Quantum Information | 183 |
| 26.1 | No-Cloning Theorem (Quantum Copier) | 183 |
| 26.2 | Quantum Cryptography | 185 |
| 26.3 | Quantum Teleportation | 185 |
| 26.4 | The Quantum Computer | 188 |
| 26.4.1 | Qubits, Registers (Basic Concepts) | 188 |
| 26.4.2 | Quantum Gates and Quantum Computers | 190 |
| 26.4.3 | The Basic Idea of the Quantum Computer | 194 |
| 26.4.4 | The Deutsch Algorithm | 194 |
| 26.4.5 | Grover’s Search Algorithm | 196 |
| 26.4.6 | Shor’s Algorithm | 198 |
| 26.4.7 | On The Construction of Real Quantum Computers | 199 |
| 26.5 | Exercises | 201 |
| 27 | Is Quantum Mechanics Complete? | 203 |
| 27.1 | The Kochen–Specker Theorem | 204 |
| 27.1.1 | Value Function | 205 |
| 27.1.2 | From the Value Function to Coloring | 206 |
| 27.1.3 | Coloring | 207 |
| 27.1.4 | Interim Review: The Kochen–Specker Theorem | 209 |
| 27.2 | GHZ States | 210 |
| 27.3 | Discussion and Outlook | 214 |
| 27.4 | Exercises | 216 |
| 28 | Interpretations of Quantum Mechanics | 219 |
| 28.1 | Preliminary Remarks | 221 |
| 28.1.1 | Problematic Issues | 221 |
| 28.1.2 | Difficulties in the Representation of Interpretations | 224 |
| 28.2 | Some Interpretations in Short Form | 225 |
| 28.2.1 | Copenhagen Interpretation(s) | 225 |
| 28.2.2 | Ensemble Interpretation | 227 |
| 28.2.3 | Bohm’s Interpretation | 228 |
| 28.2.4 | Many-Worlds Interpretation | 228 |
| 28.2.5 | Consistent-Histories Interpretation | 230 |

| | | |
|--|---|------------|
| 28.2.6 | Collapse Theories | 230 |
| 28.2.7 | Other Interpretations | 231 |
| 28.3 | Conclusion | 232 |
| Appendix A: Abbreviations and Notations | | 235 |
| Appendix B: Special Functions | | 237 |
| Appendix C: Tensor Product | | 247 |
| Appendix D: Wave Packets | | 253 |
| Appendix E: Laboratory System, Center-of-Mass System | | 263 |
| Appendix F: Analytic Treatment of the Hydrogen Atom | | 267 |
| Appendix G: The Lenz Vector | | 279 |
| Appendix H: Perturbative Calculation of the Hydrogen Atom | | 293 |
| Appendix I: The Production of Entangled Photons | | 297 |
| Appendix J: The Hardy Experiment | | 301 |
| Appendix K: Set-Theoretical Derivation of the Bell Inequality | | 309 |
| Appendix L: The Special Galilei Transformation | | 311 |
| Appendix M: Kramers' Theorem | | 323 |
| Appendix N: Coulomb Energy and Exchange Energy in the Helium Atom | | 325 |
| Appendix O: The Scattering of Identical Particles | | 329 |
| Appendix P: The Hadamard Transformation | | 333 |
| Appendix Q: From the Interferometer to the Computer | | 339 |
| Appendix R: The Grover Algorithm, Algebraically | | 345 |
| Appendix S: Shor Algorithm | | 351 |
| Appendix T: The Gleason Theorem | | 367 |
| Appendix U: What is Real? Some Quotations | | 369 |
| Appendix V: Remarks on Some Interpretations of Quantum Mechanics | | 375 |
| Appendix W: Elements of Quantum Field Theory | | 387 |
| W.1 | Foreword | 387 |
| W.2 | Quantizing a Field - A Toy Example | 388 |
| W.3 | Quantization of Free Fields, Introduction | 396 |
| W.4 | Quantization of Free Fields, Klein–Gordon | 397 |
| W.5 | Quantization of Free Fields, Dirac | 405 |

