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Copenhagen and Transactional Interpretations

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The Copenhagen interpretation (CI) never received an authoritative codification. It was a "minimum semantics" of quantum mechanics. We assume that it expresses a theory identical with the Transactional Interpretation (TI) when the observer is included into the system described by the theory. A theory consists of a mathematical structure with a physical semantics. Now, CI rests on an implicit description of the modes of time which is also presupposed by the Second Law of Thermodynamics. Essential is the futuric meaning of probability as a prediction of a relative frequency. CI can be shown to be fully consistent on this basis. The TI and CI can be translated into each other by a simple "dictionary." The TI describes all events as CI describes past events; CI calls future events possibilities, which TI treats like facts. All predictions of both interpretations agree; we suppose the difference to be linguistic.

1. INTRODUCTION

We were invited to the Loyola Conference with the request to comment upon the Copenhagen Interpretation (CI) of quantum theory as compared with the Transactional Interpretation (TI) proposed by Cramer (1986). This invitation reached us at a propitious moment. We were just preparing a presentation of CI as compared with two other recent interpretations, which we had had a chance of discussing orally with the authors: Quantum theory as a universal physical theory by Deutsch (1985), discussed with the author by C.F.W. in Austin in 1982, and the "Perspective Interpretation" by Kochen (1985), discussed with the authors in Joensuu in 1985 and Princeton in 1986; on Kochen see Görnitz and Weizsäcker (1987a). The Loyola invitation drew our attention to Cramer's TI as a third recent proposal. We decided to publish a paper on the four interpretations (CI and the three recent ones) in their mutual relationship (Görnitz and Weizsäcker, 1987b).

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In the present paper we had intended to cover three topics: (1) a brief recapitulation of Görnitz and Weizsäcker (1987b) on the four interpretations, (2) a more detailed presentation of our methodological position with respect to CI, considering the criticism as formulated by Cramer, and (3) an analysis of Cramer's own interpretation. The first topic is treated in Section 2; the second, at least in part, in Sections 3-5. The principles of our intended analysis of the final topic are briefly described in Section 6.

2. QUANTUM INTERPRETATIONS

In our view CI is self-consistent. Its supposed inconsistencies are produced by misunderstandings of its meaning. These misunderstandings can, however, be explained by two shortcomings of CI:

1. There is no authoritative codification of CI and under the conditions of its origin there probably could not be one. The problem of understanding quantum theory has forced physicists into considering the most profound philosophical questions, for which neither modern physics nor traditional philosophy (including the modern "philosophy of science") were prepared. All prominent authors of the time who wrote on these questions, such as Bohr, Heisenberg, Pauli, and von Neumann on one side, Einstein and Schrödinger on the other, fell, we feel, into some stammering when they tried to express their own positions. In our view, Bohr gave the most profound analysis of these problems, but probably for that very reason he was least understood. His complicated way of expression tried to avoid all possible misunderstandings, and precisely for that reason he lacks the simplicity that is a precondition for being understood. One of us (C.F.W.) shall try at the Joensuu Conference 1987 to analyze Heisenberg's way of presenting these problems. It seems that all the authors of CI understood each other fairly well (R. Peierls at Joensuu in 1985: "The Copenhagen Interpretation *is* quantum theory") because they had the same experience in using their terminology as a guiding tool in the actual application of quantum theory, but they were unable to express this experience clearly enough to convey it to those who did not share its nonverbal presuppositions. Einstein's genius, precisely by not sharing these presuppositions, contributed most to clarifying what were actually the difficulties of mutual understanding. EPR, Bell's theorem, and Aspect's experimental results have—to use modern language—decided "for quantum theory and against locality". Yet CI seems not yet to have been reformulated to account for this confirmation of its original intention.

