Preface

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 the 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 with them. We are also indebted to the funding agencies of the

TQM workshop series: Universidad de La Laguna, Ministerio de Educación y Cultura, Ministerio de Ciencia y Tecnología, European Union (through the Canadian–European Research Initiative on Nanostructures, CERION), and the Basque Government.

Bilbao - La Laguna,
August 2001

J. Gonzalo Muga
Rafael Sala Mayato
Iñigo L. Egusquiza

List of Contributors

Y. Aharonov
Tel Aviv University
School of Physics and Astronomy
Raymond and Beverley Sackler
Faculty of Exact Sciences
Tel Aviv 69978, Israel
beatriz@post.tau.ac.il

D. Alonso
Universidad de La Laguna
Departamento de Física Fundamental y Experimental
La Laguna, Tenerife, Spain
dalonso@ull.es

A. D. Baute
Universidad del País Vasco
Departamentos de Química Física y Física Teórica e Historia de la Ciencia; Apdo. 644
Bilbao 48080, Spain
wtbbacua@lg.ehu.es

P. Busch
University of Hull
Department of Mathematics Hull, UK
P.Busch@maths.hull.ac.uk

M. Buttiker
Université de Genève/Département de physique théorique
24 Quay Ernest-Ansermet
1211 Genève, Switzerland
buttiker@karystos.unige.ch

I. L. Egusquiza
University of the Basque Country
Department of Theoretical Physics and History of Science
48080 Bilbao, Spain
wtpegegi@lg.ehu.es

J. J. Halliwell
Imperial College
Blackett Laboratory
London SW7 2BZ, UK
j.halliwell@ic.ac.uk

C. R. Leavens
NRC
Institute for Microstructural Science
National Research Council of Canada
Ottawa, Canada K1A OR6
crl@cm8.phy.nrc.ca

J. G. Muga
Universidad del País Vasco
Departamento de Química-Física
Apdo. 644
Bilbao 48080, Spain
qfpmufrj@lg.ehu.es

D. Mugnai
Istituto di Ricerca sulle Onde Elettromagnetiche "Nello Carrara"
CNR; Via Panciatichi 64
50127 Firenze, Italy
mugnai@iroe.fi.cnr.it

A. Ranfagni
Istituto di Ricerca sulle Onde Elettromagnetiche "Nello Carrara"
CNR; Via Panciatichi 64
50127 Firenze, Italy
ranfagni@iroe.fi.cnr.it

R. Sala Mayato
Universidad de La Laguna
Departamento de Física Fundamental II
La Laguna, Spain
rsala@@ull.es

L. S. Schulman
Clarkson University
Physics Department
Potsdam, NY 13699-5820, USA
schulman@clarkson.edu

D. Sokolovski
Queen's University of Belfast
Computational Physics Research Division
Department of Applied Mathematics and Theoretical Physics
Belfast, BT7 1NN, UK
d.sokolovski@am.qub.ac.uk

A. Steinberg
University of Toronto
Department of Physics
Toronto, Ontario, Canada M5S 1A7
aephraim@physics.utoronto.ca

L. Vaidman
Tel Aviv University
School of Physics and Astronomy
Raymond and Beverley Sackler Faculty of Exact Sciences
Tel Aviv 69978, Israel
vaidman@post.tau.ac.il