DO WE REALLY UNDERSTAND QUANTUM MECHANICS?

Quantum mechanics is a very successful theory that has impacted on many areas of physics, from pure theory to applications. However, it is difficult to interpret, and philosophical contradictions and counter-intuitive results are apparent at a fundamental level. In this book, Laloë presents our current understanding of the theory.

The book explores the basic questions and difficulties that arise with the theory of quantum mechanics. It examines the various interpretations that have been proposed, describing and comparing them and discussing their successes and difficulties. The book is ideal for researchers in physics and mathematics who want to know more about the problems faced in quantum mechanics but who do not have specialist knowledge in the subject. It will also appeal to philosophers of science and scientists who are interested in quantum physics and its peculiarities.

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Foreword[1]

Quantum Mechanics is an essential topic in today's physics curriculum at both the undergraduate and graduate levels. Quantum mechanics can explain the microscopic world with fantastic accuracy; the fruits from its insights have created technologies that have revolutionized the world. Computers, lasers, mobile telephones, optical communications are but a few examples. The language of quantum mechanics is now an accepted part of the language of physics and day-to-day usage of this language provides physicists with the intuition that is essential for achieving meaningful results. Nevertheless, most physicists acknowledge that, at least once in their scientific career, they have had difficulties understanding the foundations of quantum theory, perhaps even the impression that a really satisfactory and convincing formulation of the theory is still lacking.

Numerous quantum mechanics textbooks are available for explaining quantum formalism and applying it to understand problems such as the properties of atoms, molecules, liquids, and solids; the interactions between matter and radiation; and more generally to understand the physical world that surrounds us. Other texts are available for elucidating the historical development of this discipline and describing the steps through which it went before quantum mechanics reached its modern formulation. In contrast, books are rare that review the conceptual difficulties of the theory and then provide a comprehensive overview of the various attempts to reformulate quantum mechanics in order to solve these difficulties. The present text by Franck Laloë does precisely this. It introduces and discusses in detail results and concepts such as the Einstein–Podolsky–Rosen theorem, Bell's theorem, and quantum entanglement that clearly illustrate the strange character of quantum behavior. Within the last few decades, impressive experimental progress has made it possible to carry out experiments that the founding fathers of quantum mechanics considered only as "thought experiments". For instance, it is now possible to follow the

[1] Translated by D. Kleppner.

evolution of a single atom in real time. These experiments are briefly reviewed, providing an updated view of earlier results such as convincing violations of the Bell inequalities.

This book provides a clear and objective presentation of the alternative formulations that have been proposed to replace the traditional "orthodox" theory. The internal logics and consistency of these interpretations is carefully explained so as to provide the reader with a clear view of the formulations and a broad view of the state of the discipline. At a time when research is becoming more and more specialized, I think that it is crucial to keep some time for personal thought, to step back and ask oneself questions about the deep significance of the concepts that we employ routinely. In this text, I see the qualities of clarity, intellectual rigor, and deep analysis that I have always noticed and appreciated in the work of the author during many years of friendly collaboration. I wish the book a well-deserved great success!

Claude Cohen-Tannoudji

Preface

In many ways, quantum mechanics is a surprising theory. It is known to be non-intuitive, and leads to representations of physical phenomena that are very different from what our daily experience could suggest. But it is also very surprising because it creates a big contrast between its triumphs and difficulties.

On the one hand, among all theories, quantum mechanics is probably one of the most successful achievements of science. It was initially invented in the context of atomic physics, but it has now expanded into many domains of physics, giving access to an enormous number of results in optics, solid-state physics, astrophysics, etc. It has actually now become a general method, a frame in which many theories can be developed, for instance to understand the properties of fluids and solids, fields, elementary particles, and leading to a unification of interactions in physics. Its range extends much further than the initial objectives of its inventors and, what is remarkable, this turned out to be possible without changing the general principles of the theory. The applications of quantum mechanics are everywhere in our twenty-first century environment, with all sorts of devices that would have been unthinkable 50 years ago.

On the other hand, conceptually this theory remains relatively fragile because of its delicate interpretation – fortunately, this fragility has little consequence for its efficiency. The reason why difficulties persist is certainly not that physicists have tried to ignore them or put them under the rug! Actually, a large number of interpretations have been proposed over the decades, involving various methods and mathematical techniques. We have a rare situation in the history of sciences: consensus exists concerning a systematic approach to physical phenomena, involving calculation methods having an extraordinary predictive power; nevertheless, almost a century after the introduction of these methods, the same consensus is far from being reached concerning the interpretation of the theory and its foundations. This is reminiscent of the colossus with feet of clay.