2. CI does indeed not present quantum theory as a *universal theory*: it presupposes an observer, but does not describe him. We believe that this is an actual shortcoming of CI, but an unnecessary one. Quantum theory,

according to CI, is a theory on knowledge. We believe that *just therefore* it deserves the name of a realistic theory. Knowledge means to know something. Quantum theory is a theory on what human beings can know about nature in time. This is technically expressed by explicitly referring to the "observer," to him who knows. If quantum theory as we now interpret it, following its own abstract structure and the trend of modern biology, tends to think of a description of the observer himself as an object of quantum theory, this means no more than its being, too, a theory of knowledge about knowledge in time.

It is a common feature of the three recent interpretations explicitly or tacitly to presuppose that quantum theory must describe the observer as well as any other part of the world. We fully agree with this assumption. We believe, however, that it can be easily reconciled with the central idea of CI, and that it even serves to elucidate the somewhat obscure role of the observer in many presentations of the Copenhagen view. In this sense we consider the recent interpretations not as alternatives, but as different expressions for one single step of amplifying CI by introducing the observer into the realm of quantum objects.

Without this proposal, the present interpretational debate must indeed offer a very strange image of quantum theory. Here are four interpretations, each of which maintains that it correctly describes precisely the same mathematical structure, namely quantum theory in Hilbert space, predicting exactly the same experimental results. [One apparent difference in prediction as proposed by Deutsch is discussed and removed in Görnitz and Weizsäcker (1987b), Section 7.] The only natural methodological reaction to such an image is, we feel, the suspicion that all four interpretations are no more than four different verbal expressions of exactly the same theory. Then it would be necessary to find a fourfold dictionary by which to translate the four languages into each other. This is what we actually propose to do in Görnitz and Weizsäcker (1987b).

We believe that the original intention of CI was to offer a *minimum semantics* to the formalism of quantum mechanics. What we mean here by "semantics" is explained in Section 3. In Section 4 we describe in detail the most important implicit presupposition of this minimum semantics, which, in our view, consists in the everyday understanding of time. Both problems are treated briefly in Görnitz and Weizsäcker (1987b); we hope that the more explicit description in the present paper may offer some further help for understanding the methodological situation. In Görnitz and Weizsäcker (1987b) we started out by a brief but systematic exposition of CI itself. Section 5 of the present paper may be read as a more historical comment on CI written as a *plaidoyer* for it against the accusation of inconsistency. Section 6 will offer the rudiments of the proposed dictionary.

3. WHAT IS A THEORY? WHAT IS AN INTERPRETATION?

We begin by three theses:

A. In physics, the term "theory" means a mathematical structure together with a physical (preferably empirical) semantics.
B. "Interpretation" is an ambiguous term. It may mean semantics, thus designating an integrating part of the theory, or it may mean an amplification, i.e., a set of statements added to the theory.
C. The dividing line between semantics and amplification is difficult to draw.

As a simple illustration we use an example introduced by Cramer (1986, p. 651), Newton's second law. Cramer writes it

$$F = ma \tag{1}$$

In this form it is only a sequence of signs. It receives a mathematical meaning ("mathematical semantics") by the additional statements:

$$a = d^2x/dt^2 \tag{2}$$

$$F = F(x, t) \tag{3}$$

$$m = \text{const} > 0 \tag{4}$$

These three equations become more than mere sequences of signs if we permit ourselves to use our previous knowledge of mathematical symbols. More explicitly, we say: Let "x" and "t" be real variables, x a function of t; then "a" means the second derivative of this function, "F" a given real function of x and t, "m" a positive real constant. Then (1) is a differential equation, and each given function $F(x, t)$ defines a set of solutions (1). The set of all sets of solutions defined by all possible $F(x, t)$ is the complete mathematical structure symbolized by equation (1).

This mathematical structure becomes a theory of physics by the physical semantics, which may be expressed in the verbal statements (definitions):

t is the time
x is the position of a body or mass-point
F is the force acting on the body
m is the mass of the body.

