### COLLAPSE OF THE WAVE FUNCTION Models, Ontology, Origin, and Implications

This is the first single volume about the collapse theories of quantum mechanics, which is becoming a very active field of research in both physics and philosophy. In standard quantum mechanics, it is postulated that when a quantum system is measured, its wave function no longer follows the Schrödinger equation but instantaneously and randomly collapses to one of the wave functions that correspond to definite measurement results. However, why and how a definite measurement result appears is unknown. A promising solution to this problem is collapse theories, in which the collapse of the wave function is spontaneous and dynamical. Chapters written by distinguished physicists and philosophers of physics discuss the origin and implications of wave-function collapse, the controversies around collapse models and their ontologies, and new arguments for the reality of wave-function collapse. This is an invaluable resource for students and researchers interested in the philosophy of physics and foundations of quantum mechanics.

SHAN GAO is Professor of Philosophy at the Research Center for Philosophy of Science and Technology at Shanxi University. He is the founder and managing editor of the *International Journal of Quantum Foundations* and is the author of several books, including the recent monograph *The Meaning of the Wave Function: In Search of the Ontology of Quantum Mechanics* (Cambridge University Press, 2017). His research focuses on the philosophy of physics and foundations of quantum mechanics. He is also interested in the philosophy of mind and the philosophy of science.

# COLLAPSE OF THE WAVE FUNCTION

Models, Ontology, Origin, and Implications

Edited by

SHAN GAO Shanxi University





Shaftesbury Road, Cambridge CB2 8EA, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314-321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi - 110025, India

103 Penang Road, #05-06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment, a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org Information on this title: www.cambridge.org/9781108428989

DOI: 10.1017/9781316995457

© Cambridge University Press & Assessment 2018

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press & Assessment.

First published 2018

A catalogue record for this publication is available from the British Library

ISBN 978-1-108-42898-9 Hardback

Cambridge University Press & Assessment has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

### Contents

	List of Contributors Preface	<i>page</i> vii ix
	Part I Models	1
1	How to Teach and Think About Spontaneous Wave Function Collapse Theories: Not Like Before LAJOS DIÓSI	3
2	What Really Matters in Hilbert-Space Stochastic Processes GIANCARLO GHIRARDI, ORESTE NICROSINI, AND ALBERTO RIMINI	12
3	Dynamical Collapse for Photons PHILIP PEARLE	23
4	Quantum State Reduction DORJE C. BRODY AND LANE P. HUGHSTON	47
5	Collapse Models and Space-time Symmetries DANIEL J. BEDINGHAM	74
	Part II Ontology	95
6	Ontology for Collapse Theories WAYNE C. MYRVOLD	97
7	Properties and the Born Rule in GRW Theory ROMAN FRIGG	124
8	Paradoxes and Primitive Ontology in Collapse Theories of Quantum Mechanics RODERICH TUMULKA	134

v

vi	Contents	
9	On the Status of Primitive Ontology PETER J. LEWIS	154
10	Collapse or No Collapse? What Is the Best Ontology of Quantum Mechanics in the Primitive Ontology Framework? MICHAEL ESFELD	167
	Part III Origin	185
11	Quantum State Reduction via Gravity, and Possible Tests Using Bose–Einstein Condensates IVETTE FUENTES AND ROGER PENROSE	187
12	Collapse. What Else? NICOLAS GISIN	207
13	Three Arguments for the Reality of Wave-Function Collapse SHAN GAO	225
14	Could Inelastic Interactions Induce Quantum Probabilistic Transitions? NICHOLAS MAXWELL	257
15	How the Schrödinger Equation Would Predict Collapse: An Explicit Mechanism ROLAND OMNÈS	274
	Part IV Implications	293
16	Wave-Function Collapse, Non-locality, and Space-time Structure TEJINDER P. SINGH	295
17	The Weight of Collapse: Dynamical Reduction Models in General Relativistic Contexts ELIAS OKON AND DANIEL SUDARSKY	312
	Index	346

## Contributors

**Daniel J. Bedingham** Royal Holloway, University of London

**Dorje C. Brody** Brunel University London and St Petersburg National Research University of Information Technologies, Mechanics and Optics