The difficulties of quantum mechanics originate from the object it uses to describe physical systems, the state vector $|\Psi\rangle$. While classical mechanics describes a system by directly specifying the positions and velocities of its components, quantum mechanics replaces them by a complex mathematical object $|\Psi\rangle$, providing a relatively indirect description. This is an enormous change, not only mathematically, but also conceptually. The relations between $|\Psi\rangle$ and physical properties leave much more room for discussions about the interpretation of the theory than in classical physics. Actually, many difficulties encountered by those who tried (or are still trying) to "really understand" quantum mechanics are related to questions pertaining to the exact status of $|\Psi\rangle$. For instance, does it describe the physical reality itself, or only some (partial) knowledge that we might have of this reality? Does it describe ensembles of systems only (statistical description), or one single system as well (single events)? Assume that, indeed, $|\Psi\rangle$ is affected by an imperfect knowledge of the system; is it then not natural to expect that a better description should exist, at least in principle? If so, what would be this deeper and more precise description of the reality?

Another confusing feature of $|\Psi\rangle$ is that, for systems extended in space (for instance, a system made of two particles at very different locations), it gives an overall description of all its physical properties in a single block, from which the notion of space seems to have disappeared; in some cases, the properties of the two remote particles are completely "entangled" in a way where the usual notions of space-time and of events taking place in it seem to become diluted. It then becomes difficult, or even impossible, to find a spatio-temporal description of their correlations that remains compatible with relativity. All this is of course very different from the usual concepts of classical physics, where one attributes local properties to physical systems by specifying the density, the value of fields, etc. at each point of space. In quantum mechanics, this separability between the physical contents of different points of space is no longer possible in general. Of course, one could think that this loss of a local description is just an innocent feature of the formalism with no special consequence. For instance, in classical electromagnetism, it is often convenient to introduce a choice of gauge for describing the fields in an intermediate step; in the Coulomb gauge, the potential propagates instantaneously, while Einstein relativity forbids any communication that is faster than light. But this instantaneous propagation is just a mathematical artefact: when a complete calculation is made, proper cancellations of the instantaneous propagation take place so that, at the end, the relativistic limitation is perfectly obeyed. But, and as we will see below, it turns out that the situation is much less simple in quantum mechanics: in fact, a mathematical entanglement in $|\Psi\rangle$ can indeed have important physical consequences on the result of experiments, and even lead to predictions that are, in a sense, contradictory with locality. Without any doubt, the state vector is a curious object to describe reality!

It is therefore not surprising that quantum mechanics should have given rise to so many interpretations. Their very diversity makes them interesting. Each of them introduces its own conceptual frame and view of physics, sometimes attributing to it a special status among the other natural sciences. Moreover, these interpretations may provide complementary views on the theory, shedding light onto some interesting features that, otherwise, would have gone unnoticed. The best-known example is Bohm's theory, from which Bell started to obtain a theorem illustrating general properties of quantum mechanics and entanglement, with applications ranging outside the Bohmian theory. Other examples exist, such as the use of stochastic Schrödinger dynamics to better understand the evolution of a quantum sub-system, the history interpretation and its view of complementarity, etc.

This book is intended for the curious reader who wishes to get a broad view on the general situation of quantum physics, including the various interpretations that have been elaborated, and without putting aside the difficulties when they occur. It is not a textbook designed for a first contact with quantum mechanics; there already exist many excellent reference books for students. In fact, from Chapter 1, the text assumes some familiarity with quantum mechanics and its formalism (Dirac notation, the notion of wave function, etc.). Any student who has already studied quantum mechanics for a year should have no difficulty in following the equations. Actually, there are relatively few in this book, which focuses, not on technical, but on logical and conceptual difficulties. Moreover, a chapter is inserted as an annex at the end of the book in order to help those who are not used to the quantum formalism. It offers a first contact with the notation; the reader may, while he/she progresses in the other chapters, choose a section of this chapter to clarify his/her ideas on such or such technical point.

Chapters 1 and 2 recall the historical context, from the origin of quantum mechanics to the present situation, including the successive steps from which the present status of $|\Psi\rangle$ emerged. Paying attention to history is not inappropriate in a field where the same recurrent ideas are so often rediscovered; they appear again and again, sometimes almost identical over the years, sometimes remodelled or rephrased with new words, but in fact more or less unchanged. Therefore, a look at the past is not necessarily a waste of time! Chapters 3, 4, and 5 discuss two important theorems, which form a logical chain, the EPR (Einstein, Podolsky, and Rosen) theorem and the Bell theorem; both give rise to various forms, several of which will be described. Chapter 6 gives a more general view on quantum entanglement, and Chapter 7 illustrates the notion with various processes that make use of it, such as quantum cryptography and teleportation. Chapter 8 discusses quantum measurement, in particular weak and continuous measurements. A few experiments are described in Chapter 9; among the huge crowd of those illustrating quantum mechanics in various circumstances, we have chosen a small fraction of them – those where state vector reduction is "seen in real time". Finally, Chapter 10, the longest of all chapters, gives an introduction and some discussion of the various interpretations of quantum mechanics. The chapters are relatively independent and the reader may probably use them in almost any order. Needless to say, no attempt was made to cover all subjects related to the foundations of quantum mechanics. A selection was unavoidable; it resulted in a list of subjects that the author considers as particularly relevant, but of course this personal choice remains somewhat arbitrary.

