Interpreting the Quantum World

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Introduction

This is a book about the interpretation of quantum mechanics, and about the measurement problem. The conceptual entanglements of the measurement problem have their source in the orthodox interpretation of 'entangled' states that arise in quantum mechanical measurement processes. The heart of the book is a uniqueness theorem (Bub and Clifton, 1996; see chapter 4) that characterizes alternative 'no collapse' interpretations of the theory, in particular observer-free interpretations that don't involve the measurement problem. From the perspective of the uniqueness theorem, one sees precisely where things have gone awry and what the options are.

One might wonder why, and in what sense, a fundamental theory of how physical systems move and change requires an interpretation. Quantum mechanics is an irreducibly statistical theory: there are no states of a quantum mechanical system in which all dynamical variables have determinate or 'sharp' values – no states that are 'dispersion-free' for all dynamical variables. Moreover, so-called 'no go' theorems exclude the possibility of defining new states in terms of 'hidden variables,' in which all dynamical variables – or even certain finite sets of dynamical variables – have determinate values, if we assume that the values assigned to functionally related dynamical variables by the new hidden variable states are subject to certain constraints, and we require that the quantum statistics can be recovered by averaging over these states. So it is standard practice to refer agnostically to 'observables' rather than dynamical variables (which suggest determinate values evolving in time), and to understand quantum mechanics as providing probabilities for the outcomes of measurements of observables under physically well-defined conditions.

This neutrality only goes so far. All standard treatments of quantum mechanics take an observable as having a determinate value if the quantum state is an eigenstate of that observable.[6] If the state is not an eigenstate of the observable, no determinate value is attributed to the observable. This principle – sometimes called the 'eigenvalue–eigenstate link'[7] – is explicitly endorsed by Dirac (1958, pp. 46–7) and von Neumann (1955, p. 253), and clearly identified as the 'usual' view by Einstein, Podolsky, and

[6] For an account of quantum states and their representation in Hilbert space see the appendix.
[7] The term is due to Arthur Fine (1973, p. 20).

Rosen (1935) in their classic argument for the incompleteness of quantum mechanics (see chapter 2). Since the dynamics of quantum mechanics described by Schrödinger's time-dependent equation of motion is linear, it follows immediately from this orthodox interpretation principle that, after an interaction between two quantum mechanical systems that can be interpreted as a measurement by one system on the other, the state of the composite system is not an eigenstate of the observable measured in the interaction, and not an eigenstate of the indicator observable functioning as a 'pointer.' So, on the othodox interpretation, neither the measured observable nor the pointer reading have determinate values, after a suitable interaction that correlates pointer readings with values of the measured observable. This is the measurement problem of quantum mechanics.

There are three possible ways of resolving the measurement problem: We adopt what Bell (1990) has termed a 'FAPP' ('for all practical purposes') solution, or we change the linear dynamics of the theory (which, as I see it, means changing the theory), or we change the orthodox Dirac–von Neumann interpretation principle.

FAPP solutions range from the Daneri–Loinger–Prosperi (1962, 1966) quantum ergodic theory of macrosystems[8] to the currently fashionable 'decoherence' theories. Essentially, the idea here is to exploit the fact that a macroscopic measuring instrument is an open system in virtually continuous interaction with its environment. Because of the typical sorts of interactions that take place in our world between such systems and their environments, it turns out that almost instantaneously after a measurement interaction, the 'reduced state' of the measured system and measuring instrument as a composite subsystem of the universe is, for all practical purposes, indistinguishable from a state that supposedly can be interpreted as representing a classical probability distribution over determinate but unknown values of the pointer observable. The information required to exhibit characteristic quantum interference effects between different pointer-reading states is almost immediately irretrievably lost in the many degrees of freedom of the environment. Since there are well-known difficulties with such an 'ignorance interpretation,' there is usually a further move involving an appeal to Everett's (1957, 1973) 'relative state' or 'many worlds' interpretation of quantum mechanics, where determinateness is only claimed in some relative sense. I discuss versions of this approach in chapter 8, where I argue that the measurement problem is not resolved by this manoeuvre.

