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Role of the Observer in Quantum Theory

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In quantum theory as it is currently formulated the measurement of an observable quantity of a physical system is the occasion for a change of state of the system, except when the state prior to the measurement is an eigenstate of the observable. Two proposals for interpreting this kind of change are examined in detail, and several variant proposals are considered briefly. According to the interpretation proposed by von Neumann, and by London and Bauer the change of state is completed only when the result of the observation is registered in the observer's consciousness. Although this interpretation appears to be free from inconsistencies, it is not supported by psychological evidence and it is difficult to reconcile with the intersubjective agreement of several independent observers. According to the interpretation proposed by Bohr, the change of state is a consequence of the fundamental assumption that the description of any physical phenomenon requires reference to the experimental arrangement. Bohr's proposals are valuable as practical maxims in scientific activity, but they are shown to involve the renunciation of any ontological framework in which all types of events—physical and mental, microscopic and macroscopic—can be located. It is concluded that a satisfactory account of the observation of microphysical quantities is unlikely if the present formulation of quantum theory is rigorously maintained.

I. INTRODUCTION

THERE are two distinct problems concerning the relationship between physical objects and consciousness. One is the ontological problem of accounting for the fact that two such diverse kinds of entities occur in nature and interact with each other. The other is the epistemological problem of justifying physical theories by reference to human experience. A complete solution to either of these problems would surely require a solution to the other as well. In particular, it seems that the epistemological problem cannot be completely solved without understanding how the effects of physical entities can be registered upon consciousness, since performing observations and formulating theories constitute a series of acts of consciousness. It is a remarkable fact about classical physical theory that considerable progress was made on the epistemological problem, at least on that part of the problem which has been demarcated as "scientific method," while the ontological problem remained obscure. Classical physical theory was consistently "mechanical" in the sense that the fundamental physical entities were considered devoid of sensuous qualities; and it was "empirical" in the sense that most of the classical masters recognized that the truth of physical theory is tested by its predictions regarding the observable behavior of things. However, the apparent discrepancy between the "mechanical" and the "empirical" aspects of classical physics did not seem to impede the development of the science. It was possible to relate fundamental physical concepts to common characteristics of the objects encountered in daily life and in the laboratory, and these common characteristics could somehow be directly recognized by an observer.[1] (This was already understood, in a matter-of-fact way, by Galileo and Newton, who were, after all, experimenters as well as theoreticians.) Thus, a relation between the physical *Weltbild* and experience could be established, even though the process whereby the observer performed his act of recognition was very obscure. Indeed, classical physics was indifferent to attempts to explain this relation ontologically—e.g., by means of a causal connection between mental and physical events. The network of more or less tacit rules for applying theoretical physics to ordinary objects and

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[1] It is not important, for the purposes of this paper, to distinguish the various common characteristics of objects, although they range from attributes which apparently are purely perceptual, such as "green," to those which involve theory in an essential way, such as "being an ammeter." The essential point is not whether there is a stage of perception which is independent of memory and of theoretical judgment, but that there exists some procedure for relating to experience a picture of physical reality in which consciousness has no part.

of normal procedures for dealing with the common characteristics of these objects allowed classical physics to by-pass the fundamental ontological problem. The "bifurcation of nature"—as Whitehead named the extreme separation of physical and mental entities in nature—may have been a scandal from the standpoint of metaphysics, but it became a convenient working arrangement from the standpoint of physical theory.

The replacement of classical physics by quantum theory was, of course, the result of puzzling sets of physical phenomena, and not of philosophical reconsideration. Nevertheless, there are several philosophically significant respects in which quantum physics differs from classical physics, the most important being that the concept of an "observation" plays a central role in the quantum physical picture of the world. The relation of elements of the physical theory to experience no longer seems to be extraneous to physics, but seems to be an intrinsic part of physical theory itself. Whether this is a correct characterization of quantum theory depends, to be sure, upon the exact meaning of 'observation,' and this has to be examined in detail. But *prima facie* quantum theory does differ from classical physics regarding the relationship between physical entities and consciousness. The founders of quantum theory, particularly Heisenberg[2] and Bohr,[3] discussed with much subtlety the epistemological problem of relating atomic physics to human experience; but except for a few remarks, usually tentative and oblique, they do not consider the ontological problem of mind and physical reality. It is reasonable to inquire, therefore, whether the ontological problem can be by-passed by quantum theory in much the same way as was done by classical physics. And if not, can an account of the relationship of mind to physical reality be given which is consistent with both our knowledge of psychology and the present formulation of quantum theory? In this paper I contend that the answer to both questions is negative.

II. RESUMÉ OF THE QUANTUM THEORY OF OBSERVATION

According to quantum theory, a physical system is in a definite *state* at every moment. Intuitively, the state of the system is the totality of its observable properties, but the relation of this "totality" to individual observables is peculiar to quantum mechanics. Furthermore, the states have the peculiar characteristic of obeying the *superposition principle*, and this permits us to represent the states of the system by vectors ψ of a linear vector space. An inner product (ψ,ψ') is, also, defined which is an index of the extent to which two states "overlap."

A quantity which can be assigned to the system as the result of a measurement is an *observable*. A well-performed measurement of an observable F yields a definite number belonging to a set of possible values $f_1, f_2, \ldots$ (where, for simplicity, the possibility of a continuum of values of the observable has been neglected). A state which is unchanged when a sufficiently careful measurement of F is performed is an *eigenstate* of F. Quantum theory supposes that the eigenstates of F are *complete*, in the sense that a set of vectors $u_1, u_2, \ldots$ can be selected, each representing an eigenstate, such that an arbitrary vector can be expressed in the form.

$$\psi = \psi_1 u_1 + \psi_2 u_2 + \cdots, \tag{1}$$

where the ψ_i are complex numbers. The u_i can be chosen orthonormal, i.e. the inner product $(u_i,u_j)=1$ if $i=j$ and $=0$ if $i\neq j$. In the following discussion, each value of F is assumed to be associated with only one of the u_i, since no essential question of interpretation is affected by this simplification. The representation of F by a *linear operator* α is implicit in (1), for it suffices to specify that

$$\alpha u_i = f_i u_i \tag{2}$$

and to require *linearity* of α, i.e., $\alpha(a\phi+b\psi) = a\alpha\phi+b\alpha\psi$. Because the eigenvalues f_i in (2) are real numbers, the operator α is *hermitian:* $(\alpha\phi,\psi)=(\phi,\alpha\psi)$ for any vectors ϕ and ψ. It is assumed that when F is measured in a state which is not an eigenstate, the probability that

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[2] W. Heisenberg, *The Physical Principles of the Quantum Theory* (University of Chicago Press, Chicago, Illinois, 1930).

[3] N. Bohr: (a) *Atomic Theory and the Description of Nature* (Cambridge University Press, Cambridge, England, 1934); (b) Phys. Rev. **48**, 696 (1935); (c) *Atomic Physics and Human Knowledge* (Science Editions, Inc., New York, 1961).

the value f_i will be found is

$$\mathrm{Prob}_\psi(f_i)=|\psi_i|^2, \tag{3}$$

where ψ_i is the coefficient in the expansion (1). The fundamental Eq. (3) cannot be interpreted as asserting that ψ represents a body of partial information, to the effect that there is a probability $|\psi_i|^2$ that the actual, but unknown, value of the observable F is f_i. Such an interpretation can be shown to be contradictory by considering a different observable F' with eigenstates differing from the eigenstates of F. Predictions regarding observables other than F depend, in general, not only on the absolute values of the complex coefficients ψ_i, but on their phases as well; and these phases are neglected in the interpretation of a superposition as representing partial information. When ψ is known, this is maximal information about the system, and, therefore, (3) must be interpreted as asserting that in an objective sense F is indefinite in the state represented by ψ.

There are two ways in which the state of a system may change:

(1) If the system in the state represented by ψ is subjected to a measurement of F, then a transition $\psi\rightarrow u_i$ occurs, for some i, and the probability of a particular transition is $|\psi_i|^2$.

