LO SCRIGNO DI PROMETEO

COLLANA DI DIDATTICA, DIVULGAZIONE E STORIA DELLA FISICA

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La conoscenza completa delle leggi fisiche è la meta più alta a cui possa aspirare un fisico, sia che essa abbia uno scopo puramente utilitario... sia che egli vi cerchi la soddisfazione di un profondo bisogno di sapere e la solida base per la sua intuizione della natura.

Max Planck

La Fisica ha come scopo capire il rapporto tra l'uomo e la natura, non solo da un punto di vista scientifico, ma anche filosofico, e ha cambiato in modo irreversibile la nostra vita tramite le sue ricadute tecnologiche.

La spiegazione e la divulgazione dei concetti che stanno alla sua base, dati quasi per scontati, ma lungi dall'essere noti o compresi da molti, e l'evoluzione delle tecniche sperimentali, che hanno permesso di scoprire le leggi che regolano i fenomeni naturali e delle teorie via via elaborate, sono perciò argomenti di studio e riflessione di rilevanza primaria.

Questa collana si rivolge a chi abbia desiderio di approfondire o discutere questi temi ed è aperta a chi voglia collaborarvi con contributi originali.

Vai al contenuto multimediale

Klaus Colanero

Decoherence and definite outcomes

Their relation and distinct natures

Foreword by
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In this regard I would like to thank my supervisors, Prof. Roberto Casalbuoni and Prof. Elena Castellani, for their helpful suggestions and constructive criticism.

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I cannot but thank my family who trusted I was still a sane person when undertaking those further university studies well beyond my years of youth. I am particularly grateful to my wife, Siu Wai, for her encouragement and to my daughter, Lea, for the smiles.

Foreword

by Roberto Casalbuoni*

Since the formulation of quantum mechanics, there have been serious problems about its interpretation. The long discussions between Bohr and Einstein about the Copenhagen interpretation of quantum mechanics are well known. The result of this controversy was in the famous article by Einstein, Podolski and Rosen (EPR) written in 1935. The other big criticism to the Copenhagen interpretation came out the same year by Schrödinger through his famous paradox, the Schrödinger cat. It is quite remarkable that these two major criticisms to the Copenhagen interpretation originated from two of the founding fathers of quantum mechanics. However, from the point of view of the physicists, quantum mechanics with the interpretation given by Bohr and followers worked in a marvelous way with a perfect agreement with experimental facts. Furthermore, the argumentations raised up by EPR and Schrödinger appeared of pure speculative nature. But a breakthrough occurred in the 60's with the formulation of the Bell theorem showing the experimental possibility of discriminating between quantum mechanics and local hidden variable theories. The fact that the hidden variables could be discarded on experimental basis caught the attention of physicists, leading many researchers to take the interpretation problems in serious consideration. In fact, many of the recent progresses in atomic physics and in quantum information arise from these lines of thought.

One of the most serious problems of the Copenhagen interpretation of quantum mechanics is that it requires two different time evolutions. On one side the microscopic (quantum) systems evolve in a deterministic way following the Schroedinger equation. On the other hand the observations are made with macroscopic instruments that, according to Copenhagen, are subject to a classical behavior.

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However, a macroscopic instrument of measure is made up of atoms and molecules and therefore it should obey the Schroedinger equation. In front of this problem there are two attitudes: the first one is that, for some reason, the classical world should be different from the quantistic one; the second attitude is that the classical behavior is a consequence of the quantum laws.

The assumption that a macroscopic system is made up of quantistic components has the consequence that a macroscopic system would be a linear superposition of different states. This is the origin of the paradox of the Schrödinger cat: it can be dead and alive at the same time. This problem is supposed to be solved by the decoherence theory, which assumes that the interactions of the system under exam with the environment are not negligible. Then, it follows that the superpositions of states is suppressed in an exponential way characterized by a typical time, the decoherence time. Once this suppression has become operative, the system is left in a statistical mixture. However, after a measure has been done, only one of the possible results emerging from the statistical ensemble is observed. This is the famous collapse of the wave function, which is one of the postulates of the Copenhagen interpretation. But, as we see, the decoherence theory does not solve this problem, called the problem of the definite outcomes.

This is precisely the aim of this book, to illustrate the reasons why the decoherence does not solve the definite outcomes problem, and discuss some possible solutions. The book starts with a review of the problem and with a discussion of its possible solutions in the framework of the standard quantum mechanics and with proposed variations as the Bohmian mechanics. After an extensive review of the decoherence approach the book ends with an illustration of several alternative approaches to the definite outcomes problem.

This book should be seriously considered by any scholar of the interpretative problems in quantum mechanics for the completeness and the rigor of the arguments that are discussed.

