Introduction

In this monograph I present the basic structure of an interpretation of quantum mechanics. Chapter 1 outlines the central ideas behind the interpretation and illustrates them by means of examples: Subsequent chapters fill in the details of the interpretation. But it is important to begin by explaining what I take an interpretation of quantum mechanics to be, and why any further interpretation needs to be offered. After all, quantum mechanics (in some form) is by now both a foundation for much of contemporary physics and a veteran of more than sixty years of intermittent but sometimes intense reflection on its content and meaning. What more can be, or should be, said about the interpretation of this theory?

Many physicists believe that no more needs to be said: that there is basically only one way of understanding quantum mechanics, due to Bohr, Heisenberg, Pauli, and others, and that the only remaining interpretative task is that of the physics teacher, who seeks to perfect ways of conveying this understanding to new generations of students. Sir Rudolf Peierls, one of the more lucid and distinguished of these physicists, even objects to the use of the familiar term 'Copenhagen interpretation' to refer to the way of understanding quantum mechanics due to Bohr, Heisenberg, Pauli, and others.

> Because this sounds as if there were several interpretations of quantum mechanics. There is only one. There is only one way in which you can understand quantum mechanics. There are a number of people who are unhappy about this, and are trying to find something else. But nobody has found anything else which is consistent

> yet, so when you refer to the Copenhagen interpretation of the mechanics what you really mean is quantum mechanics. And therefore the majority of physicists don't use the term; it's mostly used by philosophers.[1]

I am a philosopher, and I shall sometimes find it convenient to talk about the Copenhagen interpretation of quantum mechanics. But that may well be the only respect in which I can assent to the views expressed by Peierls in this passage. It seems to me that far from there being only one interpretation of quantum mechanics, there is today *no* fully satisfactory way of understanding this theory. Instead we are faced with an extraordinary variety of attempts to understand quantum mechanics: Indeed, it sometimes seems as if there are as many different attempts as there are people who have seriously made the attempt! But none of these attempts has either won, or deserved, universal or even widespread acceptance. It is sometimes useful to classify these different interpretation-sketches, since they do fall into certain groups. Thus one may refer to the many-worlds interpretation, to an interpretation in terms of hidden variables, to a naive realist interpretation, to the quantum logical interpretation, or to the Copenhagen interpretation. But such references should not be taken to be more definite than they are. There are, for example, many ways of trying to implement the basic ideas behind "the" many-worlds interpretation. And these do not amount to mere stylistic variants: Each of them gives rise to a very different conception of quantum mechanics.

This is true also of "the" Copenhagen interpretation. Bohr, Heisenberg, and Pauli each held significantly different views on how quantum mechanics should be understood. And the views of von Neumann and of Wigner diverge even more radically from these, although they consider themselves to be proponents of the very same interpretation, and are often taken at their word. Textbook writers typically pay lip service

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[1] This passage is quoted from the edited transcript of a radio interview, and appears on page 71 of Davies and Brown (1986).

to the ideas of Bohr, but neither state these clearly and accurately, nor use them to develop any coherent understanding of quantum mechanics.[2] One might still wonder whether there is *some* version of "the" Copenhagen interpretation which is preferable to any other, and clearly superior to all non-Copenhagen views. If so, it would lay claim to be Peierls's one true interpretation of quantum mechanics. Though I do not believe that there is any such version, justifying this belief would require an exhaustive study of the many versions that have actually been proposed, as well as a number that could have been proposed. It is not the purpose of this monograph to undertake such a study. Instead, in the second section of this introduction I shall sketch the basic ideas behind two common versions of the Copenhagen interpretation, and outline what I take to be the chief reasons for rejecting them. This is not intended as a definitive refutation of "the" Copenhagen interpretation, but as a preliminary statement of reasons for looking beyond it.

