The Emerging Quantum

Luis de la Peña · Ana María Cetto
Andrea Valdés Hernández

The Emerging Quantum

The Physics Behind Quantum Mechanics

Luis de la Peña
Instituto de Física
Universidad Nacional Autónoma
de México
Mexico, D.F.
Mexico

Andrea Valdés Hernández
Instituto de Física
Universidad Nacional Autónoma
de México
Mexico, D.F.
Mexico

Ana María Cetto
Instituto de Física
Universidad Nacional Autónoma
de México
Mexico, D.F.
Mexico

ISBN 978-3-319-07892-2 ISBN 978-3-319-07893-9 (eBook)

DOI 10.1007/978-3-319-07893-9

Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014941916

© Springer International Publishing Switzerland 2015

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law. The use of general descriptive names, registered names, trademarks, service marks, 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.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

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

Preface

Fifty years ago—in 1963, to be precise—the British physicist Trevor Marshall published a paper in the *Proceedings of the Royal Society* under the short title *Random Electrodynamics*—an intriguing title, at that time. To date this paper has received just over four citations per year, which means it is alive, but not as present as it could be, considering the perspectives it opened for theoretical physics. Shortly thereafter a related paper was published by a young US physicist, Timothy Boyer, under the longer title *Quantum Electromagnetic Zero-Point Energy and Retarded Dispersion Forces*. Boyer does not cite Marshall’s paper (although he does so in his third paper, which is followed by a productive 50-year long work in solitary), but instead he refers to the work of David Kershaw and Edward Nelson on stochastic quantum mechanics. All these papers share a central feature: they are based on conceiving quantum mechanics as a stochastic process. Marshall mentions explicitly the existence of a real, space-filling radiation zero-point field as the source of stochasticity. Boyer sees a deep truth in this, and in a note added to his manuscript he comments that “...in this sense, quantum motions are experimental evidence for zero-point radiation.”

From a historical perspective, we recall that nearly 50 years earlier—in 1916, to be precise—Nernst had proposed to consider atomic stability as experimental evidence for Planck’s recently discovered zero-point radiation. This visionary idea was largely ignored by the founders of quantum mechanics, the only (brief) exception being the Einstein and Stern paper of 1913; such is history. Both Marshall and Boyer succeed in demonstrating that some quantum phenomena can indeed be understood by the simple expedient of adding this random zero-point field to the corresponding classical description. Their pioneering work was soon followed by that of other colleagues, moved by the conviction that the random zero-point field has something important to tell us about quantum mechanics. Many other results have been obtained during this period, which constitute the essence of the theory largely known under the name of *stochastic electrodynamics*. At the same time, other researchers, notably Nelson, dedicated their efforts to develop the phenomenological stochastic theory of quantum mechanics. The perception that quantumness and stochasticity are but two different aspects of a reality, started to gain support from several sides.

So here we are, 50 years later. In the mean time, quantum mechanics has continued to develop; the new applications derived from it only serve to reaffirm it

as a powerful theory. Along with its success, however, comes an increasing recognition that its old foundational problems have not found convincing solution. Recall the birth of quantum theory: Bohr's model of the hydrogen atom was supported on a postulate that implied a fundamental violation of electrodynamics. Truly, such postulate was necessary at its moment, but urgent necessity does not restore physical consistency. Then came the mysterious matrix mechanics, and the no less mysterious de Broglie wavelength. Such obscure premises served as foundations for the interpretative apparatus of quantum theory. And obscurity and vagueness followed, along with a formidable mathematical apparatus. From this perspective, one easily concludes that better supporting and supported principles are required. More recent efforts from a number of authors attest to the conviction that quantum mechanics, and more generally quantum theory, is in need of an alternative that helps to explain the underlying physics and to solve the conundrums that have puzzled many a physicist, from de Broglie and Schrödinger to Einstein and Bell, among many others. Common to most of the recent efforts in search of an alternative is precisely the idea that the quantum description emerges from a deeper level.

Quantum mechanics constitutes usually both, the point of departure and the final reference, for all inquiries about the meaning of the theory itself. Its conceptual problems are therefore looked at from inside, which provides limited space for rationalization, and even in some instances creates a kind of circular reasoning of scant utility, as is amply testified by the unending discussions on these matters. Experience evinces that an external and wider approach is indeed required to grasp the meaning of quantum theory and get a clear, physically understandable, and preferably objective, realistic, causal, local picture of the portion of the world that it scrutinizes.