Lajos Diósi Wigner Research Center for Physics

Michael Esfeld University of Lausanne

**Roman Frigg** London School of Economics and Political Science

**Ivette Fuentes** University of Nottingham and University of Vienna

Shan Gao Shanxi University

**Nicolas Gisin** University of Geneva

Lane P. Hughston Brunel University London

vii

viii

List of Contributors

**GianCarlo Ghirardi** University of Trieste and Abdus Salam International Centre for Theoretical Physics

Peter J. Lewis Dartmouth College

Nicholas Maxwell University College London

Wayne C. Myrvold University of Western Ontario

**Oreste Nicrosini** INFN, Pavia Unit

Elias Okon National Autonomous University of Mexico

Roland Omnès University of Paris XI

Philip Pearle Hamilton College

**Roger Penrose** University of Oxford

**Alberto Rimini (deceased)** University of Pavia

**Tejinder P. Singh** Tata Institute of Fundamental Research

Daniel Sudarsky National Autonomous University of Mexico

Roderich Tumulka Eberhard-Karls University Tübingen

### Preface

In standard quantum mechanics, it is postulated that when a quantum system is measured by a measuring device, its wave function no longer follows the linear Schrödinger equation but instantaneously and randomly collapses to one of the wave functions that correspond to definite measurement results. However, this collapse postulate is ad hoc, and the theory does not tell us why and how a definite measurement result appears. A promising solution to this measurement problem is collapse theories, in which the collapse of the wave function is spontaneous and dynamical, and it is integrated with the Schrödinger evolution into a unified dynamics.

The origin of collapse theories can be traced back to as early as 1952. Shortly after David Bohm suggested his hidden-variable interpretation of quantum mechanics (Bohm, 1952), Lajos Jánossy published a paper titled "The physical aspects of the wave-particle problem," in which he argued for the reality of spontaneous wave-function collapse and also tried to alter quantum mechanics by introducing the so-called damping term into the Schrödinger equation (Jánossy, 1952). Jánossy's collapse model is incomplete in many aspects but it does illustrate the possibility of a dynamical collapse theory. Although Jánossy's work has gone unnoticed by later researchers of collapse theories, it was referred to and discussed by Werner Heisenberg, who regarded it as the "most careful attempt in this direction" (Heisenberg, 1958).

Today, collapse theories, together with Bohm's theory and Everett's theory, are widely considered as three main realistic alternatives to standard quantum mechanics. This book is the first single volume about collapse theories. It is intended not mainly as a comprehensive review of collapse theories<sup>1</sup> but more as an anthology reflecting the latest thoughts of leading experts on the subject. The

<sup>&</sup>lt;sup>1</sup> See Bassi and Ghirardi (2003), Diósi (2005), Pearle (2007, 2009), Bassi et al. (2013), and Ghirardi (2016) for helpful reviews of collapse theories.

CAMBRIDGE

х

Cambridge University Press & Assessment 978-1-108-42898-9 — Collapse of the Wave Function Shan Gao Frontmatter <u>More Information</u>

#### Preface

book is accessible to graduate students in physics. It will be of value to students and researchers with an interest in the philosophy of physics and especially to physicists and philosophers working on the foundations of quantum mechanics.

This book is composed of four parts. The first part is about collapse models. There are (at least) two key issues for collapse models. The first one is the preferred basis problem. It is still unclear what the preferred bases should be in collapse theories. If the preferred bases are smeared position eigenstates, as is commonly believed, then it seems that the theories will inevitably violate the law of conservation of energy. But if the preferred bases are energy eigenstates, then the violation can be readily avoided.<sup>2</sup> In addition, it is still unknown whether a relativistically invariant collapse model can be formulated in a satisfactory way, although the recent progress seems to suggest a positive answer. These two issues, among others, will be addressed in the first part of this book.

The second part of this book concerns the ontology of collapse theories. Since collapse theories are a realistic alternative to standard quantum mechanics, it must have an ontology. Indeed, several ontologies of collapse theories have been proposed, such as mass density ontology, flash ontology, and the recently suggested ontology of RDM (random discontinuous motion) of particles (Gao, 2017). The question, then, is which one the right ontology of collapse theories is. Another issue is whether the ontology for collapse theories may contain only the wave function. Proponents of the primitive ontology approach will give a negative answer to this question, while others may disagree. The key is to understand the physical meaning of the wave function. For example, if the wave function indeed represents a property of particles in three-dimensional space, which is itself a primitive ontology, then the answer to the question may be positive even if assuming the primitive ontology approach. These concerns about the ontology of collapse theories will be addressed and debated in the second part of this book.