(2) If the system is undisturbed during a time interval, then in that interval the "equation of motion" is the Schrödinger equation

$$ih(\partial\psi/\partial t)=H\psi, \tag{4}$$

where H is the Hamiltonian operator, i.e., the operator corresponding to the energy of the system. It follows from Eq. (4) that if the system is undisturbed, its states at two times t and t_0 are related by the equation

$$\psi(t)=U(t-t_0)\psi(t_0), \tag{5}$$

where

$$U(t-t_0)=\exp[(i/h)H(t-t_0)].$$

U is a linear operator, and furthermore, since the Hamiltonian operator H is hermitian, U is *unitary*, i.e., $(U\phi,U\psi)=(\phi,\psi)$, for arbitrary vectors ϕ and ψ.

The most systematic theory of observation in quantum mechanics was proposed by von Neumann[4] and later presented more simply (and in some ways more deeply) by London and Bauer.[5] They consider transitions of type 1, discontinuous transitions due to the performance of a measurement, to be an uneliminable aspect of quantum theory; and they explicitly understand by 'measurement' the registration of the result in a consciousness.

That a transition of type 1 cannot be due simply to interaction of the system with a measuring apparatus may be seen as follows: The apparatus is itself a physical system (system y) and, therefore, its states and observables are describable by quantum theory. For the apparatus to be usable for the purpose of measuring F in the original system of interest (system x) it must be possible to prepare the apparatus in an initial state $\phi_0(y)$ which is, in a certain sense, sensitive to states of x. That is, if a composite system $x+y$ is formed by placing x and y into contact, and if the initial state of $x+y$ is represented by

$$\Psi(t_0)=u_i(x)\phi_0(y), \tag{6}$$

where $u_i(x)$ represents one of the eigenstates of F. Then, in time t_1, system $x+y$ evolves to

$$\Psi(t_0+t_1)=u_i(x)v_i(y), \tag{7}$$

where $v_i(y)$ represents an eigenstate of some observable G of y such that $g_i\neq g_j$ if $i\neq j$. The transition of the state from $\Psi(t_0)$ to $\Psi(t_0+t_1)$ is continuous and is governed by the Schrödinger equation

$$ih[\partial\Psi(t)/\partial t]=H_{x+y}\Psi(t), \tag{8}$$

where H_{x+y} is the Hamiltonian operator of the composite system. Eq. (7) implies that a determination of the value of G in the apparatus indirectly but unequivocally determines the value of F in the original system. Suppose, however, that the initial state of x is not an eigenstate of F, but is represented by the vector ψ which can be expanded as in Eq. (1). Then

$$\Psi(t_0)=\psi_1u_1(x)\phi_0(y)+\psi_2u_2(x)\phi_0(y)+\cdots. \tag{9}$$

Since H_{x+y} is a linear operator, it follows from

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[4] J. von Neumann, *Mathematical Foundations of Quantum Mechanics* (Princeton University Press, Princeton, New Jersey, 1955).

[5] F. London and E. Bauer, *La Théorie de l'observation en mécanique quantique* (Hermann & Cie., Paris, 1939).

(6)–(9) that

$$\Psi(t_0+t_1)=\psi_1u_1(x)v_1(y)+\psi_2u_2(x)v_2(y)+\cdots. \quad (10)$$

The fact that ψ is a superposition of different u_i is reflected in the fact that the final state vector of $x+y$ is a superposition of different $u_i(x)v_i(x)$. In other words, the initial indefiniteness of F in ψ implies an indefiniteness of G in the state represented by $\Psi(t_0+t_1)$. The latter indefiniteness can, of course, be resolved by a measurement of G, which would produce the transition

$$\Psi(t_0+t_1)\rightarrow u_n(x)v_n(y) \quad (11)$$

for some value of n. But this transition is of type 1 and requires the registration of the result of the measurement in a consciousness. If, instead of such a registration, an apparatus y' sensitive to the states of $x+y$ is used, then in exact analogy to (10) the state of $x+y+y'$ at some time $t_0+t_1+t_2$ will be of the form

$$\Xi(t_0+t_1+t_2)=\psi_1u_1(x)v_1(y)v'_1(y')+\cdots. \quad (12)$$

This is a further stage in an infinite regress which seems to be terminated only by conscious awareness of the result of a measurement.

One further feature of the quantum theory of interacting systems should be mentioned: that a composite system $x+y$ may be in a definite quantum state without either x or y being in definite states. In other words, it may be impossible to express the vector Ψ, which represents the state of the composite system, in the form $\phi(x)\psi(y)$, where $\phi(x)$ and $\psi(y)$ represent states of x and y, respectively. In general, one can only describe system x as having probabilities p_1, p_2, . . . of being in appropriate states represented by ϕ_1, ϕ_2, ... Such a description is called a 'mixture,' and it differs from a superposition by the absence of any specification of phase relations among the vectors ϕ_i, thereby eliminating the possibility that a mixture is really a state in disguise. A similar description by means of a mixture is, of course, also possible for system y. This situation is counter-intuitive and in sharp contrast to that of classical physics, where the specification of the state of a composite system implies the specification of states of all subsystems.

III. THE ABILITY OF THE MIND TO REDUCE SUPERPOSITIONS

The foregoing account of the proposals of von Neumann and of London and Bauer is incomplete, since their treatment of the problem of agreement among different observers has not been summarized. Before turning to this problem, however, I believe it enlightening to examine in detail the operation whereby a single observer effects a reduction of a superposition.

von Neumann[4] says almost nothing about the consciousness of the observer, except that "the intellectual inner life of the individual . . . is extra-observational by its very nature (since it must be taken for granted by any conceivable observation of experiment)." (p. 418.) London and Bauer[5] say somewhat more:

> ". . . let us consider the set of three systems, (object x) (apparatus y) (observer z) as a single composite system. We shall describe it by a total wave function . . .
>
> $$\Psi(x,y,z)=\Sigma\,\psi_ku_k(x)v_k(y)w_k(z),$$
>
> where the w_k represent the different states of the observer.
>
> 'Objectively'—that is to say, *for us* who consider as 'object' the composite system x, y, z—the situation seems little changed in comparison with what we have encountered before, when we only considered the apparatus and the object. We now have three mixtures, one for each system, with the statistical correlations among them bound to a pure case for the total system. Indeed, the function $\Psi(x,y,z)$ represents a maximum description of the composite 'object,' consisting of x, which is the object in the strict sense, the apparatus y, and the observer z. Nevertheless, we do not know in what state the object x is found.
>
> The observer has an entirely different point of view. For him it is only the object x and the apparatus y which belong to the external world—to that which he calls 'objective.' By contrast, he has *with himself* some relations of a completely special character: He has at his disposal a characteristic and quite familiar faculty, which we may call the 'faculty of introspection.' He can thus give an account of his own state in an immediate manner. It is in virtue of this 'immanent knowledge' that he claims the right to create for himself his own objectivity, that is to say, to cut the chain of statistical coordinations expressed by $\Sigma\,\psi_k(x)v_k(y)w_k(z)$ by certifying: 'I am in the state w_k' or more simply 'I see $G=g_k$' or even directly '$F=f_k$.'
>
> It is therefore not a mysterious interaction between the apparatus and the object which brings about a new ψ during the measurement. It is only the consciousness of an '*I*' which can separate itself from the old function $\Psi(x,y,z)$ by henceforth attributing to the object a new function $\psi(x)=u_k(x)$." (Translated from pp. 42–3.)

In this passage London and Bauer seem to be stating some important, though incompletely developed, propositions regarding the place of the mind in nature. (i) The use of the product formalism $u_k(x)v_k(y)w_k(z)$ indicates that the observer z is ontologically on the same level as the microscopic system x and the apparatus y. The observer z is one system among many, and the fact that the state $w_k(z)$ can be correlated with the states $u_k(x)$ and $v_k(y)$ implies that the physical systems x and y can interact with the observer, even though the details of the interaction are unknown. In particular, London and Bauer do not seem to be attributing a transcendental position to the observer, such that the physical systems x and y somehow derive their existence from the observer. (ii) The assertion that the observer knows his own state by direct introspection implies that London and Bauer understand z to include the mind of the observer, possibly together with all or part of his body (though it is clearly also possible to consider parts of the body as physical apparatus, as von Neumann explicitly suggests). (iii) At least some of the usual principles of quantum theory are implicitly asserted to apply to states $w_k(z)$ of the observer. In particular, the reference to the sum $\sum \psi_k u_k(x)v_k(y)w_k(z)$ requires that the states of the observer be superposable and that phase relations among them be meaningful. (iv) The dynamical laws governing the evolution of states of the observer are such that the transition $\sum \psi_k u_k(x)v_k(y)w_k(z) \rightarrow u_n(x)v_k(y)w_k(z)$ occurs without any outside disturbance of the composite system $x+y+z$. This transition is possible because the observer has a property which is not shared by any other system in nature, the faculty of introspection, whereby the observer can "cut the chain of statistical coordinations." (Translated from Ref. 5, pp. 41–2.)