The main purpose of this book is to show that such alternative exists, and that it is tightly linked to the stochastic zero-point radiation field. This is a fluctuating field, solution of the classical Maxwell equations, yet by having a nonzero mean energy at zero temperature it is foreign to classical physics. The fundamental hypothesis of the theory here developed is that any material system is an open system permanently shaken by this field; the ensuing interaction turns out to be ultimately responsible for quantization. In other words, rather than being an intrinsic property of matter and the (photonic) radiation field, quantization emerges from a deeper stochastic process. A physically coherent way to understand quantum mechanics and go beyond it is thus offered, confirming the notion of emergence—the coming forth of properties of a compound system, which no one of its parts possesses.

The theory here presented has been developed along the years in an effort to find answers to some of the most relevant conceptual puzzles of quantum mechanics, by providing a physical foundation for it. It is thus not one more interpretation of quantum mechanics, but constitutes a comprehensive and self-consistent theoretical framework, based on well-defined first principles in line with a realistic viewpoint of Nature. There is neither the opportunity nor the need to

resort to ad hoc tenets or philosophical considerations, to assign physical meaning to the elements of the theory and interpret its results.

As the formalism of quantum mechanics is successfully reproduced, some may argue about the value of redoing what is already well known. However, the usual theory, with its interpretations included, seems to tell us more about our knowledge and our way of thinking about Nature, than about Nature itself. A good part of what really happens out there remains hidden, waiting to be disclosed. With this volume, our intention is to contribute to this disclosure and to share the fascinating experience of discovering some of the quantum mysteries and intricacies along the process. Moreover, a door is opened to further explorations that may unravel new physics. As the reader will appreciate, this chapter is not closed; there is much that remains unexamined, awaiting future investigations.

This book has been prepared for an audience that is conversant with at least the most basic ideas and results of quantum mechanics. More specifically, it is intended to address those readers who (either secretly or openly) seek a remedy to the apocalyptic statement by Feynman, that “nobody understands quantum mechanics.” Its contents should be of value to researchers, graduate students and teachers of theoretical, mathematical and experimental physics, quantum chemistry, foundations and philosophy of physics, as well as other scholars interested in the foundations of modern physics.

Throughout this volume, frequent reference is made to *The Quantum Dice. An Introduction to Stochastic Electrodynamics (The Dice)*, a precursor containing many ideas and results that have survived the test of time and others that have been superseded or improved here. *The Dice* and the present book differ in at least two central aspects. First, the version of stochastic electrodynamics discussed in the former was essentially limited to linear problems and failed to properly address the more general nonlinear case; this limitation is successfully lifted in the present book. Secondly, in addition to applying the Fokker-Planck method (already contained in *The Dice*) with success, particularly in Chaps. 4 and 6, new procedures are developed and crucial physical demands (as e.g., the balance of energy, and ergodicity) are identified, which converge into a theoretical framework that is clearer, richer and more unified than the former one. Further to facilitating a smooth and fruitful incursion into the territories of quantum mechanics and quantum electrodynamics, the new developments result in an expansion of the aims of the theory, for example by including the study of composite systems or by opening the door to future analysis of the system before the attainment of the quantum regime.

In addition to the bibliography at the end of the chapters, a list of suggested references (not cited in the chapters) appears at the end of the volume. In the bibliography, the items marked * refer to stochastic electrodynamics (some of them including stochastic optics) and those marked ** are general or topical reviews on stochastic electrodynamics; papers marked ‡ are overtly critical about stochastic (quantum) mechanics; those marked ‡‡ contribute to the development of that theory, but may express some important criticism about it. Some few abbreviations are used in the text, all of them easy to spell out: QM, QED, SED,

LSED, ZPF, FPE, GFPE for quantum mechanics, quantum electrodynamics, stochastic electrodynamics, linear stochastic electrodynamics, zero-point field, Fokker-Planck equation, and generalized Fokker-Planck equation, respectively. In Chap. 1—and occasionally elsewhere—CI and EI are used for the Copenhagen and ensemble interpretations of quantum mechanics, respectively.

The authors acknowledge numerous valuable observations and suggestions received during the elaboration of the manuscript. We are particularly grateful to Pier Mello, Theo Nieuwenhuizen, Vaclav Spika, and Gerhard Grössing for their support and critical comments. Draft versions of the various chapters were shared with some of our students; special thanks go to David Theurel and Eleazar Bello for their useful comments. Further, we wish to thank the Dirección General de Asuntos del Personal Académico (UNAM) and its Director General, Dante Morán, for the support received for the preparation of this volume, under contracts Numbers IN106412 and IN112714. A special word of appreciation goes to Alwyn van der Merwe for his relentless support as editor of the Springer series, and to the reviewers of Springer for their valuable comments and suggestions. Our thanks go also to Aldo Rampioni, Kirsten Theunissen and the Springer staff for their support and attentions. Finally, we wish to acknowledge the facilities provided to us throughout the years by the Instituto de Física, UNAM.

