Chapter 2: Interpretations of Quantum Mechanics and the Measurement Problem

2.1 Historical Context

Quantum physics grew from attempts to understand the behaviour of infinitesimally small sub-atomic entities. As outlined by Heisenberg, in his 1932 Noble Prize address[1], the basic postulates of the quantum theory arose from the fact that atomic systems are capable of assuming only discrete stationary states, and therefore of undergoing only discrete energy changes.

Initially the program of quantum mechanics involved attempting to model observable phenomena such as the electromagnetic emission and absorption spectrum of atoms. Classical physics had dealt with "objective" processes occurring in space and time by specifying some initial conditions and modelling the time evolution of such processes. In addressing the quantum problem, Heisenberg observed that, according to the program of classical physics, it ought to be possible to calculate the exact path of electrons "orbiting" atomic nuclei from the measured properties of the emitted and absorbed radiation. However, the program of producing a causal model in which the frequency spectrum is directly related to the path of an electron "orbiting" around an atom met with very considerable difficulties. Heisenberg's ultimate solution to the problem was to develop the theory of Matrix Mechanics[2], in which any concept which could not be experimentally verified was excluded. Heisenberg observed that by abandoning notions which were not experimentally testable, contradictions between experiment and theory

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[1] Heisenberg W., *Nobel Prize in Physics Address: A General History of the Development of Quantum Mechanics*, 1932. Published by Elsevier Publishing Co, with the permission of the Nobel Foundation. Cited from The World of Physics Vol. 2, pp. 353-367. Simon and Schuster, New York (1987).

could be avoided. Consequently, Heisenberg argued that classical concepts such as the electron trajectory (position & momentum), which remains unobservable, should be abandoned at the quantum level. Heisenberg emphasised that the existence of entities which are in-principle unobservable cannot be objectively established and belief in their existence is therefore a matter of personal choice.

Soon afterwards, Schrodinger produced his “Wave Mechanics”, in which a quantum mechanical description of a system is presented in terms of a characteristic function known as the wave function. Following the publication of his original paper[3], Schrodinger initially advanced the view that entities such as electrons and photons were, in fact, waves. A wave model, which interpreted the Schrodinger wave function as describing the spatial extent of real physical waves, seems well suited to explaining quantum interference. However, there are a number of difficulties with erecting a wave-based quantum theory to describe individual electrons which can be counted by Geiger counters and observed as spots on photographic plates.

2.2 Mathematical Structure and Statistical Interpretation

The mathematical structures of the Heisenberg and Schrodinger formulations of quantum mechanics are well understood and their formal equivalence was established very early on by Schrodinger and Dirac. Consistent with the original formulations, the general Hilbert Space representation was developed.

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[2] Heisenberg W., Z. Physik Vol. 33, p. 879 (1925).

[3] Schrodinger, E., Ann. Physik Vol. 79, pp. 361 and 489 (1925); Vol. 80, p. 437 (1926); Vol. 81, p. 109 (1926)

In deducing the correct statistical meaning for the normalised Schrodinger wave function, Max Born provided the central, experimentally verified tenet of non-relativistic quantum mechanics. Born's postulate requires that the volume integral of the square of the Schrodinger wave function's modulus give the probability of finding the particle in that volume. In a similar manner, the statistical distribution of measurement results for any other observable quantity may be determined by switching the wave function to the representation corresponding to that observable. The desired distribution is then given by the squared modulus of the transformed wave function. In this scheme, physical quantities are incorporated as representation-dependent, self-adjoint[4] mathematical operators. The point must be made emphatically that, in terms of Born's Interpretation, the Schrodinger wave function, or *state function,* describes the statistical behaviour of an aggregated collection. This quantum mechanical statistical algorithm need not constrain individual ensemble members.

