Chapter II

The Interpretations of Quantum Mechanics

2.1 Introduction

The formalism of quantum mechanics (see Appendix A and B) is widely accepted to be well-established. On the other hand, its interpretation remains an open question. The orthodox interpretation of quantum mechanics is the Copenhagen interpretation. Its modified version is the neo-Copenhagen interpretation. Early attempts at the interpretational problems of the quantum mechanical formalism resulted in the semiclassical interpretations. Hidden variable theories, though, have come from studies in many diverging subjects. Other interpretations include the stochastic interpretations, the transactional interpretation and the statistical interpretation. An abstract quantum theory has also been put forward by C. F. von Weizsäcker and his colleagues.

2.2 The Interpretation

While physicists ask what is the correct interpretation of quantum mechanics, philosophers of science are concerned about what it means to interpret such a theory (Jammer, 1974, p.9).

Ballentine (1970, pp.359-360) believes that quantum theory, and indeed any theory, can be divided into :

a) A mathematical formalism consisting of a set of primitive concepts, relations between these concepts (either postulated or obtainable by given rules of deduction), and a dynamical law.

b) Correspondence rules which relate the theoretical concepts of a) to the world of experience.

The correspondence rules must relate the primitive concepts of state and observable to empirical reality. In so doing they will provide an interpretation. While Jeffrey Bub (1974) says that an interpretation of quantum mechanics should show in what fundamental respects the theory is related to preceding theories, he proposes that quantum mechanics is to be understood as a <u>principle</u> theory, in Einstein's sense of the term (Einstein, 1963). The distinction here is between <u>principle</u> theories, which introduce abstract structural constraints that events are held to satisfy, and <u>constructive</u> theories, which aim to reduce a wide class of diverse systems to component systems of a particular kind.

John Cramer (1986, pp.648-649) implies that the interpretation of quantum mechanics concerns the meaning of the mathematics and the underlying reality behind the laws and procedures of quantum mechanics. Since interpretations of a physical theory cannot normally be subjected to experimental verification, he suggests the following criteria for critical comparision :

1) Economy : minimum number of independent postulates.

2) Compatibility : compatible with physical laws.

3) Plausibility : mechanisms, if any, should be physically plausible.

4) Insightfulness : provide insight into the underlying mechanism of nature.

2.3 The Copenhagen Interpretation

2.3.1 What Is the Copenhagen Interpretation ?

Different authors think of different things when speaking about the Copenhagen interpretation. L. E. Ballentine (1987) thinks that the term in its popular, but not necessarily historically accurate sense, includes the following propositions :

a) The state vector provides a complete description of an individual system (that is, the views of Bohr rather than those of Einstein in their famous controversy);

b) The state vector evolves according to the Schrödinger equation while the system is isolated, but changes discontinuously during measurement to an eigenstate of the observable that is measured (von Neumann's "projection postulate"). Of course this does not fully characterize the Copenhagen interpretation. In particular, Born's statistical interpretation of the wavefunction is also an essential ingredient, but it is either a postulate or a consequence of almost every interpretation, so it does not distinguish one from another.

Meanwhile, John G. Cramer (1986, pp.649-651) has identified five principal elements of the Copenhagen interpretation, as follows :

(C-1) The uncertainty principle of Heisenberg (1927) : this includes wave-particle duality, the role of canonically conjugate variables, and the impossibility of simultaneously measuring pairs of such variables to arbitrary accuracy.

(C-2) The statistical interpretation of Born (1926) : this includes the meaning of the state vector or wave function, Ψ, given by the probability law ($P = \Psi\Psi^*$) and the predictivity of the formalism only for the average behaviour of a group of similar events.

(C-3) The complementarity concept of Bohr (1928) : this includes the "wholeness" of the microscopic system and macroscopic measurement apparatus, the complementary nature of wave-particle duality, and the character of the uncertainty principle as an intrinsic property of nature rather than a peculiarity of the measurement process.

(C-4) Identification of the state vector with "knowledge of the system" by Heisenberg : this includes the identification itself and the use of this concept to explain the collapse of the state vector and to eliminate simple nonlocality problems.

(C-5) The positivism of Heisenberg (1927) : this includes declining to discuss "meaning" or "reality" and focussing interpretive discussions exclusively on observables.