Mexico, March 2014

Luis de la Peña
Ana María Cetto
Andrea Valdés Hernández

Contents

1	Quantum Mechanics: Some Questions	1
1.1	On Being Principled... At Least on Sundays	1
1.1.1	The Sins of Quantum Mechanics	5
1.2	The Two Basic Readings of the Quantum Formalism	9
1.2.1	The Need for an Interpretation	9
1.2.2	A Single System, or an Ensemble of Them?	10
1.3	Is Realism Still Alive?	11
1.4	What is this Book About?	19
1.4.1	The Underlying Hypothesis	19
1.4.2	The System Under Investigation	20
	References	25
2	The Phenomenological Stochastic Approach: A Short Route to Quantum Mechanics	33
2.1	Why a Phenomenological Approach to Quantum Mechanics?	33
2.2	The Stochastic Description of Quantum Mechanics	34
2.3	Stochastic Quantum Mechanics	36
2.3.1	Kinematics	36
2.3.2	Spatial Probability Density and Diffusive Velocity	41
2.3.3	Dynamics	43
2.3.4	Integrating the Equation of Motion	46
2.3.5	Quantum and Classical Stochastic Processes	49
2.4	On Schrödinger-Like Equations	51
2.5	Stochastic Quantum Trajectories	55
2.5.1	Wavelike Patterns	56
2.6	Extensions of the Theory, Some Brief Comments, and Assessment	57
2.6.1	A Summing Up	61
	References	61

3	The Planck Distribution, a Necessary Consequence of the Fluctuating Zero-Point Field	67
3.1	Thermodynamics of the Harmonic Oscillator	67
3.1.1	Unfolding the Zero-Point Energy	70
3.2	General Thermodynamic Equilibrium Distribution	71
3.2.1	Thermal Fluctuations of the Energy	72
3.2.2	Some Consequences of the Recurrence Relation.	74
3.3	Planck's Law from the Thermostatistics of the Harmonic Oscillator.	75
3.3.1	General Statistical Equilibrium Distribution.	75
3.3.2	Mean Energy as Function of Temperature; Planck's Formula	77
3.4	Planck, Einstein and the Zero-Point Energy.	79
3.4.1	Comments on Planck's Original Analysis	79
3.4.2	Einstein's Revolutionary Step	81
3.4.3	Disclosing the Zero-Point Field	82
3.5	Continuous Versus Discrete	83
3.5.1	The Partition Function	83
3.5.2	The Origin of Discreteness	84
3.6	A Quantum Statistical Distribution	86
3.6.1	Total Energy Fluctuations	86
3.6.2	Quantum Fluctuations and Zero-Point Fluctuations.	87
3.6.3	Comments on the Reality of the Zero-Point Fluctuations	89
	References	90
4	The Long Journey to the Schrödinger Equation	95
4.1	Elements of the Dynamics	96
4.1.1	The Equation of Motion	96
4.1.2	Basic Properties of the Zero-Point Field	97
4.2	Generalized Fokker-Planck Equation in Phase Space	99
4.2.1	Some Important Relations for Average Values.	102
4.3	Transition to Configuration Space	106
4.3.1	A Digression: Transition to Momentum Space.	108
4.3.2	A Hierarchy of Coupled Transfer Equations	108
4.4	The Schrödinger Equation	111
4.4.1	The Radiationless Approximation.	111
4.4.2	Statistical and Quantum Averages	115
4.4.3	Stationary Schrödinger Equation.	117
4.4.4	Detailed Energy Balance: The Entry Point for Planck's Constant	118
4.4.5	Schrödinger's i	121

