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Time in Quantum Mechanics

Second Edition

Springer

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Preface to the Second Edition

Time and quantum mechanics are, by and unto themselves, words of such force and attraction that the first edition of this book quite rapidly went out of print. The idea of bringing out a second edition became, thus, more compelling as time (indeed) flew on. Among the different possiblities (a wholly new text, a mere reprinting) we finally settled on a middle way, namely that each of the contributors has decided to what extent their respective chapters needed updating. One of the reasons for this decision is that the field has indeed been evolving, and the increase in editions of the TQM workshops held in La Laguna and Bilbao has provided us with quite a number of possible contributors for preparing, in addition to this second edition, a second volume with entirely new chapters. But more important is that the results and texts of the authors have withstood the passage of time and have weathered very well its ravages. All chapters have been updated, however, in order to include new results and bibliography.

We hope that this new edition meets with as much success as its predecessor and, as we write this, that in the future we can provide the interested reader with more contributions of other participants in our TQM workshops.

We are grateful to R. F. Snider and G. N. Flemming for pointing out several typos and errors of the first edition. We also acknowledge additional support from Ministerio de Educación y Ciencia (Grants BFM2003-01003, FIS2006-10268-C03-01 and FIS2004/05687), Gobierno Autónomo de Canarias (PI2004/025), and UPV-EHU (Grant 00039.310-15968/2004).

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Preface to the First Edition

Time and *quantum mechanics* have, each of them separately, captivated scientists and laymen alike, as shown by the abundance of popular publications on "time" or on the many quantum mysteries or paradoxes. We too have been seduced by these two topics, and in particular by their combination. Indeed, the treatment of time in quantum mechanics is one of the important and challenging open questions in the foundations of quantum theory.

This book describes the problems, and the attempts and achievements in defining, formalizing and measuring different time quantities in quantum theory, such as the parametric (clock) time, tunneling times, decay times, dwell times, delay times, arrival times, or jump times. The theoretical analysis of several of these quantities has been controversial and is still subject to debate. For example, there are literally hundreds of research papers on the *tunneling time*. In fact, the standard recipe to link the observables and the formalism does not seem to apply, at least in an obvious manner, to time observables. This has posed the challenge of extending the domain of ordinary quantum mechanics.

The difficulties in dealing with time in quantum theory were made explicit very early on, most clearly by Pauli in his famous "theorem," which seemed to impose a serious limitation on the possibility of formulating time as a quantum observable and which has hindered the investigation of time in quantum mechanics for many years. Another disturbing historical landmark is the discovery of quantum Zeno's effect, a paradox that arises when attempting to find an algorithm for computing time probabilities by means of frequently repeated measurements: in the continuum limit these measurements "freeze" the occurrence of events. More recently, however, in the last 15 years, there has been much interest in overcoming these difficulties. Researchers from atomic, molecular, and optical sciences, or from mesoscopic, high-energy, and mathematical physics, have converged to study different time quantities in quantum mechanics. In addition, modern laser technology and the ability to manipulate atomic and molecular motions and the internal state of quantum systems allow nowadays the experimental realization of some of the questions on time

in quantum mechanics. As a matter of fact, a number of time observables are already routinely measured in laboratories, for example arrival times in time-of-flight experiments, but the theoretical foundation of these measurements is still being discussed.

The book reflects a good number of these recent trends, but it is not an encyclopedic attempt to cover all the many different open questions, even entire fields, where time plays an important role, frequently a puzzling one, in quantum theory. It is not possible to cover all these subjects in a comprehensive manner unless the treatment becomes very superficial, so we abandoned that objective. While many of these topics are strongly related to the ones presented here, others are basically decoupled. We have thus preferred to make a more compact selection of topics based on the workshops on "Time in Quantum Mechanics" (TQM) in La Laguna and Bilbao. Our aim is to edit further volumes containing new aspects of quantum time not treated in the present one with additional material from old and new TQM workshops.

Most authors are or have been involved in the definition or study of "characteristic times" or "time observables" in quantum mechanics, and more specifically on tunneling and/or arrival times, which have been central subjects in the TQM workshop series. Even so, this book goes clearly beyond these two seed subjects. Thorny issues such as the relations between quantum mechanics and the world of classical events, the theory of measurement, hidden variable theories, time–energy uncertainty principles, superluminal effects, or extensions of the standard formalism are frequently ingredients of this research, as demonstrated in several chapters. It became evident to us that these topics, surrounding the central ones, had to be addressed too, in order to get a better handle on the original problems. Understanding the mysteries of time in quantum mechanics is thus inextricably linked to understanding quantum mechanics itself.

The chapters that follow are reviews that may serve both as an introductory guide for the non-initiated and as a useful tool for the expert. We have essentially allowed full freedom to each contributing author in choosing their presentation and emphasis. This has the major advantage of freshness and, in this manner, the actual state of the issue is much better presented: in this field, there is a host of diverse approaches, tools, languages, notations, nomenclature ... and results. Nonetheless, there has been progress, and consensus in some topics has been achieved. This consensus is also well reflected in the following chapters, as the reader will soon discover. The main disadvantage is of course that the presentation is not fully unified, and that notation and nomenclature are occasionally divergent. In particular, terms such as "tunneling," "traversal," "delay," or "arrival" times are used in different ways in different chapters.

Finally, we would like to acknowledge our coworkers D. Alonso, A.D. Baute, S. Brouard, M. Buttiker, J.A. Damborenea, V. Delgado, C.R. Leavens, D. Macías, J.P. Palao, A. Pérez, D. Sokolovski, R.F. Snider, and G.W. Wei for all their support in timing quantum mechanics and for so many good times

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Contents