Propositions (i) and (ii) are not novel: they merely state without elaboration an ontology, like that of Aristotle or Locke, in which both mental and material systems occur in nature and interact with each other. Proposition (iii) is a remarkable extrapolation of ordinary quantum theoretical characteristics to states of mind. Proposition (iv) is essentially a qualification of (iii), for it asserts that at least one of the fundamental principles of quantum theory fails to hold of states of the observer. The transition $\sum\psi_k u_k(x)v_k(y)w_k(z) \rightarrow u_n(x)v_n(y)w_n(z)$ is a nonlinear transition and is stochastic, whereas ordinary quantum theory asserts that all transitions of isolated systems are linear and nonstochastic. It follows, of course, that the temporal evolution of a state Ψ of a composite system of which a mind is a subsystem cannot be governed by a Schrödinger equation, since we have seen in Eq. (2.5) that the Schrödinger equation implies a deterministic and linear relation between the states of the system at different times. Two considerations make this conclusion seem reasonable. First, it is doubtful that there exists a Hamiltonian operator H for a system containing a mind (for this would require that energy could be expressed partially in terms of psychological variables), and without a Hamiltonian operator the Schrödinger equation cannot even be formulated. The second consideration is based on the fact, previously mentioned, that a composite system can be in a definite quantum state and yet its components need not be in definite states. In particular, if the composite system $x+y+z$ is in the state represented by $\sum\psi_k u_k(x)v_k(y)w_k(z)$, then in general the observer z is not in a definite state but must be described by a mixture. It is the peculiar property of the observer, however, that by possessing the faculty of introspection he can attend to himself in abstraction from the physical systems with which he interacts. The result of his introspection is to establish himself in a definite state. There must be an element of chance in this process, since prior to introspection there were only various probabilities for the observer to be in various definite states.

In brief, then, London and Bauer seem to be proposing that states of the observer satisfy the vectorial relations required by ordinary quantum mechanics, but do not evolve temporally in the ordinary quantum mechanical manner. Although it is a strange proposal, consisting of a partial extension of quantum theory into the domain of psychology, it contains no obvious inconsistency. Whether it is factually correct, however, is another matter, and to judge this two psychological questions must be investigated: whether mental states satisfy a superposition principle, and whether there is a mental process of reducing a superposition.

Perhaps the most obvious mental phenomenon to investigate in connection with the superposition principle is the phenomenon of perceptual vagueness. It is often said that in a physical state ψ which is not an eigenstate of an operator α, the observable corresponding to α has an indefinite or "blurred" value; and this suggests that a mental state in which certain perceptions are blurred or indistinct is a superposition of states of clear perception. An obvious difficulty in such a proposal is the obscurity of the meaning of the phase relations in a superposition of mental states. A partial answer can perhaps be given in those cases where perceptual vagueness in one area is correlated with distinctness in another area, e.g., indistinctness of visual perception while concentrating on music; for such a case is reminiscent of the fact that the phase relations in a superposition $\psi = \sum c_i u_i$ ensure that some observable F' has a sharp value in ψ, while another observable F (complementary to F') which has different values f_i in the various u_i does not have a sharp value in ψ. This answer is unsatisfactory, however, because in general perceptual vagueness does not occur as a price paid for a distinct perception of a "complementary" quality. Vagueness may be due to a variety of factors, such as sleepiness, ill-health, or emotional turmoil, which dull all perceptions and do not sharpen one at the expense of others. An even more decisive consideration, however, is the following. Suppose the observer z examines the composite system consisting of a microscopic object x and a detecting apparatus y. Let the initial state of $x+y$ be $\sum \psi_k u_x(x) v_k(y)$, and suppose that some macroscopic observable G has distinct values g_k in the various $v_k(y)$. Then, if London and Bauer are correct, the initial state of $x+y+z$ is the superposition $\sum \psi_k u_k(x) v_k(y) w_k(z)$, but very quickly this state passes over into $u_n(x) v_n(y) w_n(z)$. If vagueness has any connection with superpositions, the observer should initially experience a vague perception regarding G, but should find that this vagueness is rapidly dispelled and a sharp perception is somehow crystallized. However, introspection does not seem to reveal any such psychological process. If the observer is healthy, alert, and undistracted, and if the light is good, etc., there is no initial state of perceptual vagueness; and if these conditions are not fulfilled, there may be an initial state of perceptual vagueness even if the physical system $x+y$ is not in a superposition relative to the macroscopic observable G. In short, there seems to be no correlation between the phenomenon of vagueness and the superposed character of the physical "input" into the observer.

Several other psychological phenomena could possibly be interpreted as instances of the superposition principle: e.g., indecision, conflict of loyalty, ambivalence. The crucial objection which was brought against such an interpretation of perceptual vagueness cannot be raised in these cases, because we do not know how to correlate such phenomena in an unambiguous manner with physical "input" into the observer; and therefore, we cannot prepare the "input" in a superposed state, make a prediction regarding the psychological effect, and test the prediction by introspection. However, even though a crucial negative test of the interpretation of indecision, ambivalence, etc. in terms of superpositions does not seem to be forthcoming, there is not a trace of evidence in favor of this interpretation. In particular, in all such phenomena, the meaning of phase relations remains profoundly obscure.

Perhaps it is not too fanciful to carry the speculation one step further and suppose that when the observer z examines the system $x+y$ in a state $\sum \psi_k u_k(x) v_k(y)$, the initial state of the composite system $x+y+z$ including the observer is indeed the superposition $\sum \psi_k u_k(x) v_k(y) w_k(z)$, but that such a superposition of states of mind is not conscious. Freud's term, 'preconscious',[6] might appropriately describe such a superposition. There is psychological evidence, especially in dreams, that something which might be called a 'superposition principle' is operative in the preconscious—for instance, the image of a parent and that of a spouse may be superposed. One might suppose that when a physical input first influences the mind, the physical superposition is somehow reflected by a superposition of images

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[6] S. Freud, "The Interpretation of Dreams," *The Basic Writings of Sigmund Freud* (Random House, Inc., New York, 1938).

in the preconscious, since the preconscious does indeed seem to be endowed with the capacity for performing superpositions. The reduction of a superposition would then occur at the threshold from the preconscious to the conscious. The foregoing piece of speculation is vitiated, however, by the reflection that all the evidence we have of combinations of images in the preconscious concerns memories with interlocking emotional associations, and does not at all concern perception. Furthermore, the images which are combined are ordinarily derived from sequences of quite definite perceptions. There is, in short, no evidence of causal connection between the superposition of states corresponding to different values of an observable and combination of images in the preconscious. Consequently, this speculation seems to be only an *ad hoc* attempt to explain why we are unaware of an initial stage of vagueness when the physical "input" has a superposed character.

