International Journal of Theoretical Physics, Vol. 26, No. 10, 1987

Quantum Interpretations

Th. Görnitz[1] and C. F. v. Weizsäcker[1]

Received May 7, 1987

Four interpretations of quantum theory are compared: the Copenhagen interpretation (C.I.) with the additional assumption that the quantum description also applies to the mental states of the observer, and three recent ones, by Kochen, Deutsch, and Cramer. Since they interpret the same mathematical structure with the same empirical predictions, it is assumed that they formulate only different linguistic expressions of one identical theory. C.I. as a theory on human knowledge rests on a phenomenological description of time. It can be reconstructed from simple assumptions on predictions. Kochen shows that mathematically every composite system can be split into an "object" and an "observer." Deutsch, with the same decomposition, describes futuric possibilities under the Everett term "worlds." Cramer, using four-dimensional action at a distance (Wheeler–Feynman), describes all future events like past facts. All three can be described in the C.I. frame. The role of abstract nonlocality is discussed.

1. THE PROBLEM

Sixty years ago, Heisenberg (1927) and Bohr (1928) presented the first outline of a self-consistent interpretation of quantum mechanics, known as the Copenhagen interpretation (C.I.). Ever since, there have been debates on its meaning and validity. Einstein (1935) reluctantly acknowledged its consistency, but just therefore he refused to accept quantum mechanics itself as a complete and final theory. Bell (1965) showed that quantum mechanics as it stands does not permit completion by local hidden variables. Recent experiments (Aspect *et al.*, 1982a,b) have decided for quantum mechanics and against locality. This failure of the hope to replace quantum mechanics by an essentially different theory, together with continuing dissatisfaction with C.I., has given new impetus to attempts at an alternative interpretation. We cite the idea of Everett (1957), and we shall discuss in the present paper some new proposals by Kochen (1985), Deutsch (1985), and Cramer (1986).

[1] Arbeitsgruppe Afheldt in der Max-Planck-Gessellschaft, D 8130 Starnberg, Federal Republic of Germany.

0020-7748/87/1000-0921$05.00/0

In our view C.I. is self-consistent. Its supposed inconsistencies are produced by simple misunderstandings of its meaning. But quantum theory as presented by C.I. is not a *universal theory*; it presupposes an observer, but does not describe him. The new proposals are very promising attempts at transforming it into a universal theory. We believe, however, that these attempts can only be consistently interpreted by first understanding C.I. and accepting it within the field of its validity; they are, in our view, not alternatives, but amplifications of C.I.

We proceed in four steps.

1. Section 2 describes C.I. such as we understand it.
2. Sections 3-5 give a brief resume of our own "reconstruction of quantum theory," which is described in more detail in several other papers. We need this reconstruction for formulating the language in which we shall discuss the interpretation problem.
3. Sections 6 and 7 are the central part of the paper. They put the three new proposals into the context of a "universalized Copenhagen theory."
4. Section 8 asks preliminary questions which go beyond our present insight.

2. COPENHAGEN

The Copenhagen interpretation is quantum theory. —R. Peierls[2]

In physics, the term "theory" means a mathematical structure together with a physical, preferably empirical semantics. A mere mathematical structure, say a Hilbert space, is not yet physics. The semantics must be verbally expressed in an available language. Thus, the semantics begins historically by presupposing the verbiage of everyday speech in a given civilization and, in more mature stages, of earlier theories. In the process of theory-building, its language is continuously adapted to the emerging mathematical structure and its empirical use.

We consider C.I. as the minimum semantics that was needed to give a consistent physical meaning to the formalism of quantum mechanics. We try to express it today as adapted to the present use of the theory.

For simplicity, we describe the nonrelativistic theory of a point mass under the influence of an external force. The predictions of the theory are derived from the time-dependent Schrödinger function $\psi(x, t)$. ψ obeys the

---

[2] Discussion at the Symposium on the Foundations of Modern Physics, Joensuu (1985).

Schrödinger equation $\psi' = iH\psi$. The special solution of this equation is determined by an initial condition $\psi(x, t_0) = \psi_0(x)$, which expresses our knowledge of the state at an "initial" time t_0 as given by preparation or by an observation at time t_0 or before. Then $p_V = \int_V |\psi(x, t)|^2 \, dx^3$ gives the probability of finding the particle within a selected volume V at time t; probabilities for other observables are defined similarly.