The Bohm–Bub 'hidden variable' theory (1966a) modifies the linear dynamics by adding a nonlinear term to the Schrödinger equation that effectively 'collapses' or projects the state onto an eigenstate of the pointer reading and measured observable in a measurement process (the resulting eigenstate depending on the hidden variable). Currently the Ghirardi–Rimini–Weber theory (1986), with later contributions by Pearle (Ghirardi, Grassi, and Pearle, 1990, 1991; Pearle, 1989, 1990), is a much more

[8] For a critique, see Bub (1968).

sophisticated stochastic dynamical 'collapse' theory, formulated as a continuous spontaneous localization theory.

The remaining possibility is to adopt an alternative principle for selecting the set of observables that have determinate values in a given quantum state. This was Bohm's approach, and also – very differently – Bohr's. Bohm's 1952 hidden variable theory or 'causal' interpretation (Bohm, 1952a; Bohm and Hiley, 1993) takes the position of a system in configuration space[9] as determinate in every quantum state. Certain other observables can be taken as determinate at a given time together with this 'preferred' always-determinate observable, depending on the state at that time. Alternative formulations of Bohm's theory present different accounts of 'nonpreferred' observables such as spin. On the formulation proposed here, the theory is a 'modal' interpretation of quantum mechanics, in the broad sense of van Fraassen's notion (see chapter 6). For Bohr, an observable has a determinate value only in the context of a specific, classically describable experimental arrangement suitable for measuring the observable. Since the experimental arrangements suitable for locating a quantum system in space and time, and for the determination of momentum–energy values, turn out to be mutually exclusive, there is no unique description of the system in terms of the determinate properties associated with the determinate values of a fixed preferred observable. So which observables have determinate values is settled pragmatically by what we choose to observe, via the classically described measuring instruments we employ, and is not defined for the system alone. Bohr terms the relation between space–time and momentum–energy concepts 'complementary,' since both sets of concepts are required to be mutually applicable for the specification of the classical state of a system.

What is generally regarded as the 'Copenhagen interpretation' is some fairly loose synthesis of Bohr's complementarity interpretation and Heisenberg's ideas on the significance of the uncertainty principle. It is usual to pay lip service to the Copenhagen intepretation as the 'orthodox' interpretation of quantum mechanics, but the interpretative principle behind complementarity is very different from the Dirac–von Neumann principle. (I discuss the relationship in detail in sections 7.1 and 7.2). Unlike Dirac and von Neumann, Bohr never treats a measurement as an interaction between two quantum systems, and hence has no need for a special 'projection postulate' to replace the linear Schrödinger evolution of the quantum state during a measurement process. Both Dirac and von Neumann introduce such a postulate to describe the stochastic projection or 'collapse' of the state onto an eigenstate of the pointer reading and measured observable – a state in which these observables are determinate on their interpretation. (See Dirac, 1958, p. 36, and von Neumann, 1955, p. 351 and pp. 417–18.) The complementarity interpretation avoids the measurement problem by selecting as determinate an observable associated with an individual quantum 'phenomenon' manifested in a measurement interaction involving a specific classically describable experimental arrangement. Certain other observables, regarded as measured in the

[9] For an N-particle system, the configuration space of the system is a $3N$-dimensional space, coordinatized by the $3N$ position coordinates of the particles.

interaction, can be taken as determinate together with this observable and the quantum state.