The motivation of this book is not to express preference for any given interpretations, as has already been done in many reference articles or monographs (we will quote several of them). It is even less to propose a new interpretation elaborated by the author. The objective is, rather, to review the various interpretations and to obtain a general perspective on the way they are related, their differences and common features, their individual consistency. Indeed, each of these interpretations has its own logic, and it is important to remember it; a classical mistake is to mix various interpretations together. For instance, the Bohmian interpretation has sometimes been criticized by elaborating constructions that retain some elements of this interpretation, but not all, or by inserting elements that do not belong to the interpretation; one then obtains contradictions. The necessity for logical consistency is general in the context of the foundations of quantum mechanics. Sometimes, the EPR argument or the Bell theorem have been misunderstood because of a confusion between their assumptions and conclusions. We will note in passing a few occasions where such mistakes are possible in order to help avoiding them. We should also mention that it is out of the question to give an exhaustive description of all interpretations of quantum mechanics here! They may be associated in many different ways, so that it is impossible to account for all possible combinations or nuances. A relatively abundant bibliography is proposed to the reader, but, in this case also, reaching any exhaustiveness is impossible; some choices have been made, sometimes arbitrary, in order to keep the total volume within reasonable limits.

To summarize, the main purpose of this book is an attempt to provide a balanced view on the conceptual situation of a theory that is undoubtedly one of the most remarkable achievements of the human mind, quantum mechanics, without hiding either difficulties or successes. As we already mentioned, its predictive power constantly obtains marvelous results in new domains, sometimes in a totally unpredictable way; nevertheless this intellectual edifice remains the object of discussions or even controversy concerning its foundations. No one would think of discussing classical mechanics or the Maxwell equations in the same way. Maybe this signals that the final and optimum version of the theory has not yet been obtained?

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Many colleagues played an important role in the elaboration of this book. The first is certainly Claude Cohen-Tannoudji, to whom I owe a lot. Over the years I benefited, as many others did, from his unique and deep way to use (and even to think) quantum mechanics; more than 40 years of friendship (and of common writing) and uncountable stimulating discussions were priceless for me. Alain Aspect is another friend with whom, from the beginning of his thesis in the seventies, a constant exchange of ideas took place (it still does!). At the time, the foundations of quantum theory were not very well considered among mainstream physicists, even sometimes perceived as passé or mediocre physics; Alain and I could comfort each other and make progress together in a domain that we both found fascinating, with the encouragement of Bernard d'Espagnat. Jean Dalibard and Philippe Grangier have been other wonderful discussion partners, always open minded with extreme intellectual clarity; I wish to thank them warmly. The title "Do we really understand quantum mechanics?" was suggested to me long ago by Pierre Fayet, on the occasion of two seminars on this subject he was asking me to give. This book arose from a first version of a text published in 2001 as an article in the *American Journal of Physics*, initiated during a visit at the Theoretical Physics Institute at the California University of Santa Barbara. During a session on Bose–Einstein condensation, I was lucky enough to discuss several aspects of quantum mechanics with its organizer, Antony Leggett; another lucky event favoring exchanges was to share Wojciech Zurek's office! A little later, a visit at the Lorentz Institute of Leiden was also very stimulating, in particular with the help of Stig Stenholm. As for Abner Shimony, he guided me with much useful advice and encouraged the writing of the first version of this text.

Among those who helped much with the present version of the text, Michel Le Bellac played an important role by reading the whole text and giving useful advice, which helped to improve the text. He and Michèle Leduc also chose a wonderful (anonymous) reviewer who also made many very relevant remarks; I am grateful to all three of them. Among the other friends who also helped efficiently on various aspects are Roger Balian, Serge Reynaud, William Mullin, Olivier Darrigol, Bernard d'Espagnat and Catherine Chevalley; I am very grateful for many comments, advice, questions, etc. Markus Holzmann kindly read the whole manuscript when it was completed and made many interesting suggestions. The careful editing work of Anne Rix has been invaluable for improving the homogeneity and the quality of the text. I am grateful to Elisabeth Blind who kindly agreed that one of her wonderful paintings could be reproduced on the cover of this book.

Last but not least, concerning the last chapter describing the various interpretations of quantum mechanics, I asked specialists of each of these interpretations to be kind enough to check what I had written. I thank Sheldon Goldstein for reading and commenting the part concerning the Bohmian theory, Philip Pearle and Giancarlo Ghirardi for their advice concerning modified Schrödinger dynamics, Robert Griffiths and Roland Omnès for their comments on the history interpretation, Bernard d'Espagnat for clarifying remarks on veiled reality, Richard Healey for his help on the modal interpretation, Carlo Rovelli for his comments and suggestions on the relational interpretation, Alexei Grinbaum for illuminating comments concerning quantum logic and formal theories, and Thibault Damour for his helpful reading of my presentation of the Everett interpretation. According to the tradition it should be clear that, if nevertheless errors still subsist, the responsibility is completely the author's. Finally, without the exceptional atmosphere of my laboratory, LKB, without the constant interaction with his members, and without the intellectual environment of ENS, nothing would have been possible.