C.I. consists in taking the concept of probability seriously. A probability is the prediction (mathematically: the expectation value) of a relative frequency. [For details on this definition see v. Weizsäcker (1985, Chapter 3).] Thus, p_V can be approximately measured by repeating the "same" experiment many times. "Same" means here with the same initial condition ψ_0. In a single experiment the event cannot be predicted if $p_V \neq 1$; this fact is expressed by calling quantum mechanics indeterministic. The result of the single experiment at, say, t_1 then determines the initial condition for calculating $\psi(t)$ for $t > t_1$. This is called the state reduction or, in dramatic language, the "collapse of the wave function" by measurement.

The difficulties in the acceptance of C.I. are nearly uniquely caused by this concept of state reduction. Schrödinger originally considered ψ as an "objective" field whose time development was fully determined by his wave equation. It has, however, become usual to say that, according to C.I., ψ has two ways of changing with time: according to the wave equation between two measurements, by state reduction during a measurement. This seems awkward.

In the following we shall 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.

Theses 1 and 2 are discussed in the present section, thesis 3 in Sections 6 and 7, thesis 4 in Section 8.

By "phenomenological" we denote what an observer can actually know: what can become a "phenomenon" for him. Therewith we do not imply a "positivistic" philosophy; we shall gradually try to clarify the philosophical meanings of popular terms like "knowledge," "positivism," and "reality" in discussing theses 2–4.

Thesis 1. State reduction is phenomenologically inevitable. Historically, state reduction was introduced as a consequence of combining the statistical interpretation of a field with the conservation theorems. A statistical interpretation of a field without state reduction had been tried by Bohr *et al.* (1924). These authors interpreted the Maxwell field as a probability field for the emission and absorption of energy quanta by matter. The field at large was, so they assumed, not changed by the absorption of a quantum of energy from it at some special place x. This assumption had the inevitable consequence that energy could not be conserved in the single absorption (or emission) process, but only in the statistical average. The experiments by Bothe and Geiger (1925a,b) and Compton and Simon (1925) empirically refuted this view. The only way out was either to abandon the statistical interpretation of the wave or to admit state reduction.

We shall not discuss in detail the corresponding conclusion for the Schrödinger wave. There it is already the conservation of particle number that would be violated by sacrificing the state reduction; it would become meaningless to speak of the Schrödinger theory of a single particle. It is to be admitted that a measuring process cannot be strictly described in terms of a one-particle wave, since measurement presupposes interaction. We shall discuss the description of measurement in the ensuing theses; let it now suffice to say that measurement, too, is discussed within the validity range of the conservation laws. For the treatment of state reduction in the new proposals see Section 6.

Thesis 2. State reduction is phenomenologically consistent. If we interpret quantum theory as a theory on human knowledge, there is no problem. If we do not interpret it so, there is no solution.

"Knowledge" in these two sentences does not of course, mean "fantasy" or a "subjective state of mind." It means somebody's knowledge of reality—else it would not deserve the name "knowledge." "I know that the sun is shining" means "the sun is shining and I know it." Knowledge does not, however, refer to a presumed reality which, according to the theory itself, cannot be known and perhaps does not exist. We shall explain these distinctions in several steps.

The $\psi(x, t)$ is the catalogue of all those probabilities that can be predicted as implied by the knowledge of the initial condition ψ_0. All empirically testable probabilities are conditional probabilities. A new measurement gives new knowledge, hence changed probabilities. This is evident in classical probability: The probability of "rain tomorrow" is rightly changed by a new meteorological observation, since after this observation the expected event "rain tomorrow" belongs to a new ensemble; for both ensembles, defined by different knowledge, the different relative frequencies for the same result can be empirically tested. The difference from quantum theory is only that in the Schrödinger wave we cannot make any practical use of the classical assumption that the different ensembles express no more than different degrees of incomplete knowledge on an objectively determined course of events.