Einstein viewed the Copenhagen interpretation as 'a gentle pillow for the true believer.'[10] For Einstein, a physical system has a 'being-thus,' a 'real state' that is independent of other systems or the means of observation (see the quotations in section 1.1 and section 6.1). He argued that realism about physical systems in this sense is incompatible with the assumption that the state descriptions of quantum mechanics are complete. What Einstein had in mind by a 'completion' of quantum mechanics is not entirely clear, but on one natural way of understanding this notion (as an observer-free 'no collapse' interpretation subject to certain physically plausible constraints), the possible completions of quantum mechanics are fully characterized by the uniqueness theorem in chapter 4.[11]

This book begins with a survey of the problem of interpretation, as it arises in the debate between Einstein and Bohr. Einstein's discomfort with quantum mechanics cannot be attributed to an aversion to indeterminism. He did not argue that quantum mechanics must be incomplete *because* 'God does not play dice with the universe.' Rather, as Pauli put it, Einstein's 'philosophical prejudice' was realism, not determinism (section 1.1). It is not that all indeterministic or stochastic theories were problematic for Einstein. What Einstein objected to were stochastic theories that violate certain realist principles; or rather, he objected to taking such theories as anything more than predictive instruments that would ultimately be replaced by a complete explanatory theory.

Chapter 1 continues with a discussion of the transition from classical to quantum mechanics, and a formulation of the measurement problem as a problem generated by the orthodox (Dirac–von Neumann) interpretation of the theory. My main aim here is to bring out the different ways in which dynamical variables and properties are represented in the two theories. In classical mechanics, the dynamical variables of a system are represented as real-valued functions on the phase space of the system and form a commutative algebra. The subalgebra of idempotent dynamical variables (the characteristic functions) represent the properties of the system and form a Boolean algebra, isomorphic to the Boolean algebra of (Borel) subsets of the phase space of the system. In quantum mechanics, the dynamical variables or 'observables' of a system are represented by a noncommutative algebra of operators on a Hilbert space, a linear vector space over the complex numbers, and the subalgebra of idempotent operators (the projection operators) representing the properties of the system is a non-Boolean algebra isomorphic to the lattice of subspaces of the Hilbert space. So the transition from classical to quantum mechanics involves the transition from a Boolean to a non-Boolean structure for the properties of a system.

There are restrictions on what sets of observables can be taken as simultaneously determinate without contradiction, if the attribution of determinate values to observ-

[10] In a letter to Schrödinger, dated May, 1928. Reprinted in Przibram (1967, p. 31).

[11] See Fine (1986), especially chapter 4, for a different interpretation of Einstein's view.

ables is required to satisfy certain constraints. The 'no go' theorems for hidden variables underlying the quantum statistics provide a series of such results that severely limit the options for a 'no collapse' interpretation of the theory.

In chapter 2, I present the Einstein–Podolsky–Rosen (1935) incompleteness argument, and several versions of Bell's extension of the argument to a 'no go' theorem demonstrating the inconsistency of stochastic and deterministic hidden variables, satisfying certain locality and separability constraints, with the quantum statistics.

Chapter 3 deals with the Kochen and Specker (1967) 'no go' theorem, showing the impossibility of assigning determinate values to certain finite sets of observables if the value assignments are required to preserve the functional relations holding among the observables. I present a new proof of the theorem for a set of 33 observables (1-dimensional projectors), based on a classical tautology that is quantum mechanically false proposed by the logician Kurt Schütte in an early (1965) unpublished letter to Specker.

Chapter 4 introduces the problem of interpretation, and contains the proof of the uniqueness theorem demonstrating that, subject to certain natural constraints, all 'no collapse' interpretations of quantum mechanics can be uniquely characterized and reduced to the choice of a particular preferred observable as determinate. The preferred observable and the quantum state at time t define a (non-Boolean) 'determinate' sublattice in the lattice $\mathscr{L}$ of all subspaces of Hilbert space – the sublattice of propositions that can be true or false at time t. The actual properties of the system at time t are selected by a 2-valued homomorphism (a yes–no map) on the determinate sublattice at time t, so the range of possibilities for the system at time t is defined by the set of 2-valued homomorphisms on the determinate sublattice. From this 'modal' perspective, the possibility structure of a quantum world is represented by a *dynamically evolving* (non-Boolean) sublattice in $\mathscr{L}$, while the possibility structure of a classical world is fixed for all time as the Boolean algebra $\mathscr{B}$ of subsets of a phase space. The dynamical evolution of the quantum state tracks the evolution of possibilities (and probabilities defined over these possibilities) through the evolution of the determinate sublattice, rather than actualities, while the dynamically evolving classical state defines the actual properties in a classical world as a 2-valued homomorphism on $\mathscr{B}$ and directly tracks the evolution of actual properties. In a quantum world, the dynamical state is distinct from the 'property state' (defined by a 2-valued homomorphism on the determinate sublattice), while the classical state doubles as a dynamical state and a property state.