These five elements comprise the essential physical and philosophical characteristics of the Copenhagen interpretation. However, only elements (C-1) and (C-2) alone are being considered by most working physicists in using quantum mechanics. Indeed, (C-1) and (C-2), without any reference to (C-3), (C-4) and (C-5), are represented in many quantum-mechanics textbooks as " the Copenhagen interpretation." Thus Bohr's contention that the Copenhagen interpretation has been "proven by experiment" is perhaps correct as it applies to elements (C-1) and (C-2), but not as it applies to (C-3) through (C-5). Moreover, (C-4) has, in effect, been tested by experiment and found wanting, in that it has failed to neutralize the manifest nonlocality exhibited by carefully designed Bell inequality experiments (see Appendix C).

2.3.2 The Interpretational Problems Presented by the Quantum Mechanical Formalism

2.3.2.1 Identity : What Is the State Vector ?

In the formalism of quantum mechanics the possible states of a system are described by a state vector , a function (usually complex) that depends on position, momentum, time, energy, spin, and isospin variables, etc. The state vector (which will be represented as $|S\rangle$ in the notation of Dirac) is the most general form of the quantum-mechanical wave function Ψ. The problem of identity is to explain the physical significance of the state vector.

2.3.2.2 Complexity : Why Is the State Vector a Complex Quantity ?

Complex functions are found in classical physics, but are invariably interpreted either (1) as an indication that the solution is unphysical or (2) as a way of dealing with two independent and equally valid solutions of the equations, one real and one imaginary. Never in classical physics is the full complex function "swallowed whole" as it is in quantum mechanics. This is the problem of complexity.

2.3.2.3 Collapse : How and Why Does the State Vector Abruptly Change ?

The state vector of a system before a measurement is performed is very different from the state vector immediately after the measurement, even when the measurement is not the final state of the system but rather one of a series of sequential measurements or operations. There are two distinctly different types of change that the state vector undergoes : Type (1) changes the state vector smoothly and continuously with time as the system evolves; Type (2) changes the state vector abruptly and discontinuously with time in accordance with the laws of probability when (and only when) a measurement is made on the system. This is conventionally referred to as the "collapse of the state vector."

2.3.2.4 Nonlocality : How Are Correlations of Separated Parts of the State Vector Arranged ?

The problem of nonlocality is clearly related to that of the collapse of the state vector (see 2.3.2.3). Cramer (1986) distinguishes between two kinds of nonlocality. Nonlocality of the first kind arises from the interpretation of the state vector as a physical wave. When the state vector collapses the change implicit in the collapse occurs at all positions in space described by the state vector at the same time. A physical wave undergoing such a change would seem to require faster-than-light propagation of information.

(C-4) was constructed to avoid difficulties with nonlocalities of the first kind by denying the physical reality of the state vector and identifying it instead with "our knowledge of the system." Therefore, when a measurement is made showing that a photon is located at point A (and not at B or C), our knowledge of the photon's location abruptly changes and the magnitude of the state vector's value must suddenly drop to zero at B and C, although no spatial propagation, according to (C-4), is associated with that abrupt change.

But the intrinsic nonlocality of the quantum mechanical formalism runs deeper than this. This becomes clear when more complicated situations are considered which involve separated measurements of parts of a correlated system. In that situation, definitions of the state vector become irrelevant because real measurements are involved. This leads to a <u>nonlocality of the second kind.</u> which is associated with the enforcement of correlations in spatially separated measurements. This is the Einstein-Podolsky-Rosen (EPR) paradox (Einstein et al. 1935) (see Appendix C).

2.3.2.5 Completeness : Do Canonically Conjugate Variables Have Simultaneous Reality ?

Another problem raised in the Einstein-Podolsky-Rosen (EPR) paper (see Appendix C) is that of the correspondence between the quantum-mechanical formalism and reality for the case of pairs of canonically conjugate variables, i.e., pairs of variables like position and momentum having quantum-mechanical operators that do not commute. The EPR paper argues that "every element of the physical reality must have a counterpart in the physical theory" and points out that, in terms of the quantum-mechanical formalism, "when the operators corresponding to physical quantities do not commute, they cannot have simultaneous reality." Thus (goes the argument) there is a lack of correspondence between quantum mechanics and reality, and the former must be "incomplete."

Yet, from one point of view, the quantum-mechanical formalism contains the solution to the completeness problem. The variables do have "simultaneous reality" in the uncollapsed state vector but can never have simultaneous reality in a single component of the state vector which results from the collapse.