These statements define the physical meaning of the mathematical quantities t, x, F, m by means of words which are available in the English vernacular: time, body, force, etc. But are we sure what these words mean? Every student of the empirical foundations of classical mechanics becomes aware of the difficulty of defining them unambiguously. Newton, in introducing his theory, had to make use of the scientific language existing before the theory. Thus, where we say "mass," he said "quantity of matter". But how to measure this quantity otherwise than by comparing solutions of equation (1) with observed paths of moving bodies? Furthermore, in the Aristotelian physics prevailing before Galileo, one would have considered a force the cause of motion, hence expected force rather to be proportional to velocity than to acceleration; the law of inertia was needed to slowly produce a new use of the word "force." Thus, the theory is needed to make its own defining terms precise. Einstein said (cf. Heisenberg, 1969, Chapter 5): "only the theory tells us what can be observed."

We propose to call a theory "semantically consistent" if, or rather, to the degree to which, its semantics is expressible in terms to which the theory itself can be consistently applied. Then the enterprise of making the semantics of a new theory consistent may be called its interpretation. In this—and only in this—sense was the Copenhagen Interpretation of quantum mechanics intended to work. It attempted to provide a minimum semantics to Heisenberg's and Schrödinger's formalisms without which they would not yet have been consistent theories.

However, a perfectly semantically consistent theory has probably never existed so far in physics. Thus, in classical mechanics: What is "position"? What is "time"? How to measure them unambiguously? Newton had to invent the unempirical concepts of absolute space and time in order to fix his concepts. Mach criticized them, relativity was the consequence. Yet is General Relativity today understood as being semantically consistent? Bohr was fully aware of this problem. "That you can clean dirty glasses with dirty water and a dirty cloth: if you were to tell that to a philosopher, he would not believe it."

Relativity was not just a semantics of classical mechanics, but an amplification; yet just thereby it served to clarify the meaning of the basic concepts of mechanics. Thus, semantics and amplification are difficult to separate, and they hide under the common umbrella of being "interpretations." For this reason it has not been possible to give an authoritative text on the Copenhagen Interpretation. As a semantics it is still open-ended, and it can be improved both by further analysis and by amplification.

4. TIME

> If you do not ask me what is time,
> I know it; when you ask me,
> I cannot tell it.
>
> *St. Augustine*

We consider time as the pivotal concept on which the apparent difference between the Copenhagen and the transactional interpretations hinges. In CI this concept is used in its commonsense meaning, mostly without a further analysis of this meaning; such an analysis has, however, been given by Weizsäcker (1971, 1985). In this use of time, the qualitative difference between present, past, and future turns out to be essential. TI, on the other hand, takes its point of departure from the time-symmetrical electrodynamics of Wheeler and Feynman (1945). We will consider the Copenhagen use of the time concept as a simple empirical semantics of quantum theory, while the transactional use seems to be an additional mathematical analysis of the theory.

Empirical semantics is supposed to provide the concepts of a theory with a recognizable meaning within the field of experience. What, then, is experience? We may define experience as learning from the past for the future; in a more learned language: as finding laws from an analysis of past events, which can be used and tested by predicting future events. Experience is possible, because the past can in principle be known, partly as being retained in our memory, partly as being deducible from documents of past events: man-made documents like protocols, and nature-made documents like fossils, incoming light from stars, etc. We always presuppose the past to consist of objective facts which exist independent of our knowing them. We shall therefore call the past *factual.* The future, on the other hand, is not known to us until it has happened; physicists possess no factual awareness and no document of the future. But laws of nature, deduced from an analysis of facts of the past, permit us to make predictions on the future which can be tested by waiting until the predicted event is no longer a future event, but belongs to the present or to the past. We call events of the future *possible,* as long as they have not either happened or not happened. It is by no means evident that future events are objective facts (or are predetermined) before they have happened. Determinism in the sense of either a necessity or a factuality of future events is a metaphysical hypothesis whose value does not need to be judged if we want to give no more than an empirical semantics of a theory in physics, i.e., of what we *mean* when we say that the theory refers to experience.