Our last sentence refers explicitly to the absence of *practical* use for determinism in quantum theory as we possess it. We do not want to imply an impossibility of a background determinism, which, however, ought to be nonlocal in space and time (Section 8). One of the trivial misunderstandings of C.I. is to interpret Heisenberg's uncertainty principle as presupposing that "what cannot be measured does not exist." Only the converse is true: "what does not exist cannot be measured," and hence the consequence: "a state that does not exist according to the formalism of quantum mechanics (such as a common eigenstate of position and momentum operators) cannot be found in an experiment that admits a full description by quantum mechanics" (see Heisenberg (1969).

The two ways of change of ψ with time are thus simply explained as necessary consequences of quantum semantics. $\psi(x, t)$ contains all functions deducible from the knowledge ψ_0, and is replaced by a new function $\psi'(x, t)$ when new knowledge is acquired; the continuous time dependence of a given $\psi(x, t)$ describes the difference of prediction following from the given knowledge but applying to different future times t. The apparently paradoxical question "*when* in a measuring process is the state reduced?" has the simple answer, "when the observer becomes aware of the result of the measurement." For ψ *is* what he can deduce from his knowledge. It is a sheer misunderstanding to think that C.I. implies an "action at a distance" changing some distant reality by an influence of some magical agent called "consciousness." I am not changing the sun by becoming aware that it is presently shining. The real problem, as has been carefully studied (e.g., Cramer, 1980), is that quantum theory is nonlocal; we shall discuss that in Sections 5-8.

The apparent dependence of quantum descriptions on subjective knowledge can be mitigated by Bohr's profound remark that, as far as measuring instruments can be described in terms of classical physics, all individual observers can be sure to find the same result. We have tried to express this as the "Golden Copenhagen Rule": It does no harm to assume that the state has been reduced when the measuring instrument has registered it in an irreversible process. We shall return to the relevance of irreversibility in Sections 3 and 7.

We have so far verbally argued for the consistency of C.I. by commenting upon its structure and upon the difficulties that its critics have found in it. A strict proof of noncontradiction cannot be given within purely verbal semantics. We must now emphasize one precondition for our argument: it is the exclusion of the observer from the system he observes. In this sense, quantum theory as interpreted by C.I. is not a universal theory as defined by Deutsch (1985). "Universal" here does not necessarily mean "universally true," but "as far as it may be supposed to be true, universally applicable." C.I. offers no "quantum state of the observer." All the apparent paradoxes of C.I. are produced by neglecting (or refusing to accept) this limitation of the theory.

Bohr was fully aware of this limitation, and he was not surprised by it. As was a common attitude of physicists in his time, he was profoundly sceptical of the explanatory power of physics for organic life, not to speak of the relation of body and mind; in both problems he supposed some complementary structure that only future science might further elucidate. In this respect the present authors take a different position. We propose to study a possible amplification of C.I. such as to include a hypothetical description of the observer *by* quantum theory.

3. TIME

C.I. rests on a phenomenological description of experience. Hence its language presupposes the everyday acceptance of the modes of time: present, past, future. We *did* observe and *now* we *predict* some events. One of the difficulties critics find in C.I. derives from the fact that they take this structure of time as being "merely subjective," and that they feel a theory of physics would have to deduce the "arrow of time" from some other principle. Since in Bohr's description of measurement the irreversible registration of the result plays a decisive role, the critics emphasize the difficulty of reconciling irreversibility with the reversible structure of the wave equation.

We take a different methodological position. C.I. is not a universal theory. It describes what human beings know about the nature in which they live, but it does not describe the process of knowledge. Thus, it is permitted to accept the way in which human beings know themselves. The modes of time are the most primitive presuppositions for terms like "experience," "knowledge," "acting," or "perception" to have any meaning. Experience, e.g., might be defined as having learnt from the past for the future. The modes of time do not appear in the mathematical formalism of physics because they are effortlessly expressed in the semantics; most explicitly in the Indo-European languages in which occidental science has developed, such as Greek, Latin, English, etc.