The above resolution of the EPR completeness criticism is, however, demolished by the Copenhagen interpretation itself, since (C-4) denies the objective reality of the state vector and associates it instead with the "knowledge"of an observer. Then the "reality" of the conjugate variables becomes only a subjective one arising from the observer's lack of information, in support of the EPR criticism. However, it is not, as was supposed, a problem with the quantum-mechanical formalism, but with the interpretation of the formalism.

2.3.2.6 Predictivity : Why Can We Not Predict the Outcome of an Individual Quantum Event ?

The third criticism of quantum mechanics by the EPR paper (1935) (see Appendix C) was that a proper theory should enable the user to, "without in any way disturbing the system, ... predict with certainty ... the value of a physical quantity." Quantum mechanics, on the other hand, provides the user with a way of predicting only average behaviour of an ensemble of quantum events but not the behaviour of a particular particle in a particular event (except in the unusual circumstance when one particular outcome of the event has a predicted probability of 1.0 and all other outcomes have predicted probabilities of zero (see also 2.8)). This is the problem of predictivity.

2.3.2.7 The Copenhagen Interpretation and the Uncertainty Principle

Element (C-1), the uncertainty principle of Heisenberg (1927), is one of the most important aspects of the Copenhagen interpretation. Heisenberg's uncertainty relations are a direct consequence of the character of the solutions of the Schrödinger equation and its relativistic equivalents, solutions that are functions of products of conjugate variables such as **k.r** and Et. In fact, Heisenberg's original derivation of the uncertainty principle dealt directly with this property of the wave equation solutions by showing that the Fourier transform of a localized Gaussian position wave function is a localized Gaussian momentum-space wave function, with the momentum width of the latter Gaussian proportional to the reciprocal of the position width of the former Gaussian. This property of Gaussian distributions under Fourier transforms has many analogues in classical physics.

However (C-4) asserts that the state vector that is the carrier of these canonically conjugate quantities is not a real wave. This renders more questionable any association of the uncertainty principle of quantum mechanics with similar phenomena of classical physics (for details of 2.3.2 see, for example, Cramer, 1986, pp.651-658).

2.3.3 The Neo-Copenhagen Interpretation

Henry P. Stapp (1971; see also Ballentine, 1987, p.788) attempts to develop an interpretation of quantum mechanics that is nonlocal. His basic concepts are that the physical world must be seperated into two parts, called the observed and the observing system, and that the probabilities in the theory are probabilities of response of the measuring devices. "Collapse of the wave function" does not occur as a physical process, but only corresponds to a "change in the set of specifications on the preparation of the observed system." Stapp (1972) also radically revises what is often called "the Copenhagen interpretation" by rejecting von Neumann's "reduction" of the state vector in measurement and Heisenberg's subjectivistic statements. The very "pragmatic" aspect of the interpretation is strongly emphasized. Stapp's interpretation has been known as the "neo-Copenhagen interpretation."

2.4 Semiclassical Interpretations

The main ideas are :

2.4.1 Schrödinger's Electrodynamic Interpretation

It was presented primarily in Schrödinger's fourth paper (Schrödinger, 1926; see also Rohrlich, 1987, p.1210). His idea is that quantum mechanics is a classical theory of waves, these are the fundamental ontological objects, and matter is, in the last analysis, a complicated superposition of them. These "matter waves" are continuous functions of space and time. Furthermore, the continuity equation which is easily derivable from the free Schrödinger equation suggests an electromagnetic interpretation of the wave function Ψ . The charge density of the electron is to be identified with the electron charge e times $\Psi^*\Psi$, and the electric current density is the corresponding expression $e\hbar\ (\Psi^*\nabla\Psi - \Psi\nabla\Psi^*)/2mi$. The theory is, however, only semiclassical because of the quantization involved, which provides for the stability of the charge distribution of the electrons in the atom, this distribution cannot be stable classically.

Difficulties of Schrödinger's interpretation were apparent almost immediately. Lorentz asked, among other questions, (1) how the spreading of the wave packet can be compatible with the identification of wave packet and particle, (2) how the wave function can describe a wave in ordinary three-dimensional space when its configuration space has more than three dimensions, and (3) how a single electron in the photoelectric effect is pried loose from the complex superposition of matter waves that make up the charge distribution of all the electrons in an atom. Heisenberg questioned whether Schrödinger's interpretation would permit a derivation of Planck's law of black-body radiation. And Schrödinger himself noted that (1) since the wave function is complex, it must represent two real waves and (2) there is an inconsistency between the continuous charge distribution of the electron in the hydrogen atom and the use of Coulomb's law for point particles in his equation. Finally, Schrödinger admitted defeat publicly in 1927.

