

Lecture Notes in Physics

Founding Editors: W. Beiglöck, J. Ehlers, K. Hepp, H. Weidenmüller

Editorial Board

R. Beig, Vienna, Austria
W. Beiglöck, Heidelberg, Germany
W. Domcke, Garching, Germany
B.-G. Englert, Singapore
U. Frisch, Nice, France
F. Guinea, Madrid, Spain
P. Hänggi, Augsburg, Germany
W. Hillebrandt, Garching, Germany
R. L. Jaffe, Cambridge, MA, USA
W. Janke, Leipzig, Germany
H. v. Löhneysen, Karlsruhe, Germany
M. Mangano, Geneva, Switzerland
J.-M. Raimond, Paris, France
D. Sornette, Zurich, Switzerland
S. Theisen, Potsdam, Germany
D. Vollhardt, Augsburg, Germany
W. Weise, Garching, Germany
J. Zittartz, Köln, Germany

The Lecture Notes in Physics

The series Lecture Notes in Physics (LNP), founded in 1969, reports new developments in physics research and teaching – quickly and informally, but with a high quality and the explicit aim to summarize and communicate current knowledge in an accessible way. Books published in this series are conceived as bridging material between advanced graduate textbooks and the forefront of research and to serve three purposes:

- to be a compact and modern up-to-date source of reference on a well-defined topic
- to serve as an accessible introduction to the field to postgraduate students and nonspecialist researchers from related areas
- to be a source of advanced teaching material for specialized seminars, courses and schools

Both monographs and multi-author volumes will be considered for publication. Edited volumes should, however, consist of a very limited number of contributions only. Proceedings will not be considered for LNP.

Volumes published in LNP are disseminated both in print and in electronic formats, the electronic archive being available at springerlink.com. The series content is indexed, abstracted and referenced by many abstracting and information services, bibliographic networks, subscription agencies, library networks, and consortia.

Proposals should be sent to a member of the Editorial Board, or directly to the managing editor at Springer:

Christian Caron
Springer Heidelberg
Physics Editorial Department I
Tiergartenstrasse 17
69121 Heidelberg / Germany
christian.caron@springer.com

J.G. Muga
A. Ruschhaupt
A. del Campo (Eds.)

Time in Quantum Mechanics - Vol. 2

 Springer

Editors

J. Gonzalo Muga
Universidad Pais Vasco
Depto. Quimica Fisica EHU
Apartado, 644
48080 Bilbao
Spain
jg.muga@ehu.es

Andreas Ruschhaupt
TU Braunschweig
Inst. Mathematische Physik
Mendelssohnstr. 3
38106 Braunschweig
Germany
a.ruschhaupt@tu-bs.de

Adolfo del Campo
Imperial College London
Inst. Mathematical Sciences
53 Prince's Gate
London
United Kingdom SW7 2PG
a.del-campo@imperial.ac.uk

Muga J.G., Ruschhaupt A., del Campo A. (Eds.), *Time in Quantum Mechanics - Vol. 2*,
Lect. Notes Phys. 789 (Springer, Berlin Heidelberg 2009),
DOI 10.1007/978-3-642-03174-8

Lecture Notes in Physics ISSN 0075-8450 e-ISSN 1616-6361
ISBN 978-3-642-03173-1 e-ISBN 978-3-642-03174-8
DOI 10.1007/978-3-642-03174-8
Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2009935461

© Springer-Verlag Berlin Heidelberg 2009

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Cover design: Integra Software Services Pvt. Ltd., Pondicherry

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

*But all the clocks in the city
Began to whirr and chime:
'O let not Time deceive you,
You cannot conquer Time.*

W. H. Auden

It is hard to think of a subject as rich, complex, and important as time. From the practical point of view it governs and organizes our lives (most of us are after all attached to a wrist watch) or it helps us to wonderfully find our way in unknown territory with the global positioning system (GPS). More generally it constitutes the heartbeat of modern technology. Time is the most precisely measured quantity, so the second defines the meter or the volt and yet, nobody knows for sure what it is, puzzling philosophers, artists, priests, and scientists for centuries as one of the enduring enigmas of all cultures. Indeed time is full of contrasts: taken for granted in daily life, it requires sophisticated experimental and theoretical treatments to be accurately “produced.” We are trapped in its web, and it actually kills us all, but it also constitutes the stuff we need to progress and realize our objectives. There is nothing more boring and monotonous than the tick-tock of a clock, but how many fascinating challenges have physicists met to realize that monotony: Quite a number of Nobel Prize winners have been directly motivated by them or have contributed significantly to time measurement.¹ We feel that time flows, we feel it as an ever evolving, restless “now”, and yet, from the perspective of relativity this unfolding of events at an always renewing present instant would in fact be “an illusion.” Also, while the future awaits us and the past is gone, there is no time arrow making such a fundamental distinction in the microscopic equations of physics.