W.6 Quantization of Free Fields, Photons 418

W.7 Operator Ordering 423

W.8 Interacting Fields, Quantum Electrodynamics. 431

W.9 S-Matrix, First Order 436

W.10 Contraction, Propagator, Wick’s Theorem 447

W.11 S-Matrix, 2. Order, General 458

W.12 S-Matrix, 2. Order, 4 Lepton Scattering 462

W.13 High Precision and Infinities. 476

Appendix X: Exercises and Solutions 485

Further Reading 577

Index of Volume 1 579

Index of Volume 2 583

Contents of Volume 1

Part I Fundamentals

| | | |
|-----------|---|------------|
| 1 | Towards the Schrödinger Equation | 3 |
| 2 | Polarization | 15 |
| 3 | More on the Schrödinger Equation | 29 |
| 4 | Complex Vector Spaces and Quantum Mechanics | 41 |
| 5 | Two Simple Solutions of the Schrödinger Equation | 55 |
| 6 | Interaction-Free Measurement | 73 |
| 7 | Position Probability | 87 |
| 8 | Neutrino Oscillations | 99 |
| 9 | Expectation Values, Mean Values, and Measured Values | 109 |
| 10 | Stopover; Then on to Quantum Cryptography | 125 |
| 11 | Abstract Notation | 139 |
| 12 | Continuous Spectra | 151 |
| 13 | Operators | 165 |
| 14 | Postulates of Quantum Mechanics | 187 |
| | Appendix A: Abbreviations and Notations | 203 |
| | Appendix B: Units and Constants | 205 |
| | Appendix C: Complex Numbers | 211 |
| | Appendix D: Calculus I | 221 |
| | Appendix E: Calculus II | 237 |
| | Appendix F: Linear Algebra I | 245 |

| | |
|---|-----|
| Appendix G: Linear Algebra II | 263 |
| Appendix H: Fourier Transforms and the Delta Function | 273 |
| Appendix I: Operators | 291 |
| Appendix J: From Quantum Hopping to the Schrödinger Equation | 311 |
| Appendix K: The Phase Shift at a Beam Splitter | 317 |
| Appendix L: The Quantum Zeno Effect | 319 |
| Appendix M: Delayed Choice and the Quantum Eraser | 327 |
| Appendix N: The Equation of Continuity | 333 |
| Appendix O: Variance, Expectation Values | 335 |
| Appendix P: On Quantum Cryptography | 339 |
| Appendix Q: Schrödinger Picture, Heisenberg Picture, Interaction Picture | 345 |
| Appendix R: The Postulates of Quantum Mechanics | 351 |
| Appendix S: System and Measurement: Some Concepts | 367 |
| Appendix T: Recaps and Outlines | 373 |
| Appendix U: Elements of Relativistic Quantum Mechanics | 405 |
| Appendix V: Exercises and Solutions to Chaps. 1–14 | 441 |
| Further Reading | 513 |
| Index of Volume 1 | 515 |
| Index of Volume 2 | 519 |

Introduction

Quantum mechanics is probably the most accurately verified physical theory existing today. To date, there has been no contradiction from any experiments; the applications of quantum mechanics have changed our world right up to aspects of our everyday life. There is no doubt that quantum mechanics ‘functions’—it is indeed extremely successful. On a formal level, it is clearly unambiguous and consistent and (certainly not unimportant)—as a theory—it is both aesthetically satisfying and convincing.

The question in dispute is the ‘real’ meaning of quantum mechanics. What does the wavefunction stand for, and what is the role of chance? Do we actually have to throw overboard our classical and familiar conceptions of reality? Despite the nearly century-long history of quantum mechanics, fundamental questions of this kind are still unresolved and are currently being discussed in a lively and controversial manner. There are two contrasting positions (along with many intermediate views): Some see quantum mechanics simply as the precursor stage of the ‘true’ theory (although eminently functional); others see it as a valid, fundamental theory itself.

This book aims to introduce its readers to both sides of quantum mechanics, the established side and the side that is still under discussion. We develop here both the conceptual and formal foundations of quantum mechanics, and we discuss some of its ‘problem areas.’ In addition, this book includes applications—oriented fundamental topics, some ‘modern’ ones—for example, issues in quantum information—and ‘traditional’ ones such as the hydrogen and the helium atoms. We restrict ourselves to the field of nonrelativistic physics, although many of the ideas can be extended to the relativistic case.¹ Moreover, we consider only time-independent interactions.