This fairly complicated structure of the so-called modes of time (present, past, future) is effortlessly respected in the correct use of any Indo-European language, e.g., English. We say "I have observed," "I see here," "I expect to happen," etc. Just because of this easy handling, physicists in general are not at all aware of the time-semantical implications of the linguistic semantics in their theories. When they get a glimpse of these implications, they generally describe them by a rather nebulous metaphor like "the arrow of time." The problem alluded to in this metaphor arises from the fact that all basic theories of physics are "reversible" (a term which, itself, needs a more precise definition). Hence the irreversible difference between factual past and possible future does not seem to be deducible from the laws of physics; furthermore, as Einstein (cf. Popper, 1974; Carnap, 1963) remarked and Grünbaum (1967) emphasized, the laws of physics offer no way of qualitatively distinguishing the present (the "now") from any other moment of time.

In our view this is not an insoluble problem. It is a problem created by a high-strung wish for semantical consistency. On the one hand, our simple reflection on the everyday meaning of "experience" ought to have taught us that no empirical meaning can be attributed to any concept of physics unless we are already pragmatically able to use terms like "past," "present," "future" like "fact" and "possibility"; in this sense we all know "what we mean by time." But when asked, we cannot tell. If we accept time as a basic concept, this inability should not embarrass us; a concept which admits an explicit definition is not a basic concept. But some of those physicists and philosophers who call themselves "realists" consider such phenomena like our awareness of time as only "subjective"; they search for an "objective" description of time. This means that they will not accept "subjective phenomena" as basic for physics at all. Now it cannot be denied that a really existing state of mind of a human being is itself an objective fact. But "realists" would want to begin by describing time as a structure in the "external world." This would mean that the subjective phenomena are to be explained rather than to be merely accepted. Thus, the modes of time would have to be deduced from the laws of physics as a consequence. This ambition tends to apply the laws of physics to those phenomena, too, which were presupposed by the language in which we express these very laws of physics: it aims at full semantical consistency. From the Copenhagen view, as we try to understand it, this is a perfectly acceptable ambition, provided there is a chance of fulfilling it.

In an early paper (Weizsäcker, 1939) which has escaped the notice of most physicists, this problem was treated in view not yet of quantum theory, but of the Second Law of Thermodynamics. The equations of mechanics are reversible. Strictly speaking, this means, by the way, that they are invariant not under "time reversal," but under reversal of motion. In the example of free motion of a mass point: its state in the phase space is defined by the six real variables x_i, p_i ($i = 1, 2, 3$; $x =$ position, $p =$ momentum). Let a possible path of the mass be $x_i(t)$, $p_i(t)$. Then $x_i'(t) = x_i(-t)$, $p_i'(t) = p_i(-t)$ (time reversal) is not a solution of the equation of motion (1), as above defined, but $x_i'(t) = x_i(-t)$, $p_i'(t) = -p_i(-t)$ (motion reversal) is. In any fully deterministic theory the state at any time must uniquely determine the state at all other times, which is possible, e.g., for $t = 0$, if $x_i'(0) = x_i(0)$, $p_i'(0) = -p_i(0)$, but not for the time-reversal case. Abstractly speaking: in a deterministic theory, the reversal of any possible time sequence of a variable $x'(t) = x(-t)$ implies the change of sign of its time derivative $dx'(t)/dt = -d(x(t))/dt$; hence the need for a second-order differential equation of motion. We shall use this slightly pedantic terminology also in the case of quantum theory.