The present paper does not intend to analyze the role of the modes of time in physics (cf. v. Weizsäcker, 1939; 1985, Chapters 2-4; Görnitz and v. Weizsäcker, 1987). We just mention those structures of the modes that we presuppose in our "reconstruction" of quantum theory as a theory of knowledge. We say: Past events are now facts, future events are now only known as possibilities. Facts are irreversible realities. The whole language of "realism" can be meaningfully applied to them; they exist independent of our knowledge. This is presupposed in the "Golden Copenhagen Rule" as quoted above. Possibilities are not yet known as facts, and as far as quantum theory goes, they are not strictly predictable. There are two different meanings of the term "possibility," which we propose to call "futuric possibility" and "formal possibility." To apply it to events: we call the concept of an event that is not excluded by the laws of physics a formal possibility, and an event that we can expect in some future moment of time with nonzero probability a futuric possibility. For example, "rain" is formally possible, "rain tomorrow" is, in an Atlantic climate, usually futurically possible.

Probability is a quantification of possibility. When we defined probability as a *prediction* of a relative frequency we proposed to take it in the futuric sense in which it is used in the statistical interpretation of the wave function, and generally in stochastics. Futuric and perfectic uses of probability are indeed quite different in their meaning. "With probability 1/2 it will rain here tomorrow" is a meteorological prediction; we can call it a direct use of the concept of probability. "With probability 1/2 it was raining here yesterday" is a statement of incomplete knowledge on a fact of the past; its operational meaning is again futuric: If we ask somebody who observed it, we have a 1/2 chance that we *will* learn that it did rain indeed. The idea that futuric probability also expresses no more than incomplete knowledge of an objectively determined event is a view we cannot refute (see Section 8), but which is certainly not needed for a phenomenological description of human experience.

We just mention that in the papers quoted above we have shown that the second law of thermodynamics follows from this phenomenology of the modes of time. The probabilities considered in statistical mechanics refer directly to the possibilities of the future, not to the facts of the past. This argument evidently needs a more ample consideration than we can offer in the present paper.

4. ABSTRACT QUANTUM THEORY

In another paper (Drieschner *et al.*, 1987) we have given a reconstruction of abstract quantum theory. By "abstract" quantum theory we 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. We repeat here only the three basic postulates, in simplified language:

B7–C1. Separable Alternatives. An n-fold alterntive 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 we try to show in the quoted paper that these postulates, semantically well interpreted, are sufficient for reconstructing abstract quantum theory.

For our present purpose this reconstruction is useful because it does not specify the nature of the alternatives. They may be observables such as angular momentum or particle number or, if generalized for continuous n, position or momentum. But they might equally well be alternatives in psychological introspection, such as "shall I be glad or sorry tomorrow morning?" This applicability to mental states is directly derived from the completely abstract definition of an alternative; it does not need any hypothetical connection between the mind and the brain. Thus, abstract quantum theory would offer an adequate basis for generalizing C.I. 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 C.I., using concepts of human experience throughout.

5. CONCRETE QUANTUM THEORY

We call "concrete" quantum theory the full quantum theory of objects in a position space, such as particles or fields, including a possible quantum cosmology. In earlier papers we tried to start a reconstruction of concrete quantum theory as a consequence of the abstract theory applied to binary alternatives (v. Weizsäcker *et al.*, 1957; v. Weizsäcker, 1971, Chapter II5; Castell, 1975; v. Weizsäcker, 1985, Chapters 9 and 10). We shall present this enterprise in two forthcoming papers. We quote it here for its possible relevance with respect to the transformation of C.I. into a universal theory.

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. We suppose 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 of the basic Lie group of the binary alternatives in quantum theory. It can easily be shown that the inclusion of time into the description implies a local Lorentz invariance. Hence we consider relativity as a *consequence* of abstract quantum theory. Thus the space-time continuum, which was historically found independently of quantum theory, 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. Yet the interpretation of a tentative universal quantum theory that we present in Section 7 does not logically depend on this enterprise.