Suppose, in spite of the above evidence, that states of mind do satisfy a superposition principle. We must then investigate the further proposal of London and Bauer that the introspection of the observer effects a reduction of an initial superposition. As pointed out previously, this would be possible only if the state of the observer failed to evolve in accordance with the Schrödinger equation—furthermore, only if the evolution of the state of a composite system which includes a mind is a stochastic process. There have, in fact, been numerous speculations that mind is precisely that aspect of nature which is not governed by exact causal law. Gross evidence for such a characterization of mind can be found in human learning patterns, for consciousness and attentiveness accompany the exercise of a partially learned skill, whereas a fully mastered skill becomes mechanical and unconscious. It has been argued that this pattern in the life of a single individual has been followed on a large scale in the history of the species, so that processes like circulation, which once may have been accompanied by consciousness, are now unconscious, and processes like breathing are in transition from conscious to unconscious.[7] If this characterization of mind is correct, then it is reasonable to attribute the stochastic process of reducing a superposition to the mind's activity. The reduction of a superposition does not thereby become comprehensible from a common-sensical standpoint, but at least it is subsumed under a wider class of processes, which is a step towards scientific explanation. This line of analysis is weakened, though not decisively, by the fact that the immediate feelings associated with a fully determined observation are no different from those associated with an observation governed by probability; no more spontaneity or creativity on the part of the observer is *felt* in the second case than in the first. More decisive is the vast evidence of the evolutionary link of higher animals with the simplest organisms and even with inorganic matter. It is difficult to see how irreducibly stochastic behavior could be a structural characteristic, which could occur in a complex organism even though it is absent from all the components of the organism. Consequently, if there is an irreducibly stochastic element in the behavior or experience of higher animals, then one should expect a stochastic element in the primitive entities at the base of evolution. And if this is correct, then the Schrödinger equation, which is usually supposed to govern deterministically the state of a physical system except when it is being observed, can only be approximately valid.[8] This possibility should, in my opinion, be taken very seriously. However, it lies beyond the limits of this paper, in which quantum mechanics in its present form is assumed to hold exactly.

There is perhaps a feeling of fantasy about the foregoing discussion, in which states of mind are treated from the point of view of quantum mechanics. It is interesting to consider three suggestions which are free from this dubious extrapolation, but which, as is seen, are beset by other difficulties.

The first suggestion is to interpret the state vector ψ as a compendium of the observer's knowledge about the system, which is incomplete since he can only make statistical predictions regarding some of the observables. Accord-

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[7] E. Schrödinger, *Mind and Matter* (Cambridge University Press, Cambridge, England, 1958); H. Bergson, *Creative Evolution* (Random House, Inc., New York, 1944).

[8] The foregoing argument, with appropriate modifications, has sometimes been used to show that the elementary entities in nature have rudimentary mental characteristics, as proposed by Leibniz and Whitehead.

ing to such an interpretation, the reduction of a superposition need not be a change in the physical system itself but only in the observer's knowledge about the system. The problem of the superposability of states of mind does not arise, because the interaction of a physical system with an observer does not result in a total state vector of the physical system plus observer, as proposed by London and Bauer, but merely in new knowledge on the part of the observer, which must be incorporated into an appropriate state vector expressing his revised total knowledge of $x+y$. This interpretation, which is *prima facie* very attractive, since it does little violence to our common view of the world, has been discussed frequently, and the essential reasons for rejecting it were given in Sec. II. Consequently, I only elaborate what was said there with a few familiar comments. If the state vector ψ is not a maximum specification of the system, then an explanation is required for the fact that further specification is either redundant (could be predicted from ψ) or inconsistent (leads to predictions definitely incompatible with some of the predictions based on ψ). The only plausible explanation is the common one that the measurement which yields information supplementary to ψ disturbs the system physically and changes its state. In other words, the uncertainty principle must be interpreted as an expression of a fundamental limitation upon simultaneous measurement rather than as a limitation upon the simultaneous actuality of complementary properties of a system. But there are various physical phenomena which can be understood quite well in terms of the latter interpretations of the uncertainty principle and not at all in terms of the former. For example, good statistical mechanical calculations of entropy, as in the Sakur–Tetrode equation for a Boltzmann gas, proceed by assigning to each physical state of a system a volume h^N in phase space (where N is the number of classical degrees of freedom). This assignation is comprehensible if, for every generalized coordinate q and its conjugate momentum p, the relation

$$\Delta q\Delta p\sim h$$

expresses an ontological limitation on the specificity of q and p; but since measurements of the entropy do not presuppose knowledge of q and p, the interpretation of this uncertainty relation as a limitation upon measurement provides no rationale for the treatment of phase space in this calculation of the entropy. In general, the uncertainty relations pervade all quantum mechanical explanations of phenomena, even when there is no question of measurement of complementary quantities, and it is difficult to see how this fact can be reconciled with the claim that the state vector can in principle be supplemented by additional specifications of a system.

The second suggestion is to suppose that the physical system itself, and not merely the state vector ψ, is in some sense derivative from the mind or experience of the observer. In effect, this suggestion replaces proposition (i) above—that the mind is to be considered a natural entity ontologically on a level with physical systems—by some variety of idealism or phenomenalism. Since adequate critiques of the various forms of these philosophical theories are evidently beyond the scope of this paper, I make only three brief comments stating general reasons for skepticism about them, the first being directed primarily against Kantian idealism and the second and third being directed primarily against phenomenalism. (a) The *Weltbild* of common sense and that of natural science characterize the individual human being as an entity of limited duration and limited spatial extent, whose existence is not necessary to the existence of the universe as a whole. Consequently, an ontology which considers the universe to be derivative from one human mind (or one field of experience) is faced with the problem of relating this transcendent mind to the limited and contingent creature which persistently appears in the *Weltbild*.[9] (b) The claims of idealism and phenomenalism regarding the status of physical entities is extremely programmatic. There are only a few instances of philosophers who have tried to show in detail how the common properties of physical systems can be regarding as combinations of ideas of the mind or

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[9] This problem does not arise in Berkeley's form of idealism, in which there are many minds; but as is seen in the following section, a pluralism of minds generates a new set of problems if the reduction of a superposition is due to consciousness.

groupings of experiences, notably Russell[10] and Carnap.[11] However, both Russell and Carnap abandoned their proposals because of the evident discrepancies between their constructs and the physical things as ordinarily characterized, and particularly because of the difficulty of attributing potentialities or "disposition properties" to their constructs. One cannot help feeling that the difficulty of exhaustively characterizing a physical entity in terms of ideas and experiences is indicative of an independent existence of the entity. (c) If the program of exhibiting an electron as a construct were somehow fulfilled, the description of the construct would be fantastically complex, presumably consisting of an infinite set of conditional statements such as

> "If a cloud chamber is prepared in such a manner, then the resulting photograph will (with a certain probability) have the following appearance."

The complexity is multiplied by the fact that macroscopic objects such as cloud chambers, photographic plates, and Geiger counters would themselves be constructs referring to an infinite set of possible experiences. It is a remarkable fact, however, that extremely exact laws have been discovered for describing the motion of an electron, whereas none are known for describing the sequence of simple experiences. This fact is completely anomalous from the standpoint of a theory which takes human experience as ontologically primitive and regards electrons as complex constructs from actual and possible experiences; on the other hand, it is reasonable in a realistic ontology, in which electrons have independent existence and in which perceptions and other elements of experience are the result of complex interactions among physical objects and organisms.

The third suggestion is to agree with London and Bauer that the mind plays an essential role in the reduction of superpositions, but to deny that the superposition principle applies to states of mind. According to this suggestion, the reduction of a superposition occurs at the moment of interaction of the conscious observer with the physical system, rather than at a later stage.[12] The mind of the observer acts as a kind of filter system,[13] which forces the "input" to select one channel out of all those compatible with the superposition $\sum \psi_k u_k(x) v_k(y)$, and this selection is irreducibly stochastic. This suggestion, unlike the proposal of London and Bauer, is compatible with the psychological evidence that states of mind are not superposable. Its most obvious weakness is the difficulty of understanding why there can be no mental states reflecting the states of physical systems in which macroscopic observables have indefinite values; one cannot help suspecting that such peculiar states of physical systems do not exist, and that the present suggestion is a stratagem for disguising this fact. Some psychological objections can also be raised: for example, there is probably no sharp moment at which the observer becomes aware of the macroscopic variable. Supposing the threshold between physical input and mental registration to be the locus of the reduction of superpositions is thus *ad hoc* and implausible, though not decisively refuted by any psychological evidence regarding a *single* observer. However, when one turns to a consideration of several observers one finds crucial weaknesses in this suggestion, as in all proposals which attribute the reduction of superpositions to the mind.

IV. INTERSUBJECTIVE AGREEMENT

Suppose that the problems of Sec. III are set aside by accepting that the mind of the observer is a "black box" for reducing superpositions. A new set of problems arises when more than one observer interacts with the same physical systems, for it is important to explain how there can be agreement among them regarding the states of the physical systems and the value of observables.