I am not alone in my dissatisfaction with what I call the Copenhagen interpretation. Although many physicists at least pay lip service to this interpretation of quantum mechanics, there is a significant, and perhaps growing, minority who reject it in favor of something else. Rivals to Copenhagen orthodoxy now include naive realism,[3] (nonlocal) hidden variable theories,[4] the Everett, or many-worlds, interpretation,[5] and the quantum logical interpretation.[6] It is therefore appropriate for me to address the question of the relation of the interpretation to be presented in this mono-

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[2] David Bohm's (1951) *Quantum Theory* is a welcome exception to this generalization.

[3] See Ballentine (1970) for one physicist's presentation of this view. It is arguable that Einstein held a naive realist view of quantum mechanics. I have criticized this view in Healey (1979).

[4] See, for example, Vigier (1982).

[5] For defenses of this view see, for example, DeWitt and Graham (1973), and Geroch (1984). For objections, see, for example, Healey (1984), and Stein (1984).

[6] For one physicist's presentation of this view see Finkelstein (1962). The quantum logical interpretation seems more popular among philosophers and mathematicians: see Putnam (1968), Bub (1974), and Friedman and Putnam (1978).

graph to these other "unorthodox" approaches. It is clear that my presentation should not be considered part of either the naive realist or the quantum logical traditions. I should myself also resist its assimilation into either the hidden variable or the many-worlds tradition; though others may classify the view differently. The important point is that, in my opinion, there are powerful arguments against the usual versions of all the familiar unorthodox interpretations [though these are not so powerful as Peierls implies in the quoted passage; a quantum logical interpretation might be accused of (classical) inconsistency, but I doubt that any of the other interpretations can be shown to be *inconsistent*]. I shall sketch some of these usual versions in the second section, and then argue against them. Again, I must stress that I do not take any of these arguments to provide a definitive refutation of the interpretation against which it is offered. That would at least require considerable sympathetic reconstruction of each interpretation, combined with systematic and wide-ranging criticism. My purpose is the more limited one of establishing a prima facie case against each interpretation to motivate my own presentation of still another interpretation in the rest of this monograph.

The preceding discussion assumes that it is clear both what an interpretation of quantum mechanics would be and that it is necessary to find an interpretation that is in some sense acceptable. In fact, this is not so clear as to go without comment. Let me start from Peierls's equation of an interpretation of a theory with a way of understanding that theory. Why should it be necessary to provide, in addition to the theory itself, something further, namely a way of understanding the theory?

This would be necessary if one took the theory to be an uninterpreted formal system, on the positivist model for a scientific theory.[7] In this model, the theory would require

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[7] See, for example, Carnap (1939).

supplementation by semantic principles in order for its constituent terms and sentences to be endowed with meaning, and there may be controversy as to just what these semantic principles should be. But the general positivist model for a scientific theory has justifiably come under sustained criticism in recent philosophy of science, and there seems little reason to suppose that quantum mechanics conforms to this model better than other theories. Furthermore, disputes about how quantum mechanics should be understood extend down to the level of disagreement over how one would go about formalizing the theory; consequently, there is no agreed formal system whose semantics is in doubt.

It is true that there is widespread agreement that quantum mechanics employs certain by now well-understood mathematical structures: For example, in quantum mechanics dynamical variables are representable by self-adjoint operators on a Hilbert space, whose spectra represent possible values of these variables. But such agreement does not extend to the exact wording of the fundamental principles of the theory, nor even to just what these principles are. For example, the status of the projection postulate – von Neumann's process 1 – has long been highly controversial. There are those who have held some form of this principle to be an essential postulate of the theory; others have taken it to hold only in certain special circumstances; still others have considered the principle to be actually inconsistent with the fundamental principles of quantum mechanics. The exact statement of the basic (Born) probability rules has also been a highly controversial matter: Do these specify probabilities that a quantity has a certain value, that it will or would acquire a certain value on measurement, or that a measuring apparatus will or would record a corresponding result if the quantity is measured? In addition to disagreement over the status and exact formulation of such important theoretical principles, there has been no clearly agreed upon understanding of central notions of quantum mechanics such as those of *measurement* and of *quantum states*. Here we have an interpretative problem that more closely fits the positivist paradigm: Just what is meant by terms like 'measurement' and 'quantum state' as they figure in quantum mechanics? Finally, it is well known that the conceptual foundations of quantum mechanics have been plagued by a number of "paradoxes," or conceptual puzzles, which have attracted a host of mutually incompatible attempted resolutions – such as that presented by Schrödinger (1935), popularly known as the paradox of Schrödinger's cat, and the EPR "paradox," named after the last initials of its authors, Einstein, Podolsky, and Rosen (1935).