2.4.2 De Broglie's "Guide Wave" Interpretation

The guide wave interpretation (de Broglie, 1926; Cramer, 1986, p.682) suggests a specific underlying mechanism for the interplay of waves and particles in a quantum event. De Broglie (1964) gave the following summary :

> ... a particle is a very small object which is constantly localized in space, and a wave is a physical process which is propagated in space in the course of time according to a given equation of propagation. ... the wave has a very low amplitude and does not carry energy, at least not in a noticeable manner. The particle is a very small zone of highly concentrated energy incorporated in the wave, in which it constitutes a sort of generally mobile singularity. By reason of this incorporation of the particle in the wave, the particle possesses an internal vibration which, as it moves, remains constantly in phase with the vibration of the wave.... the mean path of the particle is determined according to the shape of the wave by a certain "guidance law," but this motion has superimposed on it continual fluctuations corresponding to a hidden variable behaviour of the particles.

It is thus apparent that the guide wave interpretation presents a very different view of quantum events from that of the Copenhagen interpretation. The "wave" in the above description is the state vector itself, which has a definite but limited reality in that it can physically travel through space but cannot carry energy, momentum, etc. The collapse does not occur, but is replaced by the action of the particle, which "rides" the state vector and arrives with the largest probability at the locations where the state vector has the largest amplitude, the general properties of the state vector being separated from those of the specific particle that tracks it.

The most serious problem of the guide wave interpretation is that it is implicitly local, and therefore inconsistent with the Bell inequality experiments (see Appendix C). There are also grounds for believing that it may be inconsistent with the formalism of quantum mechanics. From a certain point of view, the guide wave interpretation can be taken as a kind of preliminary version of the transactional interpretation (see 2.7).

2.4.3 The "Disturbance Model"

It is the notion often mentioned in textbooks, that canonically conjugate variables of a particular system under study can "actually" have simultaneous well-defined values, but that the act of making a measurement of one of these variables "disturbs" the other so that no knowledge of it can be obtained. The disturbance model (Herbert, 1985; Cramer, 1986, p.682) has been refuted by the experimental tests of Bell's inequality (see Appendix C), but remains to be held by some physicists.

2.4.4 Other Semiclassical Models

Other semiclassical interpretations (Jammer, 1974, pp.33-38, 49-54) include the hydrodynamic interpretations proposed by Erwin Madelung (1926), by A. Isakson (1927) and by Arthur Korn (1927). Their basis is the similarity of the wave equation and its implications with the equations of hydrodynamical flow. More recent hydrodynamic models were proposed by Oscar Buneman (1956), by Takehiko Takabayasi (1952, 1953), by Mario Schönberg (1954 a, b), by David Bohm and Jean-Pierre Vigier (1954, 1958) and by Lajos Jánossy (1962).

2.5 Hidden Variable Theories

2.5.1 Motivations

Motivations for hidden variables (Jammer, 1974, pp.253-267) :

1. To regard ordinary quantum theory as a kind of statistical mechanics which yields only average values of measured quantities while at a more profound -- but for the time being empirically inaccessible -- level each individual system should be regarded as performing its motion in accordance with strictly deterministic laws.

2. To dispense with the peculiar dichotomy of physics into classical and quantum phenomena and re-establish a unitary account of the physical world, a prospect of sometimes greater incitement than the desire for determinism (see also 3.6 and 4.4).

3. To search for a "completion" of quantum mechanics regarding the problem raised by the EPR argument (see Appendix C).

Although the EPR incompleteness argument was one of the major incentives for the modern development of hidden variable theories, it would be misleading to regard Einstein as a proponent of hidden variables.

2.5.2 Definitions

Jammer (1974, p.255) has distinguished between "hidden variables" and "hidden variable interpretations" or "hidden variable theories." He uses the former term if the usual formalism of quantum mechanics is retained and the latter term if it is modified, thus leading to a new theory.

There is still no generally accepted definition of hidden variables. David Bohm (1962) characterized them as "a further set of variables, describing the state of new kinds of entities existing in a deeper subquantum mechanical level and obeying qualitatively new types of individual laws." He then added that such variables, though at present "hidden", may "be revealed in detail when we will have discovered still other kinds of experiments, which may be as different from those of the current type as the latter are from experiments that are able to reveal the laws of the large-scale level."