According to London and Bauer (Ref. 5, p. 49) intersubjective agreement is possible because the measuring apparatus y is a macroscopic object. Consequently, the act whereby an observer becomes aware of the value g_i of the macroscopic observable G has only a negligible effect upon the apparatus. Another observer can then examine the apparatus and find that G has the

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[10] B. Russell, *Our Knowledge of the External World* (W. W. Norton and Company, Inc., New York, 1929).

[11] R. Carnap, *Der logische Aufbau der Welt* (Meiner, Berlin and Leipzig, 1928).

[12] Since von Neumann said practically nothing about the work of consciousness, it is possible that this suggestion is consistent with his unarticulated ideas.

[13] Cf. A. Landé, *From Dualism to Unity* (Cambridge University Press, Cambridge, England, 1960), pp. 8–12.

same value g_i which was discovered by the first observer; and if the states of the apparatus y are correlated with those of the microscopic system x, then the two observers will come to the same conclusion regarding the value f_i of an observable F in x and regarding the state of x.

Unfortunately, this explanation is not adequate, because the quantum characterization of the measuring apparatus is at odds with the common-sensical opinion that mere looking has a negligible effect upon the apparatus. There is a great difference between the state $\sum \psi_k u_k(x) v_k(y)$ and the state $u_n(x)v_n(y)$, and this difference is precipitated by "mere looking." This objection is not discussed by London and Bauer, but an answer to it may clearly be sought in either of two directions: (A) A careful analysis of the superposition of states of a macroscopic system may show that the transition $\sum \psi_k u_k(x) v_k(y) \to u_n(x)v_n(y)$ is *for all practical purposes* an insignificant change, so that the measuring apparatus can appear the same to the initial and subsequent observers. (B) It may be claimed that the first observer affects the system $x+y$ nonnegligibly by changing it from an initial unstable state, the superposition $\sum \psi_k u_k(x) v_k(y)$, to a final stable state $u_n(x)v_n(y)$; and the stability of the final state then guarantees that subsequent observers will agree in their reading of the apparatus.

An answer of type (A) has been proposed by Bohm,[14] Ludwig,[15] Feyerabend,[16] and Daneri *et al.*[17] They claim that if the $v_k(y)$ are such that a macroscopic variable G has different values g_k in the states represented by them, then there is no way of distinguishing the superposition $\sum \psi_k u_k(x) v_k(y)$ from a mixture having the proportions $|\psi_n|^2$ of the $u_n(x)v_n(y)$. The argument in Sec. II against interpreting Ψ as a body of partial information (i.e., a mixture) remains valid in principle, but it is unimportant in practice if there exists no quantity G' susceptible of actual measurement such that the statistical predictions regarding G' depend upon the phases of the coefficients ψ_k. Since the quantities which experimenters actually measure in macroscopic systems are gross, in the sense that considerable variation of the microscopic constitution of the system makes no discernible difference in their values, it is difficult to see how the phases of the ψ_k can affect the outcome of an actual measurement. Suppose now that an initial observer z notes the value of the observable G, thereby reducing the superposition $\sum \psi_k u_k(x) v_k(y)$, with probability $|\psi_n|^2$ that the final state is represented by $u_n(x)v_n(y)$. A second observer z', who knows that z has performed the observation but who is ignorant of the outcome, will optimally describe the system $x+y$ by a mixture having proportions $|\psi_n|^2$ of the $u_n(x)v_n(y)$. But this is, precisely, the mixture which is indistinguishable, for the purpose of practical predictions, from the state of $x+y$ prior to the observation by z. In this sense, the measuring apparatus appears the same both to the initial and to the subsequent observers. Two objections can be brought against this line of reasoning, one sophisticated and one quite simple, the latter being the more decisive. The sophisticated objection is that two remarkable effects have been discovered recently, the spin-echo effect[18] and the Mössbauer effect,[19] in which unexpected coherent contributions were obtained from the parts of macroscopic systems. No one claims that by means of these effects the phases in a superposition $\sum \psi_k u_k(x) v_k(y)$ can be determined, where again the $v_k(y)$ represent eigenstates in which a macroscopic observable has different values. Nevertheless, the discovery of unexpected coherence is a caution against underestimating the ingenuity of experimenters regarding phase relations in macroscopic systems. The simple objection is that agreement between two observers in reading their apparatus requires that at the conclusion of their observations they assign to $x+y$ the same state. From the legitimacy of their use of the same mixture to describe $x+y$ prior to their observations one

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[14] D. Bohm, *Quantum Theory* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1951).

[15] G. Ludwig, *Die Grundlagen der Quantenmechanik* (Springer-Verlag, Berlin, 1954). In his recent work, an article in *Werner Heisenberg und die Physik unserer Zeit* (Friedreich Vieweg und Sohn, Braunschweig, Germany, 1961), Ludwig makes the more radical proposal that quantum mechanics is not exactly correct when applied to macroscopic systems.

[16] P. Feyerabend, "On the Quantum-Theory of Measurement," *Proceedings of the Ninth Symposium of the Colston Research Society* (Butterworths Scientific Publications Ltd., London, 1957).

[17] A. Daneri, A. Loinger, and G. M. Prosperi, Nucl. Phys. **33**, 297 (1962).

[18] E. L. Hahn, Phys. Rev. **80**, 580 (1950); J. Blatt, Progr. Theoret. Phys. **22**, 745 (1959).

[19] *The Mössbauer Effect*, edited by H. Frauenfelder (W. A. Benjamin, Inc., New York, 1961).

can infer only that they make the same statistical predictions correctly characterizing an ensemble of similar situations. The agreement of the two observers in a *specific* reading of the apparatus would be a coincidence unless the examination of the first observer leaves the system $x+y$ in the state represented by a specific $u_n(x)v_n(y)$. Therefore, the first observer must have effected a change in $x+y$ which is not negligible from the standpoint of subsequent observers.

An answer of type (B) appears very reasonable if one accepts the proposal that consciousness is responsible for the reduction of a superposition. The state $\sum \psi_k u_k(x)v_k(y)$ is "unstable"[20] in the sense that the composite system $x+y+z$ undergoes the stochastic transition

$$\sum \psi_k u_k(x)v_k(y)w_0(z) \rightarrow u_n(x)v_n(y)w_n(z), \quad (1)$$

where $w_0(z)$ represents the state of the observer immediately before the observation and $w_n(z)$ represents the state of the observer correlated with the nth state of the apparatus. According to the analysis of London and Bauer there is an intermediate stage in the transition (1), in which the composite system is in the superposed state $\sum \psi_k u_k(x)v_k(y)w_k(z)$, while the existence of such an intermediate stage is denied by the last suggestion made in Sec. III; according to either account, however, the subsystem $x+y$ is in different states at the initial and final stages of (1). By contrast, the state $u_n(x)v_n(y)$ is "stable" in the sense that the system $x+y+z'$, where z' is another observer, passes only through

$$u_n(x)v_n(y)w_0'(z') \rightarrow u_n(x)v_n(y)w_n'(z'), \quad (2)$$

and throughout the process (2) the subsystem $x+y$ remains in the same state. However, a consideration of the causal relations between observers z and z' suffices to exhibit a difficulty in an answer of type (B). Suppose that both z and z' observe $x+y$ by photographing the apparatus y, z' being the first to take a photograph, but z being the first to develop and examine his film. From the assumption that reduction of a superposition occurs only when there is registration upon consciousness it follows that $x+y+z$ undergoes transition (1), and afterwards $x+y+z'$ undergoes transition (2). Thus the observation by z selects a specific image on the film of z' from among the range of images compatible with the original superposition; and this selection is a kind of causation, even though there need be no physical interaction between z and z'. An even worse discrepancy with ordinary physical causality can be adduced if the observations of their respective films by z and z' are events O and O' lying outside each other's light cones—which is certainly a possible experimental arrangement. Then, in some frames of reference, O precedes O', so that the observation by z is the cause of what z' observes, and in other frames of reference O' precedes O, thus reversing the causal relation. This is in conflict with the special theory of relativity, in which a causal relation is invariant under Lorentz transformations.