Now the seeming paradox of the Second Law is: How can the irreversible increase of entropy be a consequence of the reversible laws of mechanics? For a full analysis we must refer to Weizsäcker (1939) paper, reprinted in Weizsäcker (1971), and to the further discussion in Drieschner (1970, 1979) and Weizsäcker (1985, Chapters 2-4). But we might condense the answer to the paradox into five sentences:

1. Entropy is a measure of probability.
2. Probability in its empirical use means the prediction of a relative frequency.
3. Prediction refers to the future.
4. Hence the asymmetry between past and future in the Second Law is not a consequence of the mathematical structure of the equations of motions, but of their semantical presuppositions, i.e., of their empirical meaning.
5. Thus, the asymmetry of time is not only "subjective," but it is an objective structure of nature.

The argument then runs simply as follows: If a state of nonmaximal *a priori* probability exists at a time t_0, then the most probable possible events *will* happen in the average: the *a priori* probability (entropy) of later states will in the average be larger than at the time t_0. The same argument does not apply to states earlier than t_0, because they are already facts, and the *a priori* probability of any special fact is small. Since every past moment of time t_- was once present, at that time t_- the same argument applied to all times $t > t_-$ (which then were still in the future). Hence, the increase of entropy must have happened in all past times, as far as the phenomenal structure of time existed then.

To a limited degree there is a test of semantical consistency for this description of objective time. The facts of the past can, as we said, be known by documents (we include the engrams of our memory under this concept of a document). Why are there documents of the past, but not of the future? This question can now be answered by applying the Second Law (semantical consistency). A document is an improbable fact. According to the Second Law, it must have been preceded by even less probable facts; these are the events of which we take it to be a document. But it will be followed by more probable events, i.e., by events carrying less information. Thus, a mammoth tooth found in the tundra is a document of a whole extinct species of elephants; but it predicts nothing more than its own slow dissolution under atmospheric influences.

But this proof of consistency is not fully symmetrical. The phenomenological structure of time is (together with the equation of mechanics) sufficient for deducing the Second Law. But the Second Law is not sufficient for deducing the full phenomenological structure of time. It explains why the past can be better known than the future. But it does not explain what we mean by "now." It proves no more than a time order (which in the present language of physicists is generally called "causality"); it does not explain the most elementary phenomenon of the "flux of time." Furthermore, all physicists (including the present authors) would hesitate to state the Second Law as a fundamental law of nature which would need no further explanation. Cramer (1983) gives a good example how in his view of quantum theory the "arrow of time" (carefully defined by him) can be deduced from a cosmological model.

We submit a simple answer to Einstein's question why the "now" cannot be deduced from the laws of physics. Being laws, they are, logically seen, universal propositions, applying at any time. Hence they cannot express characteristics of a special moment of time which is even constantly changing. The meaning of the "now" belongs to the previous semantical material without which even the concept of a proposition "valid at any time" would be void of meaning. Thus, it seems that physics by its very conceptual structure is unable to explain all the phenomena which it presupposes. Yet the quest for semantical consistency is a noble enterprise and crowned by partial sucess.

5. THE COPENHAGEN INTERPRETATION

> Quantum theory is a theory of knowledge,
> i.e., it is a realistic theory.

We apologize for going on so long on pre-quantum problems. But classical statistical mechanics is just conceptually simple enough to serve as an example in which we can demonstrate how we want to use such terms as "interpretation" and "semantics." While our description of phenomenal time has not been explicitly developed by any earlier member of the Copenhagen school, we feel that we have been inspired in it by the lesson we all learned from Niels Bohr. He always insisted on never using mathematical concepts or linguistic phrases in physics without the deepest possible scrutiny of their pragmatic meaning in actual experience. This attitude is very far from "positivism" in the prejorative (and, frankly said, stupid) sense of "what cannot be observed, does not exist" or, even worse, "what has not been observed, does not exist." We consider the Copenhagen Interpretation as the attempt at giving that *minimal semantics* to the formalism of quantum mechanics without which one would not know how to apply that formalism to reality at all.

In the present section we follow Cramer's (1986) critical exposition of CI in order to show that the criticism only applies to a non-Bohrian, though widespread misunderstanding of CI.