According to Peter Mittelstaedt (1968a), on the other hand, hidden variables characterize a theory in the formulation of which one "dispenses with a pervasive realizability of the theory." The prescientific operative measurement procedures needed to define the fundamental notions of the theory, he argued, may or may not be consistent with the measurement prescriptions as derived from the body of the theory. In other words, not every theory necessarily satisfies what C. F. von Weizsäcker (1971) called "the principle of semantic consistency," the requirement that "the rules by which we describe and guide our measurement, defining the semantics of the formalism of a theory, must be in accordance with the laws of the theory." If the principle is satisfied, the theory possesses self-consistency and it is called by Mittelstaedt a classical theory; otherwise it is called nonclassical. In the case of a nonclassical theory, that is, when the operative **a priori** foundation of the theory is incompatible with the requirement of its empirical realizability, two possibilities exist : either (1) the operative **a priori** foundation, or (2) the requirement of empirical realizability has to be given up. The first possibility leads to theories of observable quantities, the second to theories of hidden variables. In the latter the originally operatively defined fundamental concepts play the role of hidden variables, which, although employed in formulating the theorems of the theory, are by their very definition unobservable. Obviously, Mittelstaedt's conception of hidden variables differs considerably from Bohm's.

Jammer's (1974, p.256) definition of hidden variables is as follows : In a given theory T about certain physical systems S certain variables v describe the states of S ; in a theory T' about S certain variables v' (which may be dynamical quantities or other hypothetical entities) which are not experimentally detectable within the framework of T describe the states of S ; if the the values of v, or of explicitly defined functions (or functionals) associated with v as used in the state description in T, can be obtained by some averaging operation over the values of v', v' are called hidden variables (with respect to T) and T' is called a hidden variable theory (interpretation) (with respect to T). Note that this definition does not stipulate that the embedding of T in T' entails the transformation of a statistical or probabilistic theory into a deterministic or causal theory.

2.5.3 Hidden Variable Theories of the First, Second and Zeroth Kind

Frederik Josef Belinfante (1973, pp.9-17) thinks that there are three kinds of hidden variable theories : hidden variable theories of the first kind, second kind and zeroth kind. For hidden variable theories of the first kind, in case of an equilibrium distribution of hidden variables, the theory will make exactly the same probability predictions as ordinary quantum theory. In this "first" kind of a theory, deviations from quantum theory would occur only in nonequilibrium distributions of the hidden variables. It is easy to perturb the hidden variables distribution in a predictable way, so that in principle it should be possible to investigate experimentally the dependence of the predictions of the theory upon the hidden variable. In practice, however, these experiments are made difficult by the extreme speed with which a perturbed distribution returns to the equilibrium distribution, so that the deviations from quantum theory would disappear before they could be detected.

Thus it is not simple at all to distinguish experimentally a hidden variable theory of the first kind from pure quantum theory. This would easily explain the great success of quantum theory, even if it were true that in principle nature would be governed by a hidden variable theory of the first kind.

On the other hand, this makes it difficult to prove conclusively by experiments that nature is governed by pure quantum theory if that would be so, because the negative outcome obtained in such case by any attempt at finding deviations from quantum theory after disturbing the hidden variable distribution could always be explained away by assuming that the relaxation (to equilibrium) takes place faster than the experiment was performed.

Therefore for a fair decision whether one should prefer quantum theory or a hidden variable theory of the first kind for explaining the facts of nature, one will have to invoke other principles. Since quantum theory has a simpler formalism than hidden variable theory, pure quantum theory for reasons of simplicity should have the preference as long as the deviations from quantum theory predicted for nonequilibrium distributions have not positively been demonstrated experimentally. This leaves the experimental burden upon hidden variable theory to prove its validity by disproving the simpler quantum theory.

There are, however, people so much dissatisfied with quantum theory that they are looking for deviations from quantum theory that would exist even if the hidden variable distribution were an equilibrium distribution (see Appendix C). These are hidden variable theories of the second kind.

Some people have tried to define by some postulates some properties which they thought any hidden variable theory should possess. They then proved that theories having the properties postulated could not exist. In each case, however, among the properties postulated there was at least one which the more realistic hidden variable theories did not possess. Therefore those so called "impossibility proofs" (see, for example, Belinfante, 1973) do not apply to hidden variable theories of the first kind or of the second kind. Belinfante calls the kind of theories that were disproved hidden variable theories of the zeroth kind. The interest of those theories is that they are a warning. They are a warning for what one can never expect any realistic hidden variable theory to accomplish.

