Preface

There are many excellent books on quantum theory from which one can learn to compute energy levels, transition rates, cross sections, etc. The theoretical rules given in these books are routinely used by physicists to compute observable quantities. Their predictions can then be compared with experimental data. There is no fundamental disagreement among physicists on how to *use* the theory for these practical purposes. However, there are profound differences in their opinions on the ontological meaning of quantum theory.

The purpose of this book is to clarify the *conceptual meaning* of quantum theory, and to explain some of the mathematical methods which it utilizes. This text is not concerned with specialized topics such as atomic structure, or strong or weak interactions, but with the very foundations of the theory. This is not, however, a book on the philosophy of science. The approach is pragmatic and strictly instrumentalist. This attitude will undoubtedly antagonize some readers, but it has its own logic: quantum phenomena do not occur in a Hilbert space, they occur in a laboratory.

The level of the book is that of a graduate course. Since most universities do not offer regular courses on the foundations of quantum theory, this book was also designed to be suitable for independent study. It contains numerous exercises and bibliographical references. Most of the exercises are "on line" with the text and should be considered as part of the text, so that the reader actively participates in the derivation of results which may be needed for future applications. Usually, these exercises require only a few minutes of work. The more difficult exercises are denoted by a star ★. A few exercises are rated ★★. These are little research projects, for the more ambitious students.

It is assumed that the reader is familiar with classical physics (mechanics, optics, thermodynamics, etc.) and, of course, with elementary quantum theory. To remedy possible deficiencies in these subjects, textbooks are occasionally listed in the *bibliography* at the end of each chapter, together with general recommended reading. Any required notions of mathematical nature, such as elements of statistics or computer programs, are given in *appendices* to the chapters where these notions are needed.

The mathematical level of this book is not uniform. Elementary notions of linear algebra are explained in minute detail, when a *physical meaning* is attributed to abstract mathematical objects. Then, once this is done, I assume familiarity with much more advanced topics, such as group theory, angular momentum algebra, and spherical harmonics (and I supply references for readers who might lack the necessary background).

The general layout of the book is the following. The first chapters introduce, as usual, the formal tools needed for the study of quantum theory. Here, however, the primitive notions are not vectors and operators, but *preparations and tests.* The aim is to define the operational meaning of these physical concepts, rather than to subordinate them to an abstract formalism. At this stage, a "measurement" is considered as an ideal process which attributes a numerical value to an observable, represented by a self-adjoint operator. No detailed dynamical description is proposed as yet for the measuring process. However, physical procedures are defined as precisely as possible. Vague notions such as "quantum uncertainties" are never used. There also is a brief chapter devoted to dynamical variables with continuous spectra, in which the mathematical level is a reasonable compromise, neither sloppy (as in some elementary textbooks) nor excessively abstract and rigorous.

The central part of this book is devoted to cryptodeterministic theories, *i.e.,* extensions of quantum theory using "hidden variables." Nonlocal effects (related to Bell's theorem) and contextual effects (due to the Kochen-Specker theorem) are examined in detail. It is here that quantum phenomena depart most radically from classical physics. There has been considerable progress on these issues while I was writing the book, and I have included those new developments which I expect to be of lasting value.

The third part of the book opens with a chapter on spacetime symmetries, discussing both nonrelativistic and relativistic kinematics and dynamics. After that, the book penetrates into topics which belong to current research, and it presents material having hitherto appeared only in specialized journals: the relationship of quantum theory to thermodynamics and to information theory, its correspondence with classical mechanics, and the emergence of irreversibility and quantum chaos. The latter differs in many respects from the more familiar classical deterministic chaos. Similarities and differences between these two types of chaotic behavior are analyzed.

The final chapter discusses the measuring process. The measuring apparatus is now considered as a *physical system,* subject to imperfections. One no longer needs to postulate that observable values of dynamical variables are eigenvalues of the corresponding operators. This property follows from the dynamical behavior of the measuring instrument (typically, if the latter has a pointer moving along a dial, the final position of the pointer turns out to be *close* to one of the eigenvalues). The thorny point is that the measuring apparatus must accept two irreconcilable descriptions: it is a quantum system when it interacts with the measured object, and a classical system when it ultimately yields a definite reading. The *approximate* consistency of these two conflicting descriptions is ensured by the irreversibility of the measuring process.

This book differs from von Neumann's classic treatise in many respects. von Neumann was concerned with "measurable quantities." This is a neo-classical attitude: supposedly, there are "physical quantities" which we measure, and their measurements disturb each other. Here, I merely assume that we perform macroscopic operations called *tests*, which have stochastic outcomes. We then construct *models* where these macroscopic procedures are related to microscopic objects (e.g., atoms), and we use these models to make statistical predictions on the stochastic outcomes of the macroscopic tests. This approach is not only conceptually different, but it also is more general than von Neumann's. The measuring process is not represented by a complete set of orthogonal projection operators, but by a non-orthogonal *positive operator valued measure* (POVM). This improved technique allows to extract more information from a physical system than von Neumann's restricted measurements.

These topics are sometimes called "quantum measurement theory." This is a bad terminology: there can be no quantum measurement theory—there is only quantum mechanics. Either you use quantum mechanics to describe experimental facts, or you use another theory. A measurement is not a supernatural event. It is a physical process, involving ordinary matter, and subject to the ordinary physical laws. Ignoring this obvious truth and treating a measurement as a primitive notion is a distortion of the facts and a travesty of physics.

Some authors, perceiving conceptual difficulties in the description of the measuring process, have proposed new ways of "interpreting" quantum theory. These proposals are *not* new interpretations, but radically different theories, without experimental support. This book considers only standard quantum theory—the one that is actually used by physicists to predict or analyze experimental results. Readers who are interested in deviant mutations will not be able to find them here.

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