Cramer (1986, pp. 649–650) distinguishes five elements in CI:

(C-1) The uncertainty principle of Heisenberg (1927).
(C-2) The statistical interpretation of Born (1926).
(C-3) The complementarity concept of Bohr (1928).
(C-4) Identification of the state vector with "knowledge" by Heisenberg [we guess: already Heisenberg (1927)].
(C-5) The positivism of Heisenberg [we guess: only in Heisenberg (1925)].

He thinks "that elements (C-1) and (C-2) fulfil the function of relating the formalism to experiment, while elements (C-3) through (C-5) perform the function of avoiding paradoxes" (p. 651). We do not object to this enumeration and to the distinction of the five elements into two classes.

The statistical interpretation (C-2) is the basic assumption of the "minimum semantics" CI. From Jammer (1974) we can learn that Born's original interpretation of his probability law ($p = \psi\psi^*$) was not yet correct, insofar as he then thought that orbits of the particles exist, but are walked through at random. Bohr and Heisenberg were aware of this inconsistency. Thus (C-1), Heisenberg's uncertainty principle, was the first consistent application of the statistical law. The orbits do not exist at all.

The correct interpretation of the uncertainty principle is indispensable for understanding CI. It is, to begin with the simplest mistake, necessary and sufficient for eliminating the idea (C-5) that Heisenberg was a "positivist." It is true that in 1925 he was still deeply impressed by the most intelligent of all positivists, who also profoundly influenced Einstein in his youth, Ernst Mach. He introduced quantum mechanics under the methodological postulate of connecting only observable quantities. But already in 1926 Einstein, in a most memorable conversation (Heisenberg, 1969, Chapter 5) convinced Heisenberg that only the theory decides what can be observed. In our present language this statement is contained in the postulate of semantical consistency. The methodological structure of the uncertainty principle was never its "positivistic" misunderstanding "position and momentum cannot be simultaneously observed, hence they do not simultaneously exist." It is the contraposition: "In quantum mechanics (after J. v. Neumann we say: in Hilbert space) there are no states in which position and momentum have simultaneously precise values; hence in a *Gedankenexperiment*, described in conformity with quantum mechanics, they cannot possibly be observed simultaneously." Heisenberg was aware of a situation which we can describe more precisely today by EPR and the Bell inequalities: the reintroduction of classical orbits (or any "locality") into quantum mechanics would completely destroy its explanatory value, which is due to the enormous "surplus information" that distinguishes the quantum phase relations from any classical model. Not even the hydrogen atom would be stable without the quantum nonlocality. Heisenberg's reaction (orally) to the EPR paper in 1935 was: "Now, after all, Einstein has understood quantum mechanics. I am just sorry for him that he still does not like it." The term "uncertainty principle" is rather a misnomer ("Everything is uncertain—says Mr. Heisenberg"). Position and momentum must be "*unbestimmt*" (without fixed values) in order to give room for the immense certainty provided by the phase relations.

We shall not extensively discuss here (C-3), i.e., Bohr's philosophy of complementarity. It is an attempt "to tell what we can meaningfully say," an exercise in epistemological caution. We concentrate on (C-4), more specifically on the meanings of the two key words "knowledge" and "reality."

"I know that the sun is presently shining": this phrase contains two statements: "the sun is presently shining" and "I know this fact." In general we omit the explicit statement on knowledge and the explicit reference to the present; we say "the sun is shining." The intention of such a phrase is to express and thereby to convey knowledge. For a statement to express knowledge it is necessary that it be true; we may define truth here as adequation to reality. Truth, yet, is not sufficient. A statement may express a true opinion without actual knowledge. An example used by Plato in the "Theaitetos" is the case that I say "this defendant is not guilty" if I do not know the facts, but have been convinced by a shrewd advocate; convinced of objective truth by false or insufficient arguments. In this strong sense of "knowledge" the *knowledge of an observed expresses a tested reality*, and we are permitted to say that quantum theory is realistic *because* it is a theory of knowledge.

