

## Preface to the English Edition

For the English edition, the German text has been revised and extended with a number of new sections. I have taken the suggestions of students into account, who have used the text as an accompaniment to lecture courses and seminars. I wish to express my sincere thanks to them and to all of the others who have discussed the book with me. I am grateful for indications of typographical errors, which have been corrected. Furthermore, I once again wish to thank Michael Nock and Stefan Bretzel for their diligent help with the manuscript.

The famous aphorism “If I have seen further it is by standing on ye shoulders of Giants”<sup>1</sup> is due to Sir Isaac Newton. This statement holds for anyone who works in the field of quantum theory today. We are only the dwarves, who owe so much to the giants. However, the question remains as to how the dwarves get up onto the shoulders of the giants as quickly and easily as possible. This book is intended to be of help precisely in this process.

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<sup>1</sup>I. Newton in his letter to R. Hooke of February 5, 1675. Further details can be found in [Mer 65].



## Preface to the German Edition

This book is a

**textbook in theoretical physics.**

It is the result of lecture courses and seminars which I have given in recent years at the University of Konstanz, Germany, on the subjects of

**quantum information theory and the  
foundations of quantum mechanics.**

Non-relativistic quantum mechanics has experienced a phase of turbulent development in the past few years. Quantum computing, quantum teleportation, quantum cryptography, and quantum information are typical buzzwords which reflect these developments, and they can be found beyond the professional circle of physics in popular-science articles and in Sunday supplements. The concept of *entanglement* is the central theoretical idea accompanying these “new directions” in quantum mechanics, which are increasingly making their way into physics curricula in schools. The theoretical fundamentals of these new developments are the subject of this book.

**For whom is the book intended?** The readers targeted are in the main students, but in addition, all those who are interested in quantum mechanics or perhaps simply fascinated by the subject. This includes not only physicists and students of physics, but also students of computer science, chemistry and other natural sciences, as well as engineers and teachers. The book presumes a basic acquaintance with quantum mechanics: it does not start from zero.

To be sure, all the basics of mathematics and physics which are required for understanding the later chapters are summarised in the initial Chapters 1 and 2; they are treated there from a point of view which may be new to many readers. These chapters serve among other things as a preparation for the fact that in quantum mechanics, the concepts of a *state* and the *evolution of a state*, including measurements, are used in a different sense from that of classical physics. The generalisations in the later chapters build on these fundamentals. The second chapter also contains a toolbox for the philosophy of science, with which we can discuss the question of the nature of the reality on which quantum mechanics is based.

Finally, the demands made upon the reader increase from chapter to chapter. The earlier chapters form a basis for the later ones; the exercises at the end of each chapter can serve as a guide for the reader as to whether he or she has sufficiently mastered the material in that chapter. Sentences printed in italics summarise the results of preceding sections. Advanced readers can rapidly scan through the text by watching for these italicised sentences.

**Goals** This book is intended to help its readers to obtain an overview of the rapid developments in quantum information theory, to acquire informed opinions concerning these developments and to understand them with an acceptable investment of time and effort.

**Limitations and complementary material** The claim to mathematical precision in this book is on the same level as in general textbooks on theoretical physics. Its content is limited to theoretical aspects; a description of the corresponding experiments and technical applications would fill again as many chapters. Each chapter, however, contains a subchapter on complementary topics and more detailed literature; here, references to experiments are included.

These subchapters also contain references to theoretical review articles and books. With their aid, the reader can obtain complementary information about the topics covered in this book and can deepen his or her knowledge. Articles and books with review character were given preference here over the original literature; i.e. the important articles in the sense of the retrospective historical development were not listed consistently, but instead, literature was cited which will be useful to the reader in obtaining a more advanced understanding of the subjects treated.

**Content** Following the first two chapters, in Chapters 3 and 4, the physics of isolated quantum systems is first developed further. Many examples and applications refer to qubits (2-level-systems). This treatment is then extended through the use of the density operator in Chapter 4. These are the most general states. Chapters 5 and 6 introduce the classical and the quantum-mechanical concepts of entropy and information.

The fundamentals of the physics of composite quantum systems are described in Chapter 7. The fact that an entangled state can contain several subsystems has a number of surprising consequences. An introduction to this topic is given in Chapter 8. Entanglement leads to correlation of the subsystems. The non-locality of the states is accompanied by the possibility of non-local measurements (Chap. 9).

The experimental observation of specific quantum correlations (EPR correlations) confirms the fundamental statement that there is no classical alternative to quantum mechanics (Chap. 10). These EPR correlations can be used as the basis of a quantum cryptography which is in principle completely secure against spying. Quantum teleportation is also based on them (Chap. 12). For the quantum computer, entanglement is an essential tool. Exploitation of quantum parallelism allows a large number of functional values to be computed in only a few operations. The problem is then reading out the results (Chap. 12).

In Chapter 13, we turn to the generalised dynamics of open quantum systems and first discuss generalised measurements, which contain projective measurements as a special case. They play an increasingly important role –together with positive operator-value measures (POVM)– in current publications. The general evolution of open quantum systems between their preparation and their measurement is described with the use of quantum operators. Various quantum channels are discussed in Chap. 14. The generalisations of projective measurements and unitary transformations lead to a new scenario of quantum physics.

Decoherence is the loss of the ability to exhibit interference, and is thus a problem for quantum computers. Conversely, environmentally-induced decoherence plays an important

role in answering the question of why classical objects exist (Chap. 15). It is tempting to apply this approach to obtaining an understanding of quantum measurement processes as well. The book closes with the supplemental proof of several theorems in Chap. 16.

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