2.5.4 The Model of Bohm and Bub

There are several hidden variable theories. We will present here the model of Bohm and Bub (1966; Mehra, 1974, pp.66-68).

At various times since 1951 Bohm has developed hidden variable theories. In 1966 he presented a new model which showed the following features : First, it reproduced the statistical predictions of quantum mechanics, if one averaged over the hidden variables. Second, it automatically reduced the wave packet during the measurement in accordance with the influence of the hidden variables. However, for very short times after the measurement, it yielded a result different from quantum mechanics. ,

The essential features of the model can be discussed by using a simple model of a quantum variable, taking the two values, say of a spin one-half system. One assumes that the general state vector Ψ,

$$|\Psi\rangle = \Psi_1|S_1\rangle + \Psi_2|S_2\rangle, \quad |\Psi_1|^2 + |\Psi_2|^2 = 1 \tag{2.1}$$

does not represent a complete description of the state, but has to be supplemented by an additional state vector $|\zeta\rangle$,

$$|\zeta\rangle = \zeta_1|S_1\rangle + \zeta_2|S_2\rangle,$$

with (2.2)

$$|\zeta_1|^2 + |\zeta_2|^2 = 1$$

where the components of $|\zeta\rangle$ are the hidden variables, having a random behaviour. The change in ζ_1 and ζ_2 is supposed to be slow, and nothing else happens during the process of measurement. The equations of motion for the components of $|\Psi\rangle$ are now determined by the hidden variables, according to

$$d\Psi_1 / dt = \text{const.}\ [(|\Psi_1|^2 / |\zeta_1|^2) - (|\Psi_2|^2 / |\zeta_2|^2)]\ \Psi_1|\Psi_2|^2 ,$$

and (2.3)

$$d\Psi_2 / dt = \text{const.}\ [(|\Psi_2|^2 / |\zeta_2|^2) - (|\Psi_1|^2 / |\zeta_1|^2)]\ \Psi_2|\Psi_1|^2 ,$$

From Equation 2.3 one finds that the normalization of $|\Psi\rangle$ remains constant. Now, if

$$|\Psi_1|^2 / |\zeta_1|^2 > |\Psi_2|^2 / |\zeta_2|^2$$

one finally arrives at $\Psi_2 = 0$ at the end of the measurement, and similarly at $\Psi_1 = 0$ after the measurement if the inequality is inverted. One therefore obtains a reduction to the state $|S_2\rangle$ for certain values of the hidden variables ζ_1, ζ_2, and a reduction to $|S_2\rangle$ for the others. It can also be proved that quantum mechanical probabilities come out correctly. However, one can demonstrate that for times in which the hidden variables are not averaged, the predictions of the Bohm-Bub theory might contradict quantum mechanics. This theory has been subjected to experimental tests and the result has been found to disagree with it (Papaliolios, 1967).

2.6 Stochastic Interpretations

<u>Stochastic interpretation</u> (Wheeler and Zurek, 1983, p.779) is a name often given to the view that :

1. The Schrödinger equation is essentially a diffusion equation, though an equation for the diffusion of probability amplitude rather than probability density itself; and

2. that this diffusion is driven by a force arising from other dynamical entities, that is, from a special class of hidden variables : random impacts of particles postulated **ad hoc**, fluctuating

fields, electromagnetic or otherwise, etc.

This outlook was first introduced by Fürth (1933) and is expounded at length in Fényes (1952). In their work quantum mechanics is described as a "time-symmetric stochastic process," with little said about the origin of the random external force. In contrast, Kalitsin (1953), inspired by Einstein and Hopf (1910) and by Einstein and Stern (1913), likewise takes the mechanics of the electron to be classical at bottom, but views the fluctuating force on it that makes it behave "quantum mechanically" as originating from the fluctuating electromagnetic field of the vacuum. Well though this treatment reproduces the ground state of the harmonic oscillator, it fails for other systems.

(1) It predicts that the electron of the hydrogen atom, originally in its ground state, will gain energy from the vacuum fluctuations.

(2) When a system breaks into two parts, as in the Einstein-Podolsky-Rosen experiment (see Appendix C), the fluctuations at the location of the one system and the other would have to have a quite artificial correlation to reproduce the well-tested predictions of standard quantum mechanics. Boyer (1980) has surveyed "stochastic electrodynamics."