The problem only arises when we ask what *kind* of knowledge quantum theory permits. Here the statistical interpretation is constitutive. The state vector (SV) yields only *statistical predictions*. We try first to eliminate two strange difficulties experienced by Cramer (1986, p. 652). First: "The notion that the solution of a simple second order partial equation . . . is somehow the mathematical reproduction of 'knowledge" seems "curious and provocative" to him, since it presupposes "a conscious and intelligent" observer. We feel, however, that observation presupposes some consciousness, and meaningful observation presupposes some level of intellect; while, on the other hand, the full ψ-function is a list of mathematical consequences of the simple knowledge gained in an observation, consequences which are true even if the observer is not aware of them. Second: The observer behaves irreversibly, e.g., by storing the result in his memory. "Somehow the thermodynamic irreversibility of the macroscopic observer is intruding into the description of a fully reversible microscopic process." True, into the description, because describing is always an irreversible act, but not into the process so described.

In this context it is most important to remember that Bohr explicitly excluded the observer or "consciousness" from the realm of those objects that are described *by* quantum theory. Without consciousness, no observation, hence no knowledge, hence no physics; in this sense the observer is a prerequisite of the meaning of statements. But Bohr did not believe that quantum theory would apply to the description *of* observers or *of* consciousness (as distinct from "*by*" observers); he was even skeptical about its application to organic life. We consider this as too strict a limitation for the field of quantum description. But Bohr's language cannot be understood unless we first learn to make the simple and strict epistemological, i.e., methodological distinction between the knower and the known. Only then can we ask the later question of whether and how the knower himself might become an object of physics, i.e., of his own objective knowledge.

The real problem is, as we said, the *statistical* nature of the knowledge. Here our analysis of phenomenal time may contribute to clarification. What the observer actually observes and hence knows is a present or past state of the object. Facts are real and unchangeable; in this sense, empirical knowledge refers to reality. But facts are known to us only as present or, by memory or implication, as past. Quantum theory in the Copenhagen Interpretation is realistic precisely in not maintaining to know what does not yet exist, i.e., the future.

6. THE TRANSACTIONAL INTERPRETATION

The purpose of TI seems to be the elimination of the modes of time. As we said in Section 2, our methodological suspicion is that TI and CI [the latter including a description of the observer as given in Görnitz and Weizsäcker (1987b)], since they refer to the same mathematical structure with the same empirical use, are no more than two different linguistic expressions of one identical theory. This suspicion can be tested if we can offer the dictionary for translating them into each other. The dictionary can be written in any one of the two languages, expressing in it what the other language says. It is very simple:

TI as described in CI: "TI describes all events as though they were in the past."

CI as described in TI: "What CI calls possibilities in the future are unknown, but fixed facts."

Mathematically, TI replaces the proceeding ("retarded") wave from an emitter toward unknown future absorption acts by a "four-dimensional action at a distance" or rather "action at a four-dimensional distance." The "objective" wave or state vector is determined only if the space-time locations of emitter and absorber are completely known; of all absorbers, and, symmetrically, of all emitters, too, but the simple examples speak of one emitter and one absorber. The "objective" wave is then the superposition of an infinite number of "retarded" waves running from emitter to absorber and of "advanced" waves "running backward in time" from absorber to emitter. The basic intention is a new explanation of the so-called "collapse of the wave-function by observation." In the temporal CI description the wave function is the list of possible probabilistic predictions following from the observer's knowledge on events that have actually happened in his past, as presently known by him. Its reduction (or "collapse") is the trivial fact that new events create new knowledge and permit new predictions. In the TI description the retarded wave starting from the emitter is what an observer who has seen the emitter can predict before he knows the absorber; the "objective" wave is a description which can be given by an observer who knows the absorption act as well. The reduction of the wave function is the logical transition from the original retarded wave to the "objective" wave.