A satisfactory interpretation of quantum mechanics would involve several things. It would provide a way of understanding the central notions of the theory which permits a clear and exact statement of its key principles. It would include a demonstration that, with this understanding, quantum mechanics is a consistent, empirically adequate, and explanatorily powerful theory. And it would give a convincing and natural resolution of the "paradoxes." I should like to add a further constraint: that a satisfactory interpretation of quantum mechanics should make it clear what the world would be like if quantum mechanics were true. But this further constraint would not be neutral between different attempted interpretations. There are those, particularly in the Copenhagen tradition, who would reject this further constraint on the grounds that, in their view, quantum mechanics should not be taken to describe (microscopic) reality, but only our intersubjectively communicable experimental observations of it. It would therefore be inappropriate to criticize a proposed interpretation solely on the grounds that it does not meet this last constraint. But this constraint will certainly appeal to philosophical realists, and for them at least it should count in favor of an interpretation if it meets this constraint, as does the interpretation presented in this monograph – or so I hope to show.[8]

Granted that quantum mechanics requires some interpretation, why is a *new* interpretation needed? Why are none of the interpretations so far offered acceptable? Even a preliminary answer to these questions calls for a discussion of the key points of some of the more prominent contemporary approaches to quantum mechanics. It is convenient to introduce this discussion by referring to the Born rules, which are customarily taken to be the central probabilistic principles of quantum mechanics: Different approaches may be distinguished by their different interpretations of the Born rules. Leaving aside joint probabilities, these may be taken to have the following form:

$$\mathrm{prob}_{\psi}(\mathcal{A}\in\Omega) = p. \tag{1.1}$$

Here p is a real number between zero and one (including those limits), $\mathcal{A}$ is a quantum dynamical variable, Ω is a (Borel) set of real numbers, and ψ is a mathematical representative of an instantaneous quantum state. A preliminary reading of (1.1) is as follows: "In quantum state ψ, the probability of finding that the value of $\mathcal{A}$ lies in Ω is p." But how is the phrase 'of finding' to be understood? Is this phrase just a redundant rhetorical device inserted to draw attention to the fact that instances of (1.1) are testable by repeatedly measuring the value of $\mathcal{A}$ on each of a large number of similar systems in quantum state ψ and observing in what fraction of the tested cases that value lies in Ω? Or would the omission of this phrase constitute a substantive distortion of the content

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[8] It is interesting to note that its appeal extends also to certain antirealists. Before offering his own interpretation of quantum mechanics, Van Fraassen (1981), certainly no scientific realist, formulates the interpretative task of the philosopher of science as that of "describing how the world can be the way that scientific theories say that it is" (p. 230).

of (1.1), which is intended to apply explicitly to the results of *measurements* of $\mathscr{A}$, and not to the value $\mathscr{A}$ has independent of whether or not it is measured?

One main approach to quantum mechanics takes the first option: According to an approach I have elsewhere characterized as **naive realist** (see Healey, 1979), the Born rules apply directly to possessed values of quantities, and only derivatively to results of measurements of these quantities. According to naive realists every quantum dynamical variable always has a precise real value on any quantum system to which it pertains, and the Born rules simply state the probability for that value to lie in any given interval. Thus, for them, the Born rules assign probabilities to events involving a quantum system σ of the form "The value of $\mathscr{A}$ on σ lies in Ω." A properly conducted measurement of the value of $\mathscr{A}$ on σ would find that value in Ω just in case the value actually lies in Ω (or, at least, would have lain in Ω had the measurement not altered the value of $\mathscr{A}$ while measuring it, just as a thermometer might alter the temperature of a substance while taking it, an effect which in this case may be corrected for to yield the hypothetical undisturbed temperature of the substance).