Different choices for the preferred determinate observable correspond to different 'no collapse' interpretations of quantum mechanics. In chapter 5, I show how the orthodox (Dirac–von Neumann) interpretation without the projection postulate can be recovered from the theorem, and how the measurement problem is avoided in 'no collapse' interpretations by an appropriate choice of the preferred determinate observable. Property states must evolve in time so as to reproduce the quantum statistics over the determinate sublattices defined by the dynamical evolution of quantum states. Since the determinate sublattice at time t is uniquely defined by the quantum state at t and a preferred observable, it suffices to provide an evolution law for the actual values of the preferred determinate observable. Following a proposal by Bell (1987, pp. 176–7) and Vink (1993), I formulate a specific stochastic equation of motion for the case of a discrete preferred observable, which reduces to the deterministic evolution law of Bohm's theory in the continuum limit, if the preferred observable is continuous position in configuration space. It turns out that the interaction between a measuring instrument and its environment plays a crucial rôle in guaranteeing that the actual value of an appropriately chosen preferred determinate observable will evolve stochastically in time so that the observable functions as a stable pointer in ideal or non-ideal measurement interactions. In this respect, the choice of preferred observable is constrained by the dynamics of system–environment interactions in our world: if we want an interpretation of quantum mechanics to account for the measurement interactions that are possible in our world, we need to choose a preferred determinate observable for which measurement correlations persist under environmental 'monitoring.' It is not the phenomenon of decoherence as a loss of interference that is relevant here. Rather, the fact that measuring instruments are open systems interacting with environments with many degrees of freedom turns out to have a very different dynamical significance in an observer-free 'no collapse' interpretation with a fixed preferred determinate observable.

In chapter 6, I show how Bohm's causal interpretation (one natural way to develop an Einsteinian realism within quantum mechanics) and the modal interpretation (in a version generalized from earlier formulations by Kochen, 1985, and by Dieks, 1988, 1989a, 1994a,b) can be seen as two observer-free 'no collapse' interpretations in the sense of the theorem. Bohm's interpretation adopts position in configuration space as a fixed preferred determinate observable, while the modal interpretation can be understood as adopting a time-dependent preferred determinate observable derived from the quantum state.

I discuss Bohr's complementarity interpretation as a 'no collapse' interpretation in chapter 7, and show how this interpretation can be related to the orthodox (Dirac–von Neumann) interpretation from the perspective of the uniqueness theorem.

The 'new orthodoxy' appears to center now on the idea that the original Copenhagen interpretation has been vindicated by the recent technical results on environmental decoherence. Sophisticated versions of this view are formulated in terms of 'consistent histories' or 'decoherent histories,' and trade on features of Everett's 'relative state' interpretation of quantum mechanics as a solution to the measurement problem (popularly understood as a 'many worlds' theory, in some sense). In chapter 8, I argue that there is no real advance here with respect to Einstein's qualms about the Copenhagen interpretation. It is still a 'gentle pillow for the true believer,' perhaps now with the added attraction of a rather fancy goose-down comforter.

The coda concludes with a review of the main themes of the argument, and its significance for the debate on the interpretation of quantum mechanics and the measurement problem.

In the appendix, I develop some mathematical machinery dealing with the structure of Hilbert space and the representation of states, probabilities, and observables in quantum mechanics. The discussion, which is intended to be self-contained for a reader with some minimal mathematical competence, covers the 'entangled' states of quantum systems that arise in measurement interactions and situations of the Einstein–Podolsky–Rosen type, and the formalism for some illustrative examples dealing with spin. No particular formal background is assumed, beyond a passing familiarity with the basic concepts of vector spaces, complex numbers, and probability theory.