Physics does not capture time in its domain without residue, but it has of course much to say about time, an essential element of its theories and of our rationalization of nature. In the case of relativity, time plays a prominent, starring role:

¹ Here is a nonexhaustive list including award years: Isidor I. Rabi (1944), Charles H. Townes (1964), Alfred Kastler (1966), Norman F. Ramsey, Hans G. Dehmelt and Wolfgang Paul (1989), Steven Chu, Claude Cohen Tannoudji, and William D. Phillips (1997), John L. Hall and Theodor W. Hänsch (2005).

Einstein changed dramatically our concept of time and thus of the world. By contrast, quantum mechanics, the other great twentieth century physical theory, has paid to time a much more modest and secondary attention, and most practitioners have even refused with stubborn determination to deal with some of its evident aspects, the “time observables,” in our opinion without a good or sufficient reason. Less controversial but not at all less interesting and much influential have been the fundamental contribution of quantum mechanics to improve time measurement with atomic clocks, as well as the development of techniques to study quantum dynamics and characteristic timescales, both at theoretical and experimental levels, complementary to the knowledge on the structure and properties of matter derived from time-independent methods.

The aim of a workshop series at La Laguna, Spain, since the first edition in 1994, and of this book series is to promote and contribute to a more intense interplay between time and the quantum world. This volume fills some of the gaps left by the first one, recently re-edited. It begins with a historical review in Chap. 1. Most chapters orbit around fundamental concepts and time observables (Chaps. 2–6), or quantum dynamical effects and characteristic times (Chaps. 7–12). The book ends with a review on atomic clocks in Chap. 13. Several authors have participated in “Time in Quantum Mechanics” workshops at La Laguna or Bilbao, but we have not imposed this as a necessary condition. As in the first volume, our recommendation to all authors has been to write reviews that may serve both as an introductory guide for the noninitiated and a useful tool for the expert, leaving them full freedom for the choice of emphasis and presentation.

We would like to acknowledge the work, patience, and discipline of all contributors, as well as the support of the University of the Basque Country (UPV-EHU), Ministerio de Ciencia e Innovación (Spain), EU Integrated Project QAP, EPSRC QIP-IRC, German Research Foundation (DFG), and the Max Planck Institute for Complex Systems at Dresden, where much of our work was completed within the “Advanced Study Group” “Time: quantum and statistical mechanics aspects” organized by L. S. Schulman during the summer of 2008.

Bilbao, Braunschweig, London, *J.G. Muga, A. Ruschhaupt, and A. del Campo*
January 2009

Contents

1	Memories of Old Times: Schlick and Reichenbach on Time in Quantum Mechanics	1
	José M. Sánchez-Ron	
1.1	Introduction: The New Physics, via Relativity, Attracts the Philosophers	1
1.2	Time in Quantum Physics: The Time–Energy Uncertainty Relation	3
1.3	Schlick on Quantum Theory	7
1.4	Reichenbach on Time in Quantum Physics	8
1.5	Reichenbach on Feynman’s Theory of the Positron	10
1.6	Epilogue	11
	References	12
2	The Time-Dependent Schrödinger Equation Revisited: Quantum Optical and Classical Maxwell Routes to Schrödinger’s Wave Equation	15
	Marlan O. Scully	
2.1	Introduction	15
2.2	The Quantum Optical Route to the Time-Dependent Schrödinger Equation	16
2.3	The Classical Maxwell Route to the Schrödinger Equation	19
2.4	The Single Photon and Two Photon Wave Functions	21
2.5	Conclusions	22
	References	23
3	Post-Pauli’s Theorem Emerging Perspective on Time in Quantum Mechanics	25
	Eric A. Galapon	
3.1	Introduction	25
3.2	Quantum Canonical Pairs	27
3.3	Time of Arrival Operators	33
3.4	Confined Time of Arrival Operators	44