2.7 Transactional Interpretation

The transactional interpretation has been proposed by John G. Cramer (Cramer, 1986, 1988; Görnitz and v. Weizsäcker, 1987, p.930). He claims that his theory is equivalent with traditional quantum mechanics in all testable predictions, but that it avoids the state reduction as a means of description. This is done by defining the "objective" wave function between two events (say , between the emission and the absorption of a particle) by the cooperation of both events; so to speak by past and future facts. He achieves this by the "absorber theory" formalism of Wheeler and Feynman (1945, 1949) which replaces the Maxwell wave equation by a four-dimensional action at a distance, including advanced potentials as well as retarded ones. He applies this formalism to the Schrödinger wave. His solution of the state-reduction problem is the following. The retarded wave originally starting from the emitter is the Schrödinger wave in the usual description. Arriving at the space-time location of the absorption act, this wave causes the absorber to emit an advanced wave running backward in time, which hits the emitter to emit an additional retarded wave, and so on. The superposition of all these waves is the "real" wave connecting emitter and absorber. The "state reduction" is nothing but the logical transition from the first component of the total wave function, which we describe as a retarded wave leaving the emitter, to the real total wave, i.e., from an incomplete picture to the full reality.

Cramer (1988) points out that while interpretations cannot be directly tested, it is possible for experimental results to favour one interpretation or another. This is what might be called a corroborative experimental result. For the transactional interpretation these are : experiments concerning absorber deficiency at cosmic distance scales (Partridge, 1973), detailed studies of the character of quantum randomness (Pagels, 1980) or searches for physical effects arising from unconfirmed transactional interpretation transactions. Further, a definitive characteristic of the transactional interpretation is that it describes causality as arising from precariously balanced cancellations that nullify the occurrence of advanced effects in quantum events. Cramer speculates that for sufficiently small distance scales or sufficiently short time scales this balance might fail and violations of microcausality might appear. Evidence for microcausality violations in high-energy electron scattering has recently been reported by Bennett (1987, a, b). He has reanalyzed data from electron-proton scattering and shown that the data exhibit a statistically significant deviation from dispersion relations based on microcausality. He proposes a semiclassical model that is "precausal" in that it contains acausal terms corresponding to advanced effects, and he shows that with such a model he is able to fit the experimental data. But Cramer says that it is too early to conclude that microcausality has failed.

2.7.1 Advanced-action Interpretations

In addition to the transactional interpretation, two other approaches to the interpretation of quantum mechanics (Cramer, 1986, p.685) have appeared in the literature which have suggested the use of advanced waves. The first of these is the "advanced action" interpretation of Costa de Beauregard proposed in 1953 (see for example, Costa de Beauregard, 1985). He pointed out that the timelike symmetry of electrons and positrons in the Feynman picture can, in principle, account for the nonlocal structure of quantum mechanics as applied to electrons and positrons in a creation annihilation event. However, Garuccio et al. (1980) have argued that there are many difficulties, e.g., it violates causality and energy conservation.

A second interpretation using advanced waves was suggested by Davidon (1976), who proposed that "an operator which factors into a tensor product of advanced and retarded solutions of the time-dependent Schrödinger equation" could lead to "a local and objective description ... for each of the remote parts in an Einstein-Podolsky-Rosen situation" (see appendix C). Cramer (1986) has pointed out that since the time-dependent Schrödinger equation, being first order in its time derivative, does not have advanced solutions, it is not clear what is the actual content of Davidon's model.

2.8 Statistical Interpretation

L. E. Ballentine (1970, 1987) argues that the quantum state function should be regarded as a description of a conceptual ensemble of similarly prepared systems, rather than as the complete description of an individual system. This is called the statistical or statistical ensemble interpretation. In Cramer's (1986, p.650) opinion this extreme view is unwarranted as long as it is appreciated that the predictivity of the quantum-mechanical formalism is severely limited in its application to isolated events. He points out that the discovery of an important particle in the development of particle physics, the Ω^- baryon, was accomplished with the observation of a single isolated quantum event.

2.9 Von Weizsäcker's Abstract Quantum Theory

C. F. von Weizsäcker and his colleagues (Görnitz and v. Weizsäcker, 1987, 1988; Drieschner et al. 1988, p.301) consider the Copenhagen interpretation not as one of several possible interpretations of a self-consistent theory called "quantum mechanics," but as the attempt at giving that minimal semantics to the formalism of quantum mechanics without which one would not know how to apply the formalism to reality at all. They argue for four theses :

1. State reduction is phenomenologically inevitable.
2. It is phenomenologically consistent.
3. It is reinterpreted but not eliminated by a quantum description of the observer.
4. It might be eliminated by going beyond quantum theory as we know it today.