In introductory courses on quantum mechanics, the practice of formal skills often takes priority (this is subsumed under the slogan ‘shut up and calculate’). In accordance with our objectives here, we will also give appropriate space to the

¹ In the second edition, some essentials of relativistic quantum mechanics are added; see the Appendix.

discussion of fundamental questions. This special blend of basic discussion and modern practice is in itself very well suited to evoke interest and motivation in students. This is, in addition, enhanced by the fact that some important fundamental ideas can be discussed using very simple model systems as examples. It is not coincidental that some of the topics and phenomena addressed here are treated in various simplified forms in high-school textbooks.

In mathematical terms, there are two main approaches used in introductions to quantum mechanics. The first one relies on differential equations (i.e., analysis) and the other one on vector spaces (i.e., linear algebra); of course, the ‘finished’ quantum mechanics is independent of the route of access chosen. Each approach (they also may be called the Schrodinger and the Heisenberg routes) has its own advantages and disadvantages; the two are used in this book on an equal footing.

The roadmap of the book is as follows:

The foundations and structure of quantum mechanics are worked out step by step in the first part (Volume 1, Chaps. 1–14), alternatively from an analytical approach (odd chapters) and from an algebraic approach (even chapters). In this way, we avoid limiting ourselves to only one of the two formulations. In addition, the two approaches reinforce each other in the development of important concepts. The merging of the two threads starts in Chap. 12. In Chap. 14, the conclusions thus far reached are summarized in the form of quite general postulates for quantum mechanics.

Especially in the algebraic chapters, we take up current problems early on (interaction-free quantum measurements, the neutrino problem, quantum cryptography). This is possible since these topics can be treated using very simple mathematics. Thus, this type of access is also of great interest for high-school level courses. In the analytical approach, we use as elementary physical model systems the infinite potential well and free particle motion.

In the second part (Volume 2, Chaps. 15–28), applications and extensions of the formalism are considered. The discussion of the conceptual difficulties (measurement problem, locality and reality, etc.) again constitutes a central theme, as in the first volume. In addition to some more traditionally oriented topics (angular momentum, simple potentials, perturbation theory, symmetries, identical particles, scattering), we begin in Chap. 20 with the consideration of whether quantum mechanics is a local realistic theory. In Chap. 22, we introduce the density operator in order to consider in Chap. 24 the phenomenon of decoherence and its relevance to the measurement process. In Chap. 27, we continue the realism debate and explore the question as to what extent quantum mechanics can be regarded as a complete theory. Modern applications in the field of quantum information can be found in Chap. 26.

Finally, we outline in Chap. 28 the most common interpretations of quantum mechanics. Apart from this chapter, a general statement applies: While it is still a controversial issue as to which (if indeed any) of the current interpretations is the ‘correct’ one, an introduction to quantum mechanics must take a concrete position and has to present the material in a coherent form. In this book, we choose the version commonly known as the ‘standard interpretation.’

A few words about the role of mathematics:

In describing objects that—due to their small size—are beyond our everyday experience, quantum mechanics cannot be formulated completely in terms of everyday life and must therefore remain to some extent abstract. A deeper understanding of quantum mechanics cannot be achieved on a purely linguistic level; we definitely need mathematical descriptions.² Of course, one can use analogies and simplified models, but that works only to a certain degree and also makes sense only if one is aware of the underlying mathematical apparatus, at least in broad terms.³

It is due to this interaction of the need for mathematical formulations and the lack of intuitive access that quantum mechanics is often regarded as ‘difficult.’ But that is only part of the truth; to be sure, there are highly formalized and demanding aspects. Many wider and interesting issues, however, are characterized by very simple principles that can be described using only a basic formalism.

Nevertheless, beginners in particular perceive the role of mathematics in quantum mechanics as discouraging. Three steps serve to counter this impression or, in the optimum case, to avoid it altogether:

First, we keep the mathematical level as simple as possible and share the usual quite nonchalant attitude of physicists toward mathematics. In particular, the first chapters go step by step, so that the initially diverse mathematics skills of the readers are gradually brought up to a common level.

In addition, we use very simple models, toy models so to speak, especially in the first part of the book, in order to treat the main physical ideas without becoming involved in complicated mathematical questions. Of course, these models are only rough descriptions of actual physical situations. But they manage with relatively simple mathematics, do not require approximation methods or numerics, and yet still permit essential insights into the fundamentals of quantum mechanics.⁴ Only in Volume 2, more realistic models are applied, and this is reflected occasionally in a somewhat more demanding formal effort.