3.5	Conjugacy of the Confined Time of Arrival Operators	46
3.6	Dynamics of the Eigenfunction of the Confined Time of Arrival Operators	52
3.7	Dynamical Behaviors in the Limit of Large Confining Lengths and the Appearance of Particle	55
3.8	Quantum Time of Arrival Distribution	58
3.9	Conclusion	61
	References	62
4	Detector Models for the Quantum Time of Arrival	65
	Andreas Ruschhaupt, J. Gonzalo Muga, and Gerhard C. Hegerfeldt	
4.1	The Time of Arrival in Quantum Mechanics	65
4.2	The Basic Atom-Laser Model	70
4.3	Complex Potentials	76
4.4	Quantum Arrival Times and Operator Normalization	82
4.5	Kinetic Energy Densities	87
4.6	Disclosing Hidden Information Behind the Quantum Zeno Effect: Pulsed Measurement of the Quantum Time of Arrival	89
4.7	Summary	93
	References	94
5	Dwell-Time Distributions in Quantum Mechanics	97
	José Muñoz, Iñigo L. Egusquiza, Adolfo del Campo, Dirk Seidel, and J. Gonzalo Muga	
5.1	Introduction	97
5.2	The Dwell-Time Operator	99
5.3	The Free Particle Case	102
5.4	The Scattering Case	106
5.5	Some Extensions	111
5.6	Relation to Flux–Flux Correlation Functions	115
5.7	Final Comments	123
	References	124
6	The Quantum Jump Approach and Some of Its Applications	127
	Gerhard C. Hegerfeldt	
6.1	Introduction	127
6.2	Repeated Measurements on a Single System: Conditional Time Development, Reset Operation, and Quantum Trajectories	129
6.3	Application: Macroscopic Light and Dark Periods	141
6.4	The General N -Level System and Optical Bloch Equations	145
6.5	Quantum Counting Processes	150
6.6	How to Replace Density Matrices by Pure States in Simulations	154
6.7	Inclusion of Center-of-Mass Motion and Recoil	161

6.8	Extension to Spin-Boson Models	165
6.9	Discussion	170
	References	173
7	Causality in Superluminal Pulse Propagation	175
	Robert W. Boyd, Daniel J. Gauthier, and Paul Narum	
7.1	Introduction	175
7.2	Descriptions of the Velocity of Light Pulses	176
7.3	History of Research on Slow and Fast Light	178
7.4	The Concept of Simultaneity	185
7.5	Causality and Superluminal Pulse Propagation	187
7.6	Quantum Mechanical Aspects of Causality and Fast Light	191
7.7	Numerical Studies of Propagation Through Fast-Light Media	194
7.8	Summary	202
	References	202
8	Experiments on Quantum Transport of Ultra-Cold Atoms in Optical Potentials	205
	Martin C. Fischer and Mark G. Raizen	
8.1	Introduction	205
8.2	Experimental Apparatus	211
8.3	Details of the Interaction	212
8.4	Quantum Transport	213
8.5	Quantum Tunneling	225
8.6	Conclusions	236
	References	236
9	Quantum Post-exponential Decay	239
	Joan Martorell, J. Gonzalo Muga, and Donald W.L. Sprung	
9.1	Introduction	239
9.2	Simple Models and Examples	247
9.3	Three-Dimensional Models of a Particle Escaping from a Confining Potential	252
9.4	Physical Interpretation of Post-exponential Decay	258
9.5	Toward Experimental Observation	261
9.6	Final Comments	271
	References	272
10	Timescales in Quantum Open Systems: Dynamics of Time Correlation Functions and Stochastic Quantum Trajectory Methods in Non-Markovian Systems	277
	Daniel Alonso and Inés de Vega	
10.1	Introduction	277
10.2	Atoms in a Structured Environment, an Example of Non-Markovian Interaction	278

10.3	Two Complementary Descriptions of the Dynamics of a Quantum Open System	279
10.4	Dynamics of Multiple Time Correlation Functions	284
10.5	Examples	291
10.6	Discussion and Conclusions	298
	References	299
11	Double-Slit Experiments in the Time Domain	303
	Gerhard G. Paulus and Dieter Bauer	
11.1	Introduction	303
11.2	Wave Packet Interference in Position and Momentum Space	304
11.3	Time-Domain Double-Slit Experiments	313
11.4	Strong-Field Approximation and Interfering Quantum Trajectories	325
	References	337
12	Optimal Time Evolution for Hermitian and Non- Hermitian Hamiltonians	341
	Carl M. Bender and Dorje C. Brody	
12.1	Introduction	341
12.2	PT Quantum Mechanics	342
12.3	Complex Classical Motion	346
12.4	Hermitian Quantum Brachistochrone	347
12.5	Non-Hermitian Quantum Brachistochrone	354
12.6	Extension of Non-Hermitian Hamiltonians to Higher- Dimensional Hermitian Hamiltonians	358
	References	360
13	Atomic Clocks	363
	Robert Wynands	
13.1	Introduction	363
13.2	Why We Need Clocks at All	364
13.3	What Is a Clock?	368
13.4	How an Atomic Clock Works	369
13.5	The “Classic” Caesium Clock	372
13.6	The Ramsey Technique	375
13.7	Atomic Fountain Clocks	379
13.8	Other Types of Atomic Clocks	396
13.9	Optical Clocks	402
13.10	The Future (Maybe)	407
13.11	Precision Tests of Fundamental Theories	409
13.12	Conclusion	412
	References	412
	Index	419