Perhaps the main problem for the naive realist comes from a set of arguments based on no-hidden-variable proofs.[9] These seem to show that even if the precise values principle endorsed by the naive realist were true, it would be impossible to assign a value to every dynamical variable on each of a large number of similar systems in such a way that for each quantity, the fraction having each value is even close to the probability specified by the Born rules. It seems mathematically impossible to interpret the Born rules uniformly as

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[9] See, for example, Healey (1979), and Redhead (1987). The main no-hidden-variable results are contained in Gleason (1957) and Kochen and Specker (1967). The naive realist approach also has particular difficulties in accounting for violations of the Bell inequalities without postulating a kind of instantaneous action at a distance which is in conflict with the basic principles of relativity theory; see Chapter 5.

giving probability distributions over possessed values of dynamical variables. Since this claim continues to be disputed, and the arguments surrounding it are both complex and dependent on highly mathematical results, I cannot pursue the issue further here. But the naive realist approach has always been at most an interesting heretical alternative to the more orthodox Copenhagen viewpoint which I consider next.

In the Copenhagen view, the Born rules explicitly concern the probabilities for various possible *measurement results*. They do not concern possessed values of dynamical variables. Indeed, according to this view, on each system there will always be some dynamical variables which do not possess precise values. In the Copenhagen interpretation, the Born rules assign probabilities to events of the form "The measured value of $\mathscr{A}$ on σ lies in Ω." Since the statement of the Born rules then involves explicit reference to measurement (or observation), to complete the interpretation it is necessary to say what constitutes a measurement. Proponents of the Copenhagen interpretation have typically either treated 'measurement' (or 'observation') or cognates as primitive terms in quantum mechanics, or else have taken each to refer vaguely to "suitable" interactions involving a "classical system."

Each of these accounts is problematic. If "measurement" remains a primitive term, then it is natural to interpret it epistemologically as referring to an act of some observer which, if successful, gives him or her knowledge of some structural feature of a phenomenon. But then, quantum mechanics seems reduced to a tool for predicting what is likely to be observed in certain (not very precisely specified) circumstances, with nothing to say about the events in the world which are responsible for the results of those observations we make, and with no interesting implications for a world without observers. And indeed this instrumentalist/pragmatist conception of quantum mechanics has often gone along with the Copenhagen interpretation. On the other hand, if a measurement is a "suitable" interaction with a "classical system," we need to know what interactions are suitable, and how there can be any "classical systems," if quantum mechanics is incompatible with and supersedes classical mechanics.

In order to clarify and amplify these problems, it is useful to distinguish between two different versions of the Copenhagen interpretation. I suspect that whereas the first version is more familiar to many physicists, it is the second version which comes closer to representing Bohr's own view. In what I shall call the *weak version* of the Copenhagen interpretation, the dynamical properties of an individual quantum system are fully specified by means of its quantum state. A dynamical variable $\mathcal{A}$ possesses a precise real value a_i on a system if and only if that system is describable by a quantum state for which the Born rules assign probability one to the value a_i of $\mathcal{A}$. In that state, a measurement of $\mathcal{A}$ would certainly yield the value a_i. In other states, for which there is some chance that value a_i would result if $\mathcal{A}$ were measured, and some chance that it would not, it is denied that $\mathcal{A}$ has any precise value prior to an actual measurement of it. Nevertheless, within the limits of experimental accuracy, measurement of a dynamical variable always yields a precise real value as its result, and this raises the question of the significance to be attributed to this value, given that it is typically not the value the variable possessed just before the measurement, nor the value it would have had if no measurement had taken place. One natural response is to say that the measured variable *acquires* the measured value as a result of the measurement: And then the Born rules explicitly concern the probabilities that dynamical variables acquire certain values upon measurement. Putting this response together with the condition for ascribing a precise real value to a variable given earlier, one concludes that after a precise measurement of a dynamical variable, a system is describable by a quantum state for which the Born rules assign probability one to the measured value of that variable. And this is one form of the **projection postulate** – a con-