The third measure involves exercises and some support from the Appendix. At the end of almost every chapter, there is a variety of exercises, some of them dealing with advanced topics. They invite the reader to work with the material in

²This applies at least to physicists; for as Einstein remarked: ‘But there is another reason for the high repute of mathematics: it is mathematics that offers the exact natural sciences a certain measure of security which, without mathematics, they could not attain.’ To give a layman without mathematical training an understanding of quantum mechanics, one will (or must) rely instead on math-free approaches.

³Without appropriate formal considerations, it is impossible to understand, for example, how to motivate the replacement of a physical measurement variable by a Hermitian operator.

⁴We could instead also make use of the large reservoir of historically important experiments. But their mathematical formulation is in general more complex, and since in the frame of our considerations they do not lead to further-reaching conclusions than our ‘toy models,’ we restrict ourselves to the latter for clarity and brevity.

order to better assimilate and more clearly grasp it, as well as of course to train the necessary formal skills.⁵

The learning aids in the Appendix include chapters with some basic mathematical and physical background information; this allows the reader to refresh ‘passive’ knowledge without the need to refer to other sources or to become involved with new notations.

Moreover, the no doubt unusually extensive Appendix contains the solutions to many of the exercises and, in addition, some chapters in which further-reaching questions and issues are discussed; although these are very interesting in themselves, their treatment would far exceed the framework of a lecture course.

The footnotes with a more associative character can be skipped on a first reading.

A note on the term ‘particle’: Its meaning is rather vague in physics. On the one hand, it denotes ‘something solid, not wavelike’; on the other hand ‘something small’, ranging from the elementary particles as structureless building blocks of matter, to objects which themselves are composed of constituent ‘particles’ like the α particle and other atomic nuclei or even macroscopic particles like sand grains. In quantum mechanics, where indeed it is often not even clear whether a particular object has mainly particle or mainly wave character, the careless use of the term may cause confusion and communication problems.

Accordingly, several terms which go beyond ‘wave’ or ‘particle’ have been suggested, such as quantal particle, wavical, wavicle, quantum object, quanton. Throughout this book, we will use the term ‘quantum object,’ unless there are traditionally established terms such as ‘identical particles’ or ‘elementary particles.’ The consistent use of ‘quantum object’ instead of ‘particle’ may perhaps seem somewhat pedantic, but we hope that it will help to ensure that fewer false images stick in the minds of readers; it is for this reason that this term is also found in many high-school textbooks.

Quantum mechanics is a fundamental theory of physics, which has given rise to countless applications. But it also extends deep into areas such as philosophy and epistemology and leads to thinking about ‘what holds the world together at its core’; in short, it is also an intellectual adventure. The fascinating thing is that the more one becomes acquainted with quantum mechanics, the more one realizes how simple many of its central ideas really are.⁶ It would be pleasing if *Quantum Mechanics for Pedestrians* could help to reveal this truth.

⁵‘It is a great support to studying, at least for me, to grasp everything that one reads so clearly that one can apply it oneself, or even make additions to it. One is then inclined to believe in the end that one could have invented everything himself, and that is encouraging.’ Georg Christoph Lichtenberg, *Scrap Books*, Vol. J (1855).

⁶‘The less we know about something, the more complicated it is, and the more we know about it, the easier it is. This is the simple truth about all the complexities.’ Egon Friedell, in *Kulturgeschichte der Neuzeit; Kulturgeschichte Agyptens und des alten Orients* (*Cultural history of modern times; the cultural history of Egypt and the ancient Near East*).

Let us close with a remark by Richard Feynman which holds true not only for physics in general, but even more for quantum mechanics: ‘Physics is like sex: Sure, it may give some practical results, but that’s not why we do it.’

Overview of Volume 2

Now we have established the basic framework of quantum mechanics in Volume 1 in the form of postulates, we turn to two other major topics in Volume 2.

First, we want to fill the framework of quantum mechanics with life, i.e., to discuss some applications (solutions for simple potentials, angular momentum, symmetries, identical particles, scattering, quantum information). These chapters are to some extent more technical, since we cannot use toy models, as in the first volume, but instead have to consider ‘real’ systems.

Second, we will extend the framework of quantum mechanics prudently to address modern developments such as entanglement and decoherence. Finally, we turn again to the realism debate; the final chapter presents some of the current interpretations of quantum mechanics.