They then give a reconstruction of abstract quantum theory (see also 3.6). By "abstract" they designate the general frame of quantum theory in Hilbert space without reference to position space and to concepts like particle and field. "Reconstruction" means the attempt to formulate simple postulates on prediction and to derive the basic concepts of abstract quantum theory from them. Their three basic postulates are :

B7-C1 Separable Alternatives. An n-fold alternative is a set of n mutually exclusive states, exactly one of which will turn out to be present if and when an empirical test of this alternative is made. There exist alternatives whose decision is independent of the decision of other alternatives.

C2 Indeterminism If x and y are two mutually exclusive states, there are states z connected with both of them by conditional probabilities different from zero and one.

C3 Kinematics The conditional probabilities between connected states are not altered when the states change in time.

By plausibility arguments they try to show in Drieschner et al. (1988) that these postulates semantically well interpreted, are sufficient for reconstructing abstract quantum theory. Thus, abstract quantum theory would offer an adequate basis for generalizing Copenhagen interpretation into a universal theory, including a description of the observer's state of mind. On the other hand, it stays indeed within the conceptual frame of the Copenhagen interpretation using concepts of human experience throughout.

They try to start a reconstruction of concrete quantum theory as a consequence of the abstract theory applied to binary alternatives (von Weizsäcker, 1985). By "concrete" quantum theory they mean the full quantum theory of objects in a position space, such as particles or fields, including a possible quantum cosmology.

Using von Weizsäcker's concept of the "ur" -- the quantized binary alternative (from German **Ur-Alternativen** = original alternatives (Görnitz, 1986))-- Görnitz (1988 a, b) shows that any decidable alternative can be subdivided into a succession of binary (yes-no) alternatives. The abstract quantum theory of a single binary alternative contains in its symmetry group the group SU(2). This group is then supposed to be a symmetry group, too, of all alternatives composed of successive binary alternatives, i.e., of all alternatives of physics. SU(2) is locally isomorphic to SO(3), the rotation group in a three-dimensional real space. He supposes this to be the reason the laws of physics have a local R^3 symmetry. This means that the position space of physics as empirically known is the symmetric space (in the sense of Elie Cartan) of the basic Lie group of the binary alternatives in quantum theory. He then shows that the inclusion of time into the description implies a local Lorentz invariance. Hence he considers relativity as a consequence of abstract quantum theory. Thus the space-time continuum would turn out to be a systematic consequence of quantum theory. This would be a further encouragement of the intention to interpret quantum theory as a universal theory.

2.9.1 Other Proposals for a Universal Quantum Theory

1. Kochen (1985) calls his proposal the perspective interpretation. He proves that in any quantum system that can mathematically be described as composed of two subsystems, any one of these subsystems may be described as observing the other one.

2. Deutsch (1985) uses the title, "Quantum theory as a universal physical theory." He concentrates on a problem that is left open in Kochen's paper : how is it decided which one of the Ψ_i states will actually be found in the measurement ? This is the problem of state reduction. Deutsch chooses the solution first proposed by Everett (1957), the so-called many-world theory. In this view the state vector is never reduced. In any decision process such as measurement all competing results happen simultaneously, but such that the observer who observes one of the possible results is not aware of the other simultaneous results. Thus, the world is either constantly split into more and more simultaneous worlds, or there is an infinity of simultaneous worlds, some of which, in any decision, take one of the possible ways, some another (Deutsch, 1986).

According to Deutsch, this is not just an alternative interpretation as compared with Copenhagen interpretation, but a different theory. He offers a thought-experiment which should give different results according to his theory from those following from the Copenhagen interpretation. He shows that the existing formalism, in either the Copenhagen or the Everett interpretation, must be supplemented by an additional structure, the "interpretation basis." This is a preferred ordered orthonormal basis in the space of states. Quantum measurement theory is developed as a tool for determining the interpretation basis.

3. Cramer (1986) calls his proposal the transactional interpretation (see 2.7).

Von Weizsäcker (Görnitz and v. Weizsäcker, 1987) then applies his universal quantum theory to the three interpretations, which he understands as being different versions of the same theory, i.e., they are essentially identical in their description of real knowledge with each other and with the Copenhagen interpretation. Indeed, he proposes that one deduce a "dictionary" or set of interpretational transformations that can render one interpretation in the terms or "language" of another. This demonstrates a sort of equivalence principle for interpretations. But Cramer (1988) argues that theories that can be mapped into each other are not necessarily interchangable.