2.3 The Correspondence Principle

The Correspondence Principle requires that, under appropriate limiting circumstances (usually expressed as $\lim \dot{g} \rightarrow 0$) quantum mechanics reduce to classical mechanics. In this way, quantum mechanics can be viewed as a mathematical generalisation, which for large objects is consistent with classical mechanics.

2.4 The Copenhagen Interpretation

While the mathematical structure of quantum mechanics is extremely well understood, it is clear that this structure provides very little insight into the nature of any "continuously

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[4] Self-adjoint or Hermitian operators have real eigenvalues and hence are the only class of operators which can represent real physical magnitudes.

existing reality”. Schrodinger[5] eventually conceded that the quantum mechanical formalism developed provides only a statistical algorithm for making predictions about measurement results and does not provide any clear picture of entities existing between measurement events. It therefore gives no insight into the nature of any possible underlying reality and fails to support a “principle of causality” in any form.

Adherents to the "Copenhagen interpretation" of quantum mechanics assert that a “complete description of reality” is in fact provided by Born's experimentally verified statistical hypothesis (above) and that models describing the time evolution of individual entities between observations are neither useful nor possible. Niels Bohr summarises the Copenhagen view well claiming that “*in quantum mechanics we are not dealing with an arbitrary renunciation of a more detailed analysis of atomic phenomena, but with a recognition that such an analysis is in principle excluded.*[6]”

In an effort to challenge the Copenhagen interpretation, which proposed that quantum theory provided a complete description of individual quantum entities rather than a statistical algorithm for determining the behaviour of quantum ensembles, Einstein and others developed a variety of objections to various peculiarities inherent in the Copenhagen viewpoint. Schrodinger’s Cat and the non-locality following from the EPR paradox rank as the most famous of these challenges. In contrast with Bohr, Einstein

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[5] Schrodinger E., *Science & Humanism; Physics in Our Time*, Cambridge 1951. Cited from Newnam J.R., *Causality and Wave Mechanics* in The World of Mathematics Vol II, pp. 1056-1068. George Allen & Unwin Ltd (1960).

[6] Goldstein S., *Quantum Theory Without Observers - Part One,* in Physics Today, March 1998, pp. 42-46.

asserted that the wave function provided a description of only quantum ensembles and not of individual quantum entities[7].

Toulmin[8] observes that much of the unfocussed and unresolved controversy concerning the interpretation of quantum mechanics has its roots in the fact that Einstein and his supporters have refused to accept the change in standards of "*what needs explaining*" which has been made with the development of the Copenhagen interpretation of quantum mechanics. In Einstein's view, these changes require one to restrict the horizon of scientific endeavour in an unjustifiable way. Einstein's opponents, on the other hand, claim that his objections show only that he has not properly understood the theory. Toulmin does not deal with the substance of the dispute but draws significant attention to the language in which the dispute is carried on. The dispute is couched in terms of the question, "*Is a quantum mechanical description of a physical system complete or not?*" Toulmin argues that this way of posing the problem confuses the issue, giving it too sharp an appearance of opposition. A complete or exhaustive description of a physical system is one from which one can, using the currently accepted laws of nature, infer all properties of the system for which it is a physicist's ambition to account. Where two physicists do not share a common standard of what does and does not need to be explained, there is no hope on their agreeing that the corresponding description can be called complete. The use of the word complete, with its implicit reference to particular criteria of completeness, may serve to conceal rather than reveal the point at issue. A similar moral holds more generally where, in the absence of any explanation, the term "*reality*" is

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[7] Einstein A. and Franklin J., *Physics and Reality* (1936). Cited from Dewitt B.S. and Graham N.R., *Resource Letter IQM-1 on the Interpretation of Quantum Mechanics*, American Journal of Physics. Vol. 39 pp. 724-738 (1971). See especially pp. 730 & 731.

frequently used. Heisenberg highlighted this when asked directly the question: "*Is there a fundamental level of reality?*" He responded as follows:

"This is just the point; I do not know what the words fundamental reality mean. They are taken from our daily life situation where they have a good meaning, but when we use such terms we are usually extrapolating from our daily lives into an area very remote from it, where we cannot expect the words to have a meaning. This is perhaps one of the fundamental difficulties of philosophy: that our thinking hangs in the language. Anyway, we are forced to use the words so far as we can; we try to extend their use to the utmost, and then we get into situations in which they have no meaning."[9]

2.5 Hidden Variable Theories

In spite of the Copenhagen interpretation, there have been extensive efforts to introduce theories providing a deeper description of nature. Principally these theories have taken the form of "hidden variable" theories in which certain properties of individual quantum entities always pre-exist before an act of measurement. One motivation for the hidden variables program is that the Copenhagen interpretation of the Schrodinger equation is unable to account in a satisfying way for the process of measurement wherein a discontinuous transition from a spread-out state to a definite experimental result occurs. Schrodinger wave functions evolve continuously and smoothly through time and after a particle and an apparatus interact they are described by a single, overall wave function from then on. This transition to a correlated state should result in the state of the

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[8] Toulmin S., *The Philosophy of Science,* pp. 118-9. Hutchison and Company, London. (Sixth Impression 1962).

[9] Buckley P. and Peat F.D., *A Question of Physics; Conversations in Physics and Biology,* pp. 3-16. Routledge and Kegan Paul, London and Henley (1979). See especially p. 9.

apparatus becoming less definite, rather than the particle’s state becoming more definite. However, at the macroscopic level, definite measurement results are always obtained. The Copenhagen “analysis” of the measurement process simply invokes Von Neumann's Projection Postulate, which asserts that the state vector evolves according to the Schrodinger equation while the system is isolated, but changes discontinuously during measurement to an eigenstate of the observable that is measured[10]. Because of the apparent necessity that the postulate apply only for "measurement" interactions, not for "non-measurement" interactions, there has been much controversy concerning this infamous Measurement Problem and the Copenhagen interpretation in general since they were first proposed.

Hidden variables programs frequently take their motivation from other areas of physics such as the classical theory of gases, which is understood as a macroscopic approximation arising statistically from the aggregated behaviour of a large number of microscopic gas molecules. On the other hand, advocates of the Copenhagen interpretation have attempted to produce "impossibility proofs" intended to demonstrate the incompatibility of hidden variables theories with quantum mechanics. Von Neumann claimed to present a proof that hidden variables theories were not possible, but the proof failed since it made the incorrect assumption that an algebraic rule which must hold in the mean for non-commuting observables must also hold for the individual hidden values[11].

Since the formalism of quantum mechanics does not necessarily imply the Copenhagen interpretation, the possibility of constructing different models that are observationally

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[10] Ballentine L.E., *Resource Letter IQM-2: Foundations of Quantum Mechanics since the Bell Inequalities.* American Journal of Physics Vol. 55, pp. 785-792 (1987).

equivalent to conventional quantum mechanics remains open[12]. Although certain types of hidden variables models can be ruled out, it is not possible to invalidate all hidden variables models. Writing in Physics Today (1998), Goldstein[13] claims that the Bohr-Einstein debate has actually been resolved in favour of Einstein since a number of observer-free formulations of quantum mechanics, in which the process of measurement can be analysed in terms of more fundamental concepts, have been produced. Examples of observer-free formulations include: Decoherent Histories, Spontaneous Localisation and Pilot Wave theories (including Bohm's Model).

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[11] Von Neumann J., *Mathematical Foundations of Quantum Mechanics*, Princeton U. P., New Jersey (1955). Also, Bell J.S., Rev. Mod. Phys. Vol.38, p. 447 (1966).

[12] Cushing J.T., *Quantum Mechanics: Historical Contingency & the Copenhagen Hegemony.* p. 42. University of Chicago Press (1994).

[13] Goldstein S., *Quantum Theory Without Observers - Part One.* Physics Today, March 1998, pp. 42-46.