Introduction

Quantum Mechanics is the most successful physical theory we have: it tells us why the sun burns and tables are solid. It is also the most baffling. For quantum mechanics (at least as usually interpreted), the total information about the state of a system (a particle or a group of particles) is given by a vector $|\Psi\rangle$ (psi) whose temporal evolution, governed by the Schrödinger equation, is deterministic in the sense that given the value of $|\Psi\rangle$ at a time, its previous or subsequent values are fixed. $|\Psi\rangle$ allows us to know two things: the possible values *a*, *b*, … that any observable (an individual physical quantity such as energy or position) of the system will display upon measurement, and the probability associated with the display of each of these values. However, quantum mechanics cannot tell us why upon measurement of an observable one obtains a specific value *a*, and some technical results show that one cannot unqualifiedly say in all cases that *a* was the value of the observable just before measurement. If we assume that, roughly put, at all times an observable admitted by quantum mechanics has a definite and precise value, then the theory must be incomplete (there must be more to the physical state of the system than $|\Psi\rangle$ lets on) because it fails to predict with certainty what that value is.

The orthodox interpretation of quantum mechanics (the one typically found, often implicitly, in textbooks), upholds the completeness of the theory by maintaining that aside from peculiar situations (eigenstate cases) and unchanging properties such as mass, electrical charge, or spin number, quantum systems have individual properties only when they are measured. Typically, an electron, when not observed, has a definite mass but no position (that is, it is nowhere, like a Cartesian soul) and no energy (that is, not zero energy but no property of energy). However, as soon as we measure these properties, they suddenly appear as if measurement led them from potentiality to actuality.

To complicate things, in spite of its centrality, quantum measurement itself is problematical because if the Schrödinger equation applies both to the system being measured and to the measuring apparatus (a reasonable assumption since it is made up of quantum particles like anything else), then its linearity seems to make measurement outcomes impossible. Hence, the standard interpretation holds that at measurement Schrödinger equation does not apply, and a new law for the evolution of $|\Psi\rangle$, the non-linear collapse-law that abruptly and inexplicably turns $|\Psi\rangle$ into the state vector associated with *a*, takes over. Collapse is mysterious, suspiciously ad hoc, and the source of constant controversies and wild theories, with some (Wigner, for example) arguing that only the interaction between quantum particles and a mind results in the appearance of individual properties and the corresponding collapse.

Minimally, one can say that on the standard interpretation what kinds of individual properties a system obtains depends on what sort of measurements are carried out: if we measure position, then the electron will acquire one; however, had we measured momentum, it would have acquired momentum, not position. Other interpretations are just as radical. For example, De Witt has held that at each measurement the universe literally splits into almost identical and non-interacting copies, thus producing an unbelievably exuberant ontology well beyond the dreams of a mad metaphysician. By contrast, Griffiths has opted for a restricted variety of realism, arguing that the quantum world can only be described from individual perspectives that may not be combined on pains of meaninglessness. It is as if pictures of the same building taken from different vantage points could not be synthesized to form a complete representation of it. Others, Rovelli, for example, have argued that a system has properties not absolutely but only relationally, namely, with respect to another system.

Leaving general interpretations of quantum mechanics aside, even some of its specific results are an affront to common sense. For example, groups of quantum particles of the same species and sufficiently close to each other display strange statistical behavior that can be illustrated with an analogy. Imagine two fair coins behaving like quantum particle in close proximity. Then, upon flipping them, there is only one way of getting a tails and a heads instead of two, as is the case with normal (macroscopic) coins. In other words, it looks as if the two quantum coins have lost their identity while remaining two, raising the old metaphysical issue of the nature of identity in a new and disturbing light because quantum particles do exist. In short, there is no doubt that the problems and discussions surrounding quantum mechanics are of interest not only to scientists but also to metaphysicians, epistemologists or indeed, to the educated public.

Given the importance of quantum mechanics to metaphysics and epistemology one would expect that several substantive up to date works would exist introducing the reader both to quantum theory and to its philosophical and conceptual implications. However, although justified such an expectation is only partially satisfied. To be sure, there are several books discussing quantum mechanics and its interpretive issues. Among the best ones, leaving aside Home's highly technical *Conceptual Foundations of Quantum Physics*, are Whitaker's *Einstein, Bohr and the Quantum Dilemma*, which discusses interpretive issues (almost) without any formalism, and Albert's *Quantum Mechanics and Experience*, which teaches some quantum formalism and its interpretive problems by introducing the effective equivalent of a spin-half system. However, neither discusses the links between quantum mechanics and many traditional philosophical issues such as the nature of identity and free will. In addition, both lack a substantive exposition and discussion of relatively new interpretations such as Griffiths' or Rovelli's.