It seems evident that this mathematical structure permits the transition between both interpretations by our dictionary. CI will say: The "objective" wave can only be known after the absorption has happened; it is then a description of a past sequence of emission and absorption events. TI will say: The "future" absorption is in the "objective" space-time continuum a fact, true even at a "subjective time" of the observer at which he cannot yet know it; in this sense the state vector as determined by emitter and absorber exists "objectively" even when it is not so known.

As long as the two interpretations do not predict different experimental results, there is no way of empirically deciding between them and hence no way of empirically giving their difference another meaning than just as the use of different languages for the same thing. More difficult is the philosophical question of whether there is an advantage of clarity or of possible connections with an understanding of reality beyond present-day physics. Here we plead, provisionally at least, for continuing in everyday language, as used by experimentalists and the "man in the street," i.e., for CI. This is not only a pragmatic attitude. Our methodological reason was given at the end of Section 4: A description of time by a mere real coordinate t cannot explain the basic phenomenon of the "now," while presupposing the now as a basic fact of reality, we can describe all the rest so far consistently. The situation would be changed if the facticity of future events might become present knowledge, as some prophets or clairvoyants maintain. This would mean a changed empirical situation; it would force us to enter into the interpretation debate anew.

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REFERENCES

Bohr, N. (1928). *Naturwissenschaften*, **16**, 245.
Born, M. (1926). *Zeitschrift für Physik*, **38**, 803.
Carnap, R. (1963). In *The Philosophy of R. Carnapp*, P. A. Schilpp, ed., Library of Living Philosophers, No. 11, La Salle, Illinois.
Cramer, J. G. (1983). *Foundations of Physics*, **13**, 887.
Cramer, J. G. (1986). *Reviews of Modern Physics*, **58**, 647.
Deutsch, D. (1985). *International Journal of Theoretical Physics*, **24**, 1.
Drieschner, M. (1970). Quantum mechanics as a general theory of objective prediction, Thesis, Hamburg.
Drieschner, M. (1979). *Voraussage, Wahrscheinlichkeit, Objekt*, Springer Lecture Notes in Physics, No. 99, Berlin.
Görnitz, Th., and Weizsäcker, C. F. v. (1987a). Remarks on S. Kochen's interpretations of quantum mechanics, paper submitted to the Symposium on the Foundations of Modern Physics, Joensuu.
Görnitz, Th., and Weizsäcker, C. F. v. (1987b). Quantum interpretations, *International Journal of Theoretical Physics*, **26**, 921.
Grünbaum, A. (1967). The anisotropy of time, in *The Nature of Time*, T. Gold and D. L. Schuhmacher, eds., Cornell University Press, Ithaca, New York.
Heisenberg, W. (1925). *Zeitschrift für Physik*, **33**, 879.
Heisenberg, W. (1927). *Zeitschrift für Physik*, **43**, 172.
Heisenberg, W. (1969). *Der Teil und das Ganze*, Chapter 5, Piper, Munich.
Jammer, M. (1974). *The Philosophy of Quantum Mechanics*, Wiley, New York.
Kochen, S. (1985). In *Symposium on the Foundations of Modern Physics*, P. Lathi and P. Mittelstädt, eds., World Scientific, Singapore.
Popper, K. (1974). In *The Philosophy of Karl Popper*, P. A. Schilpp, ed., Library of Living Philosophers, No. 14, La Salle, Illinois.
Weizsäcker, C. F. v. (1939). *Annalen der Physik*, **36**, 275.
Weizsäcker, C. F. v. (1971). *Die Einheit der Natur*, Hanser, Munich [*The Unity of Nature*, Farrar, Straus, Giroux, New York, 1980].
Weizsäcker, C. F. v. (1985). *Aufbau der Physik*, Hanser, Munich.
Wheeler, J. A., and Feynman, R. P. (1945). *Reviews of Modern Physics*, **17**, 157.