A possible reply to these objections is that the ordinary characteristics of causal relations need not apply to the relation between z and z', because the effect of an observation by one of them upon the experience of the other is undetectable. Whether z performs an observation or not, the ultimate result of the observation by z' is to find the system $x+y$ in a state represented by some $u_n(x)v_n(y)$, since this is what happens in the last stage of both processes (1) and (2). Thus z' can only tell that an initial superposition has been reduced, but he cannot know whether precipitating the reduction was his own work or the work of z. Hence z cannot use his power to reduce superpositions as a communication device for transmitting information to z'.[21] Furthermore, this conclusion

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[20] Instability in this sense is completely different from the "meta-stability" of the apparatus y (e.g., the supersaturation of the vapor in a cloud chamber) which underlies the physical transition $u_n(x)\phi_0(y) \rightarrow u_n(x)v_n(y)$ described in (2.6) and (2.7).

[21] The inability of z to communicate with z' by reducing a superposition is in no way due to the fact that only a single observation is involved. We may imagine that z and z' both photograph an indefinitely large number of pieces of apparatus, each measuring a different microscopic system in the state $\Sigma \psi_k u_k$. They may agree that in order to answer "yes" to a predesignated question z will examine all his films within some specified time interval, and in order to answer "no" he will refrain from examining them. In the former case, z causes each of the films of z' to pass into a definite state, though z' will not know which prior to examining them; and, in the latter case, each film will be in an indeterminate state until z' performs his observations. In both cases, however, the statistics of the films observed by z' can be described by exactly the same mixture. An essential reason for this statistical identity is that prior to any observation by either z or z' each of the films is only part of a composite system in a definite state and is not itself in a definite state.

permits various consistent, though desperate, resolutions of the conflict with relativity theory which arise when O and O' lie outside each other's light cones: for instance, the temporal order of O and O' may be regarded as indeterminate (i.e., relative to the frame of reference) with respect to the transmission of detectable signals between these two events, but there may nevertheless be an absolute temporal order between them which determines whether the reduction of the superposition was due to z or to z'.

The foregoing arguments are familiar, particularly in connection with the paradox of Einstein, Podolsky, and Rosen,[22] and they suffice to dispel the suspicion that by considering observation upon systems which are spatially separated but in correlated states a contradiction can be exhibited in quantum mechanics. Nevertheless, there seems to be no one who seriously maintains the position now under consideration: that agreement among observers is due to a causal relation between their acts of observation, but a causal relation which is not circumscribed by the usual limitations of relativity theory. The consistency of this position does not seem to be adequate compensation for its counter-intuitive and *ad hoc* character.

It is difficult, at this point in the analysis, to resist the promptings of common sense, that the agreement between observers z and z' is due simply to a correspondence between the physical configurations of the emulsions on their films. This attractive but reactionary proposal can be resisted only by re-iterating what it implies: that the superposition in the microscopic system x is reduced when x interacts with the apparatus y, in contradiction to the linear dynamics of quantum theory.

von Neumann has proposed an explanation of intersubjective agreement which is quite different from any considered above, but which in no way relaxes the rigorous application of quantum mechanical principles to physical systems. According to him, quantum theory is compatible with

> "the so-called principle of the psycho-physical parallelism—that it must be possible so to describe the extra-physical process of the subjective perception as if it were in reality in the physical world—i.e., to assign to its parts equivalent processes in the objective environment, in physical space." (Reference 4, pp. 418–9.)

Whenever there is a measurement, the world is divided into two parts, one part comprising the system being observed and the other the observer. The boundary between these parts is largely arbitrary, for the observer may be understood to include the experimenter's body along with some of his laboratory equipment; or the observer may consist only of a consciousness together with some part of the nervous system.

> "That this boundary can be pushed arbitrarily far into the interior of the actual observer is the content of the principle of the psychophysical parallelism." (Reference 4, p. 420.)

von Neumann then proceeds to prove that if the formalism of quantum mechanics is applied to the observed part of the world, the predictions obtained are independent of the location of the boundary. The essence of his argument is that the expansion coefficients in Eqs. (2.1), (2.10), and (2.12) are all the same; so that whether the observed part of the world consists of x, or of $x+y$, or of $x+y+y'$, etc., the probability of finding the value f_i of an observable F of the microscopic x is always $|\psi_i|^2$. The agreement of different observers is asserted to be a corollary of this result, but the proof of this corollary is left by von Neumann as an exercise for the reader. (Reference 4, p. 445.)

von Neumann seems to be asserting that any observer can describe the mental processes of any other observer as if they were physical processes, in other words that one observer can treat all others behavioristically. It follows that from the point of view of observer z, the concurrence of z' regarding an observable G of the measuring apparatus is equivalent to a control reading of the apparatus by means of some auxiliary physical device. From z's standpoint, states of z' are correlated with those of the apparatus y in the same physical way that states of the apparatus are correlated with those of the microscopic system x. Hence z can effect a reduction of a superposition $\sum \psi_k u_k(x) v_k(y) w_k'(z')$ by observing G directly in y or indirectly via z' (e.g., by asking questions and noting the answers). Furthermore, once the superposition is reduced, a remeasurement of G in either way is

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[22] A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. **47**, 777 (1935); D. Bohm and Y. Aharonov, Phys. Rev. **108**, 1070 (1957).

certain to yield the same result. I believe that this is in outline the proof of the corollary which von Neumann left for the reader.

The obvious difficulty with von Neumann's argument is its irrelevance to the question of agreement between z and z' when both are considered as ultimate subjects. If both observe a physical system and independently effect the same reduction of a superposition, their agreement seems to be "pre-established harmony." If the first to make the observation reduced the superposition, leaving no option to the other, one is again confronted with the difficulties discussed above regarding the causal relation between the two observers. Consequently, unless "pre-established harmony" is accepted, the only *Weltbild* in which quantum theory is rigorously maintained appears to be one in which there is a single ultimate subject. This is a different conclusion from the common skeptical position regarding the existence of other minds, and in one respect it is stronger. It does not say that I am unsure other people have the same kind of subjective characteristics as myself, but rather that if they have minds then certainly their minds lack some of my powers, particularly the ability to reduce a superposition. This conclusion agrees with Wigner's analysis[23] of a thought-experiment in which a friend is used as an instrument for detecting a photon:

> "It is not necessary to see a contradiction here from the point of view of orthodox quantum mechanics, and there is none if we believe that the alternative is meaningless, whether my friend's consciousness contains either the impression of having seen a flash or of not having seen a flash. However, to deny the existence of the consciousness of a friend to this extent is surely an unnatural attitude, approaching solipsism, and few people will go in their hearts along with it."[24]

V. BOHR: THE COMPLEMENTARITY PRINCIPLE IN EPISTEMOLOGY

Throughout the first four sections of this paper it was implicitly assumed that intrinsic characteristics of things in nature are clearly distinguishable from characteristics which are relative to an observer. I do not think that the presentation of the position of von Neumann or of London and Bauer was distorted because of this assumption, and indeed the lucidity of their work is probably due partly to the fact that they accepted it. However, it may be suspected that the counter-intuitive conclusions to which they were led—particularly that a change in the state of physical system is effected by the registration of the result of a measurement in a consciousness—resulted from a rigid distinction between objectivity and subjectivity. This suggestion is implied in the writing of Niels Bohr, for an essential feature of his philosophy and of all the cognate varieties of the "Copenhagen interpretation" is a flexibility in contrasting objectivity and subjectivity. In this section, I try to formulate Bohr's position briefly and to assess its explanation of the role of the observer in quantum mechanics. All that I state, both in exegesis and in criticism, is tentative, since his writing is both obscure and profound.

Bohr's philosophy consists essentially of the systematic formulation and application of the principle of complementarity. In its narrowest formulation, this principle is a renunciation of a single picture of the microphysical object in favor of a set of mutually exclusive descriptions appropriate in different circumstances. Bohr interprets quantum mechanics as a theory of quantum phenomena, and he uses the word 'phenomenon'

> "to refer exclusively to the observations obtained under specified circumstances, including an account of the whole experimental arrangement." (Ref. 3c, p. 64.)