6. THREE PROPOSALS FOR A UNIVERSAL QUANTUM THEORY

1. Kochen (1985) calls his proposal the *perspective interpretation*. The author proves that in any quantum system (e.g., the world) that can mathematically be described as composed of two subsystems, any one of these subsystems may be described as observing the other one. The mathematical tool of this description is the "polar decomposition" as introduced by Schmidt (1906). The Hilbert space H of the total system is the tensor product of the Hilbert spaces of the two parts: $H = H_1 \otimes H_2$. It is possible to introduce arbitrary orthonormal bases in both factor spaces H_1 and H_2. If a state vector Φ of the total system in H is given, there exists, however, a special choice of the two bases such that Φ can be described as diagonal; $\Phi = \sum_i \lambda_i \phi_i \otimes \psi_i$, $\phi_i \in H_1$, $\psi_i \in H_2$. Thus, a given pure state of the composed system always defines a unique pair of corresponding bases in both parts that enables us to consider a state ψ_i in one part as a measurement of the corresponding state ϕ_i in the other part and vice versa. Kochen further shows that in a measurement process $\Phi(t)$ can be continuously decompsed into $\phi_i(t)$ and $\psi_i(t)$ such that after the end of the interaction, when the two systems are sufficiently far from each other, $\sum_i |\lambda_i|^2 \psi_i$ can be considered as a diagonalized density matrix of the measuring instrument. An observation of the state of the instrument will then give ψ_i with the classical probability $|\lambda_i|^2$, thus automatically satisfying Bohr's condition that the result of the measurement should be describable in classical terms.

2. Deutsch (1985) uses the title, "Quantum theory as a universal physical theory." In the description of the measuring process he, too, uses Schmidt's polar decomposition. 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-worlds 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 simultaneous other results. Thus, the world is either constantly split into more and more simultaneous worlds, or (Deutsch, 1986) there is an infinity of simultaneous worlds, some of which, in any decision, take one of the possible ways, some another.

According to Deutsch, this is not just an alternative interpretation as compared with C.I., but a different theory. He offers a thought-experiment which should give different results according to his theory from those following from C.I. He presupposes that a quantum description of a complete experiment is possible, including the quantum state of the observer. His experiment might be called a "time-mirror." A binary alternative (Stern-Gerlach experiment) is decided. The observer writes down (a) *that* the alternative has been decided, but *not* (b) *which* result has been found. Then the process goes on under a Hamiltonian which forces the parts of the whole system, *including the observer,* to go the whole original process backward such that the imprint in the observer's memory of the measurement is undone while the sheet of paper (a) stating that there has been a decision is preserved. Deutsch then shows that according to the unreduced wave function the two possible measuring results must interfere with each other. On the other hand, he maintains that this cannot be the case according to C.I. since the state has been irreversibly reduced by the measuring act (in our description: the observer's act of taking cognizance). To say it simply: the state reduction is an additional assumption which violates the Schrödinger equation; hence C.I. is not the Schrödinger theory, but the many-world interpretation preserves the Schrödinger theory.

3. Cramer (1986) calls his proposal the *transactional interpretation.* 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 formalism of Wheeler and Feynman (1945), which replaces the Maxwell wave equations 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 at the very place and moment of the emission, inducing 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.

7. A COPENHAGEN ANSWER

The Copenhagen tradition has much to learn from these and other analogous proposals. In the present paper we concentrate on the three proposals. We presume that all three are mathematically correct; we discuss their physical content. Briefly, our result will be that they are not alternatives, but mathematical and substantial amplifications of C.I., yet expressed in a language that contains undue simplifications that create an insufficient understanding both of C.I. and of their own positions.

The polar decomposition as used by Kochen and Deutsch offers a consistent, purely quantum mechanical description of the measuring process, at least as far as the interaction of object and measuring instrument is involved [on Kochen see our more detailed paper (Görnitz and v. Weizsäcker, 1987)]. In Kochen's presentation, the total state vector ϕ defines which basis, i.e., which observable can be measured. In a more conventional description (Görnitz and v. Weizsäcker, 1987; v. Weizsäcker, 1985, Chapter 11.2d), the measured observable must be part of the interaction Hamiltonian; thus, it defines a polar decomposition and hence the possible states $\phi_\lambda(t)$, given that Hamiltonian.

Another important mathematical contribution is Cramer's application of the Wheeler-Feynman formalism to the Schrödinger theory. We intend to discuss this in a separate paper.

Essential in all three proposals is the substantial amplification of making quantum theory universal by including the observer into the system as described by quantum theory. We fully agree with this intention. We suppose that most of the difficulties found in C.I. derived from not seeing that Bohr never had the idea that quantum theory ever might become "universal" in this sense; we explained this by Bohr's historical position in Section 2. On the other hand, the new proposals sound somehow strange as compared to the usual language of physicists; they will probably encounter difficulties of acceptance in the scientific community. But these two-edged difficulties may leave the public with the impression that quantum theory is not understood at all. Cramer quotes Feynman (1967): "I think it is safe to say that no one understands quantum mechanics".

