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.

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Edited by

SHAN GAO
Shanxi University

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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

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[1] but more as an anthology reflecting the latest thoughts of leading experts on the subject. The

[1] See Bassi and Ghirardi (2003), Diósi (2005), Pearle (2007, 2009), Bassi et al. (2013), and Ghirardi (2016) for helpful reviews of collapse theories.

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.[2] 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

[2] 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).

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.

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