4.5	Further Insights into the Quantum Description	122
4.5.1	Fluctuations of the Momentum.	123
4.5.2	Local Velocities: ‘Hidden’ Information Contained in ψ	124
4.5.3	A Comment on Operator Ordering	126
4.5.4	Trapped Motions	127
4.5.5	‘Schrödinger’ Equation for a Classical System?	129
4.6	Phase-Space Distribution and the Wigner Function.	131
4.7	What We Have Learned So Far About Quantum Mechanics	132
	References	146
5	The Road to Heisenberg Quantum Mechanics	151
5.1	The Same System: A Fresh Approach.	151
5.1.1	Description of the Mechanical Subsystem	152
5.1.2	Resonant Solutions in the Stationary Regime.	154
5.2	The Principle of Ergodicity	159
5.2.1	The Chain Rule	163
5.2.2	Matrix Algebra.	165
5.3	Physical Consequences of the Ergodic Principle.	168
5.3.1	Establishing Contact with Quantum Theory.	168
5.3.2	The Radiationless Approximation.	169
5.3.3	The Canonical Commutator $[\hat{x}, \hat{p}]$	172
5.4	The Heisenberg Description.	176
5.4.1	Heisenberg Equation, Representations, and Quantum Transitions.	176
5.4.2	The Hilbert-Space Description and State Vectors . . .	178
5.4.3	Transition to the Schrödinger Equation	179
5.4.4	The Stochastic Representation	182
5.5	Concluding Remarks.	183
	References	192
6	Beyond the Schrödinger Equation	195
6.1	Radiative Corrections. Contact with QED	196
6.1.1	Radiative Transitions	197
6.1.2	Breakdown of Energy Balance	199
6.1.3	Atomic Lifetimes: Einstein’s A and B Coefficients . .	201
6.1.4	A More General Equation for the Balance Breakdown	204
6.1.5	Radiative Corrections to the Energy: The Lamb Shift	207
6.1.6	External Effects on the Radiative Corrections	212

6.2	The Spin of the Electron	215
6.2.1	Unravelling the Spin	216
6.2.2	The Isotropic Harmonic Oscillator	218
6.2.3	General Derivation of the Electron Spin	221
6.2.4	Angular Momentum of the Zero-Point Field	224
6.2.5	Gyromagnetic Factor for the Electron	226
6.3	Concluding Comments	228
	References	223
7	Disentangling Quantum Entanglement.	237
7.1	The Two-Particle System.	238
7.1.1	The Field in the Vicinity of the Particles.	238
7.1.2	Looking for Stationary Solutions	240
7.1.3	The Common Random Variable	242
7.1.4	Establishing Contact with the Tensor Product Hilbert Space	244
7.1.5	Implications of Ergodicity for the Common Random Field Variable	246
7.2	Correlations Due to Common Resonance Modes	248
7.2.1	Spectral Decomposition.	248
7.2.2	State Expansion Versus Energy Expansion	250
7.2.3	State Vectors: Emergence of Entanglement	250
7.2.4	Entanglement as a Vestige of the ZPF	252
7.2.5	Emergence of Correlations.	253
7.3	Systems of Identical Particles.	256
7.3.1	Natural Entanglement	256
7.3.2	The Origin of Totally (Anti)symmetric States	257
7.3.3	Comments on Particle Exchange	258
7.4	Spin-Symmetry Relations	259
7.4.1	Two Electrons in the Singlet State	260
7.4.2	The Helium Atom	261
7.5	Final Comments	263
	References	264
8	Causality, Nonlocality, and Entanglement in Quantum Mechanics	267
8.1	Causality at Stake.	267
8.1.1	Von Neumann's Theorem	268
8.1.2	Bohm's Counterexample	270
8.2	Essentials of the de Broglie-Bohm Theory.	272
8.2.1	The Guiding Field	272
8.2.2	Quantum Trajectories	275
8.2.3	The Measurement Task in the Pilot Theory	280

8.3	The Quantum Potential	282
8.3.1	Linearity and Nonlocality	283
8.3.2	Linearity and Fluctuations	285
8.3.3	The Quantum Potential as a Kinetic Term.	287
8.4	Nonlocality in Bipartite Systems	290
8.4.1	Nonlocality and Entanglement	293
8.4.2	Momentum Correlations	296
8.4.3	The Whole and the Parts	298
8.4.4	Nonlocality and Noncommutativity.	299
8.5	Final Remarks	303
	References	304
9	The Zero-Point Field Waves (and) Matter.	309
9.1	Genesis of de Broglie's Wave	310
9.1.1	The de Broglie 'Clock'	311
9.1.2	Energy, Frequency and Matter Waves.	313
9.1.3	The de Broglie Wave	315
9.2	An Exercise on Quantization à la de Broglie	317
9.3	Undulatory Properties of Matter	320
9.4	Cosmological Origin of Planck's Constant.	323
	References	329
10	Quantum Mechanics: Some Answers.	331
10.1	The Genetic Gist of the Zero-Point Field.	331
10.1.1	Origin of Quantization	334
10.1.2	Recovering Realistic Images	335
10.2	Some Answers	336
10.3	The Photon	338
10.4	Limitations and Extensions of the Theory	341
	References	344
	Suggested Literature	347
	Index	355