We are less pessimistic. We have explained why we consider C.I. as consistent for a nonuniversal quantum theory, and we believe that it can be extended into a universal theory precisely if we keep in mind what we have learnt from Bohr. Quantum theory is a theory of human knowledge on events in time. If it is to describe the human observer, too, then it must be read also as a theory of human knowledge on human knowledge as an event in time. This may still not be the last step in our "natural philosophy," but it is a step that can be taken by doing no more than analyzing quantum theory as we possess it today, under the additional assumption that it is applicable to the human mind, described as a quantum system.

The three proposals approach this problem, but none of them does it fully.

Kochen shows that any partial system can be treated mathematically as a measuring instrument observing the other part. But he speaks as though the measuring instrument were immediately aware of its own state. Yet the focal task of a theory on knowledge about knowledge is to describe the process of self-perception. In Kochen's formalism this would be the description of how the classical density matrix is reduced into a state in which the observer knows which of the states is actually present; we dare say that Kochen has used the traditional concept of state reduction in its most challenging form: "How am I getting aware of my state of mind at time t_1, which I was only able to predict with probability at times $t < t_1$?"

Cramer speaks only of processes of emission and absorption, not of observation in a more pregnant sense. In particular he does not discuss *when* the observer becomes aware of the absorption process. In ordinary theory this cannot happen earlier than at the time of absorption. Hence his "objective" wave function can only be described *ex eventu*; it is not a possible means of prediction. For prediction he falls back on the ordinary retarded Schrödinger wave. The merits of his theory can only be discussed in the framework of "temporal nonlocality" (see Section 8).

Deutsch is the only one of the three authors who, in his thought-experiment, makes actual use of the assumption that there is a time-dependent state vector describing the observer's process of knowledge. He is forced and able to do so because, in accepting Everett's interpretation, he has consciously faced the difficulties of the idea of state reduction in a universal theory. But we suppose that the Everett interpretation "sounds strange" precisely because it uses a few words in an inadequate manner.

Let us first remark that none of the three authors really escapes the acceptation of state reduction as soon as he describes the knowledge which a human observer can have. This state reduction is just what is also called quantum mechanical indeterminism. Kochen seems to accept a continuing objective state reduction. Cramer explains why the observer at the time of emission cannot know the "objective" wave, which is only determined by an unpredictable absorption process in his future. Everett says that the state vector is never reduced. But for the single observer it is unknown in which "world" he will find himself after the next interaction process. After the next decision it is of no avail for him to believe that he has an "alter ego" who experienced the opposite outcome, unless, as in the thought-experiment, there is a superposition between him and his alter ego.

We shall not try to resolve these questions in the three interpretations. We will rather propose our own interpretation of universal quantum theory, and then apply it to the three interpretations, which we will understand as being different versions of the same theory.

In the present section we keep unchanged the phenomenology of time as presented in Section 3. That means that in the present section we consider universal quantum theory as a theory on what a human observer can know in time on possible objects of observation, now including his own mind, taken to be such an "object."

The past is factual, the future is possible. Facts and possibilities can be "dated," i.e. ascribed a time t at which we assume them to have happened (past) or have a chance of happening (future). The "now" is the moment in which possibilities dated for the special moment that the clock is now showing turn into facts (or nonfacts: the possible event has either happened or not). Quantum mechanical indeterminism says that, insofar as quantum theory is our only means of theoretically describing experience, this difference between fact and possibility cannot be eliminated. The only statement added by universal quantum theory is that this also applies to my own self-knowledge: memory and anticipation, too, are different in the field of introspection.

We now say that Cramer, Everett, and Deutsch "sound strange" because they aim at neglecting or eliminating *this* basic phenomenological difference of fact and possibility.

Cramer describes future events like facts, which means how they would be described when they will have happened, i.e., when they will be events of the past. This is in line with most versions of "realism" (not, however, with Popper), which describe all events in space-time like facts and reduces our awareness of the difference between past and future to some unexplained "subjectivity" of our perception. In our own interpretation we have no difficulty in accepting Cramer's picture as a description of past events, and of the possibilities for future events that might be turned into real and hence, afterward, past events.