He insists that obscurity results from speaking of physical attributes of objects without reference to the measuring instruments with which they interact. Furthermore, even though the phenomena themselves cannot be accounted for by classical physical *explanations*, they must inevitably be described in terms of classical physical *concepts*, because these concepts are indispensable in characterizing the measuring instruments. The indeterministic transition which occurs when, for example, a position measurement is followed by a momentum measurement can be understood straightforwardly in terms of the scheme of complementarity. Because of

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[23] E. P. Wigner, in *The Scientist Speculates*, edited by I. J. Good (William Heinemann, London, 1962).

[24] Dr. Howard Stein (personal communication) commented that if quantum mechanics implies solipsism then it must be self-contradictory, since manifestly no person could have discovered it alone!

wave-particle dualism and the relation between momentum and wave-number, the experimental arrangements for measuring the position and momentum of a particle are mutually exclusive (Ref. 3c, pp. 41–7); but since any microphysical phenomenon inextricably involves a type of experimental arrangement, the transition from a position to a momentum determination consists of the rupture of one well-defined state of a composite system and the initiation of another well-defined state of a different composite system in a manner which cannot be controlled (Ref. 3c, p. 40). It seems possible for Bohr to avoid attributing the reduction of a superposition to the consciousness of the observer, for the experimental arrangement and the experimental result can be described completely in terms of "everyday concepts, perhaps refined by the terminology of classical physics." (Ref. 3c, p. 26). But whenever everday and classical concepts can be unambiguously applied, it is possible to distinguish sharply between the objects observed and the observer (Ref. 3c, p. 25). Intersubjective agreement is thus assured in the reading of the measuring apparatus; and hence the outcome of a quantum mechanical measurement is objectively determined when a spot is made on a photographic plate or a Geiger counter discharges, etc., without dependence upon the registration of the result in the observer's consciousness (Ref. 3c, p. 64 and p. 88).

The insistence upon a classical description of the measuring apparatus, not as a convenient approximation but as a matter of principle, clearly differentiates Bohr's interpretation of quantum mechanics from that of von Neumann and of London and Bauer. It is tempting, therefore, to accept Feyerabend's characterization[25] of Bohr's point of view as "positivism of higher order," that is to say, a positivism in which the "given" for scientific construction consists not of subjective perceptions but rather of descriptions in terms of classical physics. According to this interpretation, the senses in which microscopic and macroscopic objects are real are quite different, for a microscopic object is "now characterized as a set of (classical) *appearances* only, without any indication being given as to its nature" (Ref. 25, p. 94.) Occasional passages in Bohr's writings support Feyerabend's interpretation that microphysical symbolism is only a convenient shorthand for describing intricate relations among macrophysical objects, which are taken to be the fundamental building blocks in his ontology. For example,

> "there can be no question of any unambiguous interpretation of the symbolism of quantum mechanics other than that embodied in the well-known rules which allow to predict the results to be obtained by a given experimental arrangement described in a totally classical way." (Ref. 3b, p. 701.)

Other passages, cited below, indicate that Feyerabend's formulation of Bohr's position is incomplete. However, the strength of this formulation should be acknowledged: that for the working physicist, particularly the experimentalist, "positivism of higher order" provides a practical compromise between microphysical realism and phenomenalism. In contrast to phenomenalism, which encounters difficulties in attempting to characterize ordinary objects, this position operates *ab initio* with everyday concepts and classical physical concepts, which suffice to characterize laboratory equipment and to permit unambiguous communication among observers.[26] And in contrast to microphysical realism, this position does not run the danger of postulating attributes and processes which are inaccessible to observation. Nevertheless, in spite of the advantages of this "positivism of higher order" as a working philosophy, it is doubtful that it can be maintained under critical scrutiny. Perhaps the worst flaw is that the interpretation of the microphysical formalism as a shorthand for macrophysical observations is a program, of which only a small part has been carried out. It is commonly said that every hermitian operator upon the space of state vectors of a given system represents an observable of the system.[27] Yet, only for a small number of the nondenumerable infinity of such operators has experimental apparatus capable of measuring

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[25] P. Feyerabend, The Aristotelian Society Suppl. **32**, 75 (1958).

[26] This is one of the reasons why most of the logical positivists abandoned phenomenalistic languages in favor of physicalistic languages.

[27] In careful treatments, this statement is made only of those hermitian operators for which a solution to the eigenvalue problem exists; cf. J. von Neumann, Ref. 4, pp. 167–9; and P. A. M. Dirac, *The Principles of Quantum Mechanics*, (Clarendon Press, Oxford, 1947), 3rd ed., p. 38.

the values of the corresponding observables been built or even designed. When such apparatus exists, as in the case of the position, linear momentum, angular momentum and energy operators, then it is reasonable to say that the corresponding eigenstates of the microscopic object are merely convenient ways of speaking about the various experimental results obtainable with the apparatus. But such an interpretation is not reasonable when no one has the least idea for designing the apparatus appropriate for a given operator. In the formalism of quantum mechanics the operators for which no measuring apparatus has been designed enter upon exactly the same footing as those for which apparatus exists, and there is no way of eliminating the former without curtailing the superposition principle, which would cripple the present formulation of quantum mechanics. This situation is understandable from the point of view of microphysical realism, which does not equate reality with accessibility for measurement, but it is incompatible with the interpretation of quantum mechanical symbolism as a shorthand for classical appearances.[28] Another flaw in "positivism of higher order" is its fundamental obscurity regarding the ontological status of macrophysical objects. If these objects have an objective existence, then they must have intrinsic properties independent of human observers. Their properties cannot be specified in terms of classical physics without limitation, because of the uncertainty principle; but if the intrinsic character of a macrophysical object includes a specification of the extent to which each classical quantity is applicable, presumably in terms of definite probability distributions, then the object is effectively in a quantum mechanical state. However, admitting that a macroscopic object is intrinsically characterized by a quantum mechanical state leads to the difficulties which were found in the interpretation of quantum mechanics of von Neumann and of London and Bauer: the state of a macroscopic object can be a superposition of states in which a macroscopic observable has distinct values, and the reduction of this superposition can be effected only by the consciousness of the observer. There are passages in which Bohr appears to avoid these difficulties by retreating from "positivism of higher order" to a novel combination of idealism and phenomenalism, in which even macroscopic objects have the status of organizations of experience and in which the concepts of classical physics become forms of perception (e.g., Ref. 2a, p. 1). Many questions of interpretation can be raised regarding these passages: for example, the expression "forms of perception" is reminiscent of Kant, but since Bohr never suggests that classical physical concepts have an *a priori* origin, it is not clear why "all experience must ultimately be expressed in terms of classical concepts" (Ref. 2a, p. 94). These questions of interpretation are not pursued here, however, since some general reasons for rejecting idealism and phenomenalism were stated at the end of Sec. III. The important point here is that an examination of the status of macrophysical objects shows "positivism of higher order" to be an unstable half-way position between a realistic interpretation of microphysical objects and an idealistic or phenomenalistic interpretation of all physical entities, and therefore, whether or not one ought to attribute this position to Bohr, it is not tenable.

I suspect that Bohr was aware of the difficulties inherent in a macrophysical ontology, and in his most careful writing he states subtle qualifications concerning states of macroscopic objects. For example,

> "The main point here is the distinction between the *objects* under investigation and the *measuring instruments* which serve to define, in classical terms, the conditions under which the phenomena appear, Incidentally, we remark that, for the illustration of the preceding considerations, it is not relevant that experiments involving an accurate control of the momentum or energy transfer from atomic particles to heavy bodies like diaphragms and shutters would be very difficult to perform, if practicable at all. It is only decisive that, in contrast to the proper measuring instruments, these bodies together with the particles would constitute the system to which the quantum-mechanical formalism has to be applied." (Ref. 3c, p. 50.)

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[28] The above criticism is also stated by P. Feyerabend, "Problems of Microphysics," *Frontiers of Science and Philosophy* (University of Pittsburgh Press, Pittsburgh, 1962). He cites similar criticisms by E. Schrödinger, Nature **173**, 442 (1954), and P. Bridgman, *The Nature of Physical Theory* (Princeton University Press, Princeton, New Jersey, 1936). A possible answer is to interpret quantum mechanical states in terms of the scattering matrix, all elements of which are in principle measurable; see R. E. Cutkosky, Phys. Rev. **125**, 745 (1962), and the references given there. The extent to which such an interpretation is possible is controversial, and I have not studied the literature sufficiently to comment on the question.