When writing a book that involves a mathematized subject, the first issue facing an author is deciding how much mathematics to employ. Fortunately, linear algebra, the mathematical conceptual framework for quantum mechanics, is not especially difficult and presupposes minimal previous mathematical knowledge. Even so, one must make a choice. The typical policy is to use as little mathematics as possible; indeed, occasionally one finds reviews of books praising the author for having "explained" some difficult subject without using one single formula. This attitude, I believe, is mistaken and irritatingly condescending, especially in quantum mechanics, where often results are highly counterintuitive, without 'sensible' physical explanation, and resting on a mathematical formalism whose link to the physical world is, at best, opaque. I still remember taking a course in quantum mechanics and philosophy and getting more and more irritated as physicists (or philosophers of science) kept telling me what the formulas 'meant' (or better, what *they* thought the formulas meant, although apparently in the fog of quantum mechanical interpretations the distinction was lost) instead of teaching me how to obtain them. From personal experience, and from talking to colleagues and students, I have become convinced that one should introduce as much mathematics as possible, as long as the mathematical machinery is clearly explained and to the point. This is what I have tried to do in the present introductory work, which aims at allowing non-scientists or non-philosophers with some tenacity and interest to learn both the basic machinery of quantum mechanics and the basic interpretive and philosophical issues surrounding it. After learning the material one will be able to tackle more technical and specialized works such as Griffiths, R., (2002) or Laloë, F., (2001), or read most articles on the subject without further ado. To get to much of the material in Home, D., (1997), a very technical work, it is necessary to master the content of the supplement, of which more later.

A book like this must contain not only some quantum mechanical but also some philosophical machinery, as it were. Hence, one is again faced with a decision, namely, how deeply to wade into philosophy. Unfortunately, while one can 'do' all the mathematics we need by mere symbol manipulation, the same is not true with respect to philosophy. There is no symbolism to master, but the price is that there is no syntactical manipulation leading from a philosophical proposition to another. In short, after the algebraic revolution of the seventeenth century, often mathematics is easier than it looks and philosophy is harder than is seems. For this reason, when introducing philosophical notions I have kept things as simple and clear as possible without, I hope, being pedestrian, bearing in mind that some readers might know some, or even much, quantum mechanics but no philosophy at all. This book, as the title says, is introductory.

The work is divided in two parts. The first part, comprising chapters 1-5, discusses the basic structure of quantum mechanics by introducing linear algebra, spin-half systems, Schrödinger's wave function, and the evolution operator. The second part, comprising the remaining eleven chapters, deals with interpretive and philosophical issues centering on property realism and quantum mechanical measurement. In chapter 6, most of the philosophical views necessary to understand the debates about quantum mechanics are introduced. Chapter 7 discusses the uncertainty principle, Heisenberg's claim that it does not apply to the past, and Ehrenfest's theorem with the related issue of the connection between quantum and classical mechanics. The derivation of the generalized uncertainty principle, which conceptually belongs in the formalism of quantum mechanics, has been located in this chapter to give the reader a philosophical breather after the machinery of chapters 2 though 5. Chapter 8 is devoted to Bohr's and Einstein's views and to a discussion of arguments originating with Einstein to the effect that quantum mechanics is incomplete. Chapter 9 presents some important no-go (a widespread solecism) theorems that show how some apparently plausible interpretations of quantum mechanics are in fact untenable, and introduces the measurement problem. Chapters 10 and 11 deal with the measurement problem, traditionally considered the central conceptual difficulty in the foundations of quantum mechanics, and some of the many proposed solutions to it. Chapter 12 discusses the consistent histories interpretation and chapter 13 discusses Bohmian mechanics. The three final chapters are more strictly philosophical than the rest and concern the nature of individuals, physical things, holism, and free will in the light of quantum mechanical results. Any relevant piece of quantum mechanical machinery not covered in the first part, such as entangled systems and density operators, is introduced and explained at the appropriate moment.

Most chapters contain a set of exercises with detailed solutions and thought questions. Even if, strictly speaking, doing the exercises is not a precondition for a proper understanding of the material, it is advisable to try to do most of them and look at their solutions.

Ideally, in order to appreciate the revolutionary nature of quantum mechanics and see how the prediction of extraordinary phenomena such as tunneling come about, one should learn some classical mechanics and enough calculus to understand some of the analytic solutions of the Schrödinger equation. Unfortunately, the incorporation of this material would lengthen this already longish work by more than one half, and therefore I have omitted it. Nevertheless, for those who are willing to learn more I have added a supplement containing this material, together with exercises and solutions. Occasionally, the supplement repeats some of the material in the main text; however, I decided that continuity and self-containment was worth the inconvenience of a little duplication.

The bibliography in quantum mechanics and its interpretations is simply immense; consequently, the one at the end of the book is not only partial, but it certainly fails to list many very useful sources. Still, here a list of texts that, in my opinion, may be especially helpful in clarifying or expanding the material, especially as it relates to the supplement. For elementary calculus, see Mendelson, E., (1985); for my money, the best calculus book is Ash, C., and Ash, R. B., (1986); for more mathematics related to physics, consult Boas, M., L., (1983), and for linear algebra, Lipschutz, S., (1991). For classical mechanics, see French, A. P., (1965), and at a more advanced level, Spiegel, M. R., (1967); sections of the first volume of Feynman, R. P., Leighton, R. B., Sands, M., (1963) are also worth a look. Reed, B. C., (1994) is probably the best short and easy introduction to the Schrödinger equation and its application to simple systems; Gillespie, D. T., (1970), is also useful. A text that is longer, often prolix, but useful when one becomes familiar with it, is Morrison, M., (1990); Griffiths, D. J., (1995) is a more advanced, very terse standard quantum mechanical text; Cohen-Tannoudji, C., Diu, B., and Laloë, F., (1977) is an even more advanced and detailed two-volumes book. The third volume of Feynman, R. P., Leighton, R. B., Sands, M., (1963) is also helpful. For a description of many recent quantum mechanical experiments important for foundational issues, one may consult Greenstein, G., and Zajonc, A., (1997) and Baggott, J., (2004). Other useful works related to specific topics are listed in the footnotes.