Everett, on the other hand, describes the past as though it were future. This can be easily seen if we translate Everett's interpretation by a "one-word dictionary" into the traditional one. We say: What Everett and his followers call many *worlds* are just many *possibilities.* In C.I. the unreduced wave function is precisely the catalogue of all those possibilities (with their respective probabilities) that one observer can predict who knows a special initial condition and knows no outcome of any later observation. Thus, he will also describe what is now past for *us* as though it were still future: undecided possibilities.

Deutsch is fully aware that this dictionary would make a debate between Everett and Copenhagen devoid of any decidable meaning unless there are empirically relevant differences between the two views. This is the purpose of his thought-experiment. Our answer is: In a consistent universal quantum-theory it would be extremely improbable that his experiment might be actually performed with a conscious observer; but, assuming it were performed, we agree with his prediction that the superposition of the two cases would be observable; C.I., consistently used, *does not* predict the opposite.

This answer arises from a discussion of irreversibility whose details we must reserve to another paper (see, however, the publications quoted in Section 3). We said that the facts of the past are irreversible. Irreversibility of a process means an extremely small probability of its being undone by a later reversal of the sequence of events. This improbable thing is precisely what Deutsch's "time-mirror" experiment proposes to do for the fact of an imprint in the memory of the observer. As soon as we accept the idea that states of mind can be subject to quantum theory, we must accept their reversibility, though with exceedingly small probability, too.

The question is only whether this consideration does not strictly forbid the "universal" quantum theory if we want to stick to C.I. Bohr intermediately simplified this problem by limiting his consideration to the measuring instrument rather than including mental states. If we accept his statement that the measuring process must be classically described, we have a choice of two interpretations. Bohr sometimes considered the possibility, later elaborated by Ludwig (1954), that macroscopic events should be excluded from quantum description; then there would be two theories, classical and quantum, for different fields of experience, and perhaps a third, still unknown one, embracing both of them. The common view, however, which Bohr did not reject and which the present authors share, is that quantum theory applies to macroscopic bodies as well. Then the classical description of the instrument only means that by typical quantum behavior it would cease to be a useful instrument.

This consideration can be easily translated into the way we speak of the mind. Similar to the classical description of matter is the Cartesian description of consciousness as fully knowing itself. If we were to interpret "knowledge" in the Copenhagen context as such an indelible fact of consciousness, then we would have to accept Deutsch's description of the consequence of C.I. as destroying the phase relations between coexisting states. But this view is untenable in a universal application of quantum theory. It produces "paradoxes" like "Wigner's friend," which is easily resolved by describing awareness like a process of measurement on a quantum system. Bohr was fully aware of the weakness of the Cartesian idea of consciousness; one of the present authors learned from Bohr a statement by William James: "Consciousness is an unconscious act" (v. Weizsäcker 1983). Everyday consciousness is precisely not a state of full self-awareness.

Just because we see universal C.I. in agreement with Deutsch's description of the thought-experiment we lose, however, any possibility of an empirical distinction between C.I. and Everett. Thus, we continue to think that "many worlds" is no more than a strange expression for "many possibilities."

Thus, we end with the conclusion that the three alternative interpretations are essentially identical in their description of real knowledge with each other and with the Copenhagen interpretation, universally understood.

8. NONLOCALITY

We ought not to be surprised by finding a dictionary between four descriptions of nature that use different language and different aspects of an essentially identical mathematical structure and promise to lead to the same observable results. The question remains whether these differences are hence to be considered as strictly meaningless. The answer is not trivial. The differences are in the semantics, and, as we pointed out in Section 2, semantics is not unambiguous, and is hence an open field for improvement.

The differences are clearly rooted in different philosophical attitudes. C.I. is the product of a strictly epistemological procedure. To Einstein's dictum, "God does not play at dice," Bohr answered, "The question is not whether God plays at dice or not, but what we mean by saying that God is or is not playing dice." What can we know?—This is Bohr's question. All other interpretations seem to start from some preconceived idea of reality to which someone wants to stick independent of our being presently able or unable to gain empirical knowledge on it.