The third part of this book is about the physical origin of wave-function collapse. In fact, the first question collapse theories must answer is just this: What causes the (spontaneous) collapse of the wave function? There have been a few suggested answers to this question, a well-known one of which is Penrose's gravity-induced collapse conjecture. In this part, several authors, including Penrose himself, will give further new analysis of the origin of wave-function collapse. The last part of this book concerns the possible implications of collapse theories for our understandings of space-time and cosmology. This part may be more speculative. But if collapse theories are indeed in the right direction to solve the measurement problem, then it will be quite reasonable or even imperative to consider the applications

<sup>&</sup>lt;sup>2</sup> It has been shown that a collapse model with the preferred bases being energy eigenstates can still be consistent with experiments and our experience (Gao, 2013, 2017).

CAMBRIDGE

Cambridge University Press & Assessment 978-1-108-42898-9 — Collapse of the Wave Function Shan Gao Frontmatter More Information

#### Preface

of these theories, which may help solve the deep puzzles in other fields of modern physics, such as quantum gravity and cosmology. The last two parts of this book also contain a concise review of experimental tests of collapse theories (see Chapter 16) and a new test suggestion (see Chapter 11).

Different from other quantum theories, collapse theories are becoming a lively field of research in both philosophy and physics. I hope this anthology will arouse more researchers' interest in these promising and testable quantum theories. I thank all contributors for taking the time to write these new essays in the anthology. I am particularly grateful to Steve Adler, Lajos Diósi, Roman Frigg, GianCarlo Ghirardi, Nicolas Gisin, Philip Pearle, and Roger Penrose for their help and support. I thank Simon Capelin of Cambridge University Press for his kind support as I worked on this project, and the referees who gave helpful suggestions on how the work could best serve its targeted audience. Finally, I am deeply indebted to my parents, QingFeng Gao and LiHua Zhao, my wife Huixia, and my daughter Ruiqi for their unflagging love and support.

#### References

- Bassi, A. and Ghirardi, G. C. (2003). Dynamical reduction models. Phys. Rep. 379, 257.
- Bassi, A., Lochan, K., Satin, S., Singh, T. P., and Ulbricht, H. (2013). Models of wavefunction collapse, underlying theories, and experimental tests. *Rev. Mod. Phys.* 85, 471.
- Bohm, D. (1952). A suggested interpretation of quantum theory in terms of "hidden" variables, I and II. *Physical Review* 85, 166.
- Diósi, L. (2005). Intrinsic time-uncertainties and decoherence: comparison of 4 models. *Brazilian Journal of Physics* 35, 260.
- Gao, S. (2013). A discrete model of energy-conserved wavefunction collapse, *Proceedings* of the Royal Society A 469, 20120526.
- Gao, S. (2017). *The Meaning of the Wave Function: In Search of the Ontology of Quantum Mechanics*. Cambridge: Cambridge University Press.
- Ghirardi, G (2016). Collapse Theories. *The Stanford Encyclopedia of Philosophy* (Spring 2016 Edition), Edward N. Zalta (ed.), https://plato.stanford.edu/archives/spr2016/ entries/qm-collapse.
- Heisenberg, W. (1958). *Physics and Philosophy: The Revolution in Modern Science*. New York: Harper and Row. p.113.
- Jánossy, L. (1952). The physical aspects of the wave-particle problem. Acta Physica Academiae Scientiarum Hungaricae 1(4), 423.
- Pearle, P. (2007). How stands collapse I. *Journal of Physics A: Mathematical and General* 40, 3189.
- Pearle, P. (2009). How stands collapse II. in Myrvold, W. C. and Christian, J. eds., *Quantum Reality, Relativistic Causality, and Closing the Epistemic Circle: Essays in Honour of Abner Shimony*. The University of Western Ontario Series in Philosophy of Science, 73(IV), 257.