Introduction

> The continuing dispute about quantum measurement theory [. . .] is not between people who disagree on the results of simple mathematical manipulations. Nor is it between people with different ideas about the actual practicality of measuring arbitrarily complicated observables. It is between people who view with different degrees of concern or complacency the following fact: so long as the wave packet reduction is an essential component, and so long as we do not know exactly when and how it takes over from the Schrödinger equation, we do not have an exact and unambiguous formulation of our most fundamental physical theory.
>
> J.S. Bell

In the last few years the general notion of *decoherence* in quantum mechanics has become increasingly common among physicists, philosophers of physics and quantum information scientists. And rightly so, because it represents both a further application of the predictive and explicative power of quantum theory, and an attempt to break the stalemate situation with respect to the interpretation of quantum mechanics. Powerful as it might be, however, the decoherence programme has not solved the measurement problem yet. Specifically, and contrary to some claims, it has not solved the definite outcomes problem, better known as the problem of the wave function collapse. Due to the wide scope of the decoherence programme, which could be summarized as the attempt to recover the classical phenomena from quantum physics, the problem of definite outcomes happens to be often confused with other, loosely related, issues. Such a confusion is the main motivation of this study.

This book has three aims:

a) to clarify in detail the relation between the decoherence mechanism and the problem of definite outcomes;
b) to dispel common misconceptions about the measurement problem in quantum mechanics;
c) to present some recent alternative approaches in the quest for a satisfactory solution of the definite outcomes problem.

Since the turn of the twenty–first century, it has become quite common, especially among physicists, to think that the successes of the decoherence programme in explaining the emergence of classical phenomena have solved the measurement problem. Such an idea is unfortunately incorrect because, while the decoherence mechanism accounts very well for the disappearing of interference in macroscopic systems and provides an enlightening understanding for the appearance of preferred robust pointer states, it does not offer, by itself, an explanation for the apparent collapse of the state vector.

At a time when the decoherence programme is becoming well defined both in its scope and in its physical and mathematical foundations, it seems necessary to identify in detail the place of definite outcomes within the decoherence framework. This appears all the more relevant considering the promising and fascinating developments in experimental techniques for macroscopic quantum state control on the one hand, and in quantum information and computation on the other.

Also, it is still difficult to overstate the importance of reducing misconceptions about the measurement problem in quantum mechanics. After more than eighty years since the formulation of the Schrödinger equation and the unprecedented success of quantum theory, it is quite peculiar that the problem of definite outcomes is still considered by most either a metatheoretical issue to be dealt with by means of a consistent interpretation, or a problem already solved for all practical purposes by the decoherence programme. As a matter of fact, not all practical issues are addressed by the decoherence programme. At the same time it is legitimate and reasonable to try and look for solutions to the problem within physics itself, either through an even finer grained analysis of system–apparatus–environment dynamics, or through the introduction of new physical laws whose consequences can be subjected to experimental test.

With regard to the physics based approach to the problem, theoretical constraints to its viability are examined and recent proposals for feasible experimental tests are introduced.

What is not in the scope of this work is a complete review of the results and successes of the decoherence programme in explaining the emergence of classical phenomena from quantum dynamics. Instead, as the title suggests, the focus will be specifically on the relation between decoherence and definite outcomes. In the same spirit, the different interpretations of quantum mechanics are not presented in a comprehensive manner, but they are analyzed from the specific point of view of the definite outcomes problem and with respect to the theoretical and experimental results of the decoherence programme.

In pursuing the aims listed above, philosophical assumptions and implications of each approach are explicitly analyzed in order to have a clear distinction between physical, logical and metaphysical issues involved. Weaknesses and merits of the various theoretical and interpretive approaches are highlighted.

This book is organized as follows. In Chapter 1 the definite outcomes problem is defined and analyzed. Remarkable experiments on superposition states of macroscopic systems are examined and their implications for the standard interpretation pointed out. The basic ideas of the decoherence formalism are also introduced, in order to provide a clear foundation for the subsequent considerations. The distinct natures of decoherence and state vector reduction are presented and some misconceptions in relation to the interpretation of certain experimental results are clarified.

In Chapter 2 the most commonly adopted interpretations are reviewed with particular attention to the issue of definite outcomes and the application of the decoherence programme. In order to underline the different approaches with respect to state vector reduction, the interpretations are grouped in theory extending solutions and interpretive solutions.

Chapter 3 is devoted to the theory of decoherence. Attention is put on identifying the essential and general aspects within the great formal diversity in the application of the theory to different systems. The distinction is made between decoherence formalism and decoherence mechanism showing that, while the Born rule is a pre–condition for the interpretation of the formalism based on reduced density matrices, decoherence itself can and does occur regardless of the state vector reduction, due to orthogonalization of the entangled environment states. The analysis is again focused on clarifying connections and implications for the definite outcomes problem. Misconceptions with regard to merits and limitations of the decoherence programme are addressed.

Environment–induced and gravity–induced collapse proposals are discussed in Chapter 4. The impossibility of a "for all practical purposes" solution of the definite outcomes problem, based on an environment–induced collapse, is discussed.