We intend to discuss this philosophical problem in a later paper. We make only one remark on "nonlocality." This concept needs a generalization. In our reconstruction, space is only introduced as a special property of quantum systems in concrete quantum theory. But our second postulate means precisely a "nonlocality" with respect to *any* alternative. All considerations done with respect to the EPR experiment with objects in a large spatial distance will be equally applicable to any other observable by whose values the two objects can be distinguished. In this abstract and hence general interpretation, nonlocality is just a way of expressing the immense "surplus information" that characterizes quantum theory with its phase relations as compared with its classical limiting case. The uncertainty principle for noncommuting observables is no more than a necessary condition for the existence of this surplus information. Without nonlocality not even the stability of the hydrogen atom would be explained.

Thus, quantum indeterminism will not be avoided by a transition to nonlocal hidden variables, as long as we try to determine the future by the state at one time: the present. Cramers' description means a "temporal nonlocality." The present state will indeed fully determine the near future, if at all, only by a full knowledge of the far future of the whole world. One might call that the "holism" of quantum theory—a problem for philosophical discussion.

ACKNOWLEDGMENT

This work was supported in part by the Deutsche Forschungsgemeinschaft (to Th. G.).

REFERENCES

Aspect, A., Grangier, P., and Roger, G. (1982a). *Physical Review Letters*, **49**, 91.
Aspect, A., Dalibard, J., and Roger, G. (1982b). *Physical Review Letters*, **49**, 1804.
Bell, J. S. (1985). *Physics*, **1**, 195.
Bohr, N. (1928). *Naturwissenschaften*, **16**, 245.
Bohr, N., Kramers, H. A., and Slater, J. C. (1924). *Zeitschrift für Physik*, **24**, 69.
Bothe, W., and Geiger, H. (1925a). *Naturwissenschaften* **13**, 440.
Bothe, W., and Geiger, H. (1925b). *Zeitschrift für Physik*, **32**, 639.
Castell, L. (1975). In *QTS II*, Hanser, Munich, p. 147.
Compton, A. H., and Simon, A. W. (1925). *Physical Review*, **26**, 289.
Cramer, J. G. (1980). *Physical Review D*, **22**, 362.
Cramer, J. G. (1986). *Review of Modern Physics*, **58**, 647.
Deutsch, D. (1985). *International Journal of Theoretical Physics*, **24**, 1.
Deutsch, D. (1986). In *The Ghost in the Atom*, P. C. W. Davies and J. R. Brown, eds., Cambridge University Press.
Drieschner, M., Görnitz, Th., and v. Weizsäcker, C. F. (1981). Reconstruction of abstract quantum theory, *International Journal of Theoretical Physics*, to appear.
Einstein, A. (1935). *Physical Review*, **47**, 777.
Everett, H. (1957). *Review of Modern Physics*, **29**, 454.
Feynman, R. P. (1967). *The Character of Physical Law*, MIT, Cambridge, p. 129.
Görnitz, Th., and v. Weizsäcker (1987). Remarks on S. Kochen's interpretations of quantum mechanics, submitted to the Symposium on the Foundation of Modern Physics, Joensuu.

Heisenberg, W. (1927). *Zeitschrift für Physik*, **43**, 172.

Heisenberg, W. (1969), *Der Teil und das Ganze*, Piper, Munich, p. 111.

Kochen, S. (1985). In *Symposium on the Foundation of Modern Physics*, P. Lathi and P. Mittelstädt, eds., World Scientific, Singapore.

Ludwig, G. (1954). *Die Grundlagen der Quantenmechanik*, Springer-Verlag, Berlin.

Schmidt, E. (1906). *Mathematishe Annalen*, **63**, 433.

Schmidt, E. (1907). *Mathematishe Annelen*, **64**, 161.

v. Weizsäcker, C. F. (1939). *Annalen der Physik*, **36**, 275.

v. Weizsäcker, C. F. (1971). *Die Einheit der Natur*, Hanser, Munich.

v. Weizsäcker, C. F. (1983). *Wahrnehmung der Neuzeit*, Hanser, Munich.

v. Weizsäcker, C. F. (1985). *Aufbau der Physik*, Hanser, Munich.

v. Weizsäcker, C. F., Scheibe, E., and Süssmann, G. (1957). *Zeitschrift für Naturforschung*, **13a**, 705.

Wheeler, J. A., and Feynman, R. P. (1945). *Review of Modern Physics*, **17**, 157.