Bohr is saying that from one point of view the apparatus is described classically and from another, mutually exclusive point of view, it is described quantum mechanically. In other words, he is applying the principle of complementarity, which was originally formulated for microphysical phenomena, to a macroscopic piece of apparatus. This application of complementarity on a new level provides an answer to the difficulty regarding macrophysical objects which confronted "positivism of higher order": the macrophysical object has objective existence and intrinsic properties in one set of circumstances (e.g., when used for the purpose of measuring) and has properties relative to the observer in another set of circumstances,[29] thereby evading the dilemma of choosing between realism and idealism. Two important conclusions follow from this discussion. The first is that Bohr's point of view is only partially represented by the macrophysical ontology which Feyerabend attributes to him; and accordingly, one should not dismiss as mere *façons de parler* his occasional statements that atoms are real and have individuality (e.g., Ref. 3a, p. 93). The second conclusion is that Bohr's extension of the principle of complementarity beyond its original function of reconciling apparently contradictory microphysical phenomena is not gratuitous, as critics have often claimed.[30] The internal logic of his position requires the application of complementarity to macroscopic measuring instruments. It is, therefore, not surprising that Bohr should consider the application of complementarity to other domains, such as biology and psychology, to be more than merely a hopeful extrapolation of a conceptual device which proved successful in microphysics.

Perhaps the most explicit formulation of the generalized principle of complementarity is the following:

> "For describing our mental activity, we require, on one hand, an objectively given content to be placed in opposition to a perceiving subject, while, on the other hand, as is already implied in such an assertion, no sharp separation between object and subject can be maintained, since the perceiving subject also belongs to our mental content. From these circumstances follows not only the relative meaning of every concept, or rather of every word, the meaning depending upon our arbitrary choice of view point, but also that we must, in general, be prepared to accept the fact that a complete elucidation of one and the same object may require diverse points of view which defy a unique description. Indeed, strictly speaking, the conscious analysis of any concept stands in a relation of exclusion to its immediate application." (Reference 3a, p. 96.)

As an example of the generalization of complementarity, Bohr states that the display of life and the conformity to physical laws are both proper descriptions of an organism, but are observed in mutually exclusive experimental arrangements. Similarly, he argues that determinism and free will are complementary aspects of the behavior of an organism. Behavioristic and introspective psychology are evidently complementary, and even within introspective psychology a scheme of explanation using complementarity is necessary:

> ". . . it must be emphasized that the distinction between subject and object, necessary for unambiguous description, is retained in the way that in every communication containing a reference to ourselves we, so-to-speak, introduce a new subject which does not appear as part of the content of the communication." (Ref. 3c, p. 101)

Critics have pointed out, with considerable justification, the looseness of Bohr's arguments in these contexts: for example, that he presents no decisive evidence of conflict between organic behavior and conformity to physical law analogous to the conflict between the wave and particle aspects of light, and that the operational interferences of two types of observation is not always sufficient grounds, even in atomic physics, for denying the possibility of simultaneous sharp values of the respective quantities.[31] However, I am not here concerned with specific weaknesses of Bohr's remarks on biology and psychology, but rather with the general epistemological view which emerges from his remarks: that *given any domain of phenomena there is a standpoint from which this domain can be observed in mutually exclusive ways.* Several further quotations suffice to show the radical character of his position:

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[29] D. Bohm, Ref. 14, Chap. 23, states this generalization of the principle of complementarity more explicitly than Bohr.

[30] For example, A. Grünbaum, J. Philosophy **54**, 713 (1957).

[31] See, for example, P. Feyerabend, Ref. 28, and A. Grünbaum, Ref. 30.

> "the notion of complementarity serves to symbolize the fundamental limitation, met with in atomic physics, of the objective existence of phenomena independent of the means of their observation." (Reference 3c, p. 7.)

> "Without entering into metaphysical speculations, I may perhaps add that an analysis of the very concept of explanation would, naturally, begin and end with a renunciation as to explaining our own conscious activity." (Reference 3c, p. 11.)

> "Such considerations point to the epistemological implications of the lesson regarding our observational position, which the development of physical science has impressed upon us. In return for the renunciation of accustomed demands on explanation, it offers a logical means of comprehending wider fields of experience, necessitating proper attention to the placing of the object–subject separation. Since, in philosophical literature, reference is sometimes made to different levels of objectivity or subjectivity or even of reality, it may be stressed that the notion of an ultimate subject as well as conceptions like realism and idealism find no place in objective description as we have defined it." (Reference 3c, pp. 78–9.)

It is clear that Bohr considers the distinction between subject and object to be a necessary condition for knowledge and communication; but he believes the separation of subject and object can be performed in arbitrarily many different ways, and never in such a way that an absolute subject or an absolute object exists. Evidently, there is a profound difference between Bohr's position and that of von Neumann and of London and Bauer, who acknowledge an ultimate subject in any act of observation, and this difference accounts for their different treatments of measurement in quantum mechanics.

As practical maxims for scientific activity some of Bohr's proposals are sound. It is reasonable, in any investigation, to delimit the objects of investigation and to be aware of the way in which the description of the objects depends upon the conditions of observation. It is also possible that the alternative descriptions of organisms, minds, cultures, etc. must be taken to be complementary, though the evidence regarding this is fragmentary and inconclusive. The only very weak point in the program of complementarity, from the standpoint of scientific investigation, is the absence of any analogue in the domains of biology and psychology to the systematic statistical relations between complementary descriptions in microphysics, and, of course, it is these statistical relations which establish the predictive power of quantum theory.

If the program of complementarity is taken to be a philosophical system, rather than a set of practical suggestions in science, then there are strong objections against it. The indefiniteness and arbitrariness of the distinction between subject and object seems to imply the renunciation of an ontological framework for locating the activity of knowing.[32] Knowledge is certainly a phenomenon of immense complexity, and yet one cannot seriously doubt that it is a natural phenomenon, involving the interaction of an organism with various other natural entities. Since this interaction can occur in many different ways, the choice of which is partly under the control of the organism itself, it is understandable that the "placing of the object–subject separation" is variable. But if no ontological framework is presupposed, the object–subject separation could no longer be understood as a natural event, but only as a mode of organizing the content of experience. Bohr evidently believes that the renunciation of an ontological framework is imposed by "the old truth that we are both onlookers and actors in the great drama of existence" (Ref. 3a, p. 119). But a quite different philosophical conclusion could equally well be drawn from this old truth: that we must try to formulate a view of nature which accommodates all our experience, including experience of ourselves as onlookers in the world; and we must formulate a theory of knowledge which suffices to provide a rationale for this view of nature. In such a complete and coherent view entities capable of having subjective experience could be

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[32] The affinity between Bohr's philosophy of complementarity and Hegel's dialectic is evident, even though Bohr proposes nothing comparable to the ultimate synthesis in the Absolute Idea and though he explicitly disavows the conception of levels of reality (Ref. 3c, p. 79). There is, also, a strong affinity between Bohr and Kant, which to my knowledge has not been sufficiently stressed by commentators. It was noted above that there is a Kantian flavor in the recurrent characterization of the concepts of classical physics as "forms of perception." More significant, perhaps, is the similarity between Bohr's renunciation of an absolute ontological framework and Kant's renunciation of a treatment of the thing-in-itself by theoretical reason. It is reasonable to attribute to Bohr the belief that when one attempts to characterize objects intrinsically, the principle of complementarity engenders contradictions analogous to Kant's antinomies of pure reason.

identified as having objective status in nature, and subjective experience would be shown to be capable of envisaging an objectively real world. Bohr has given no decisive evidence that such a view is unattainable, and the alternative which he outlines is too indefinite to serve as a surrogate.

The foregoing objection against Bohr's epistemological position implicitly contains a criticism of his account of observation in quantum mechanics. If the arbitrariness of the subject–object relation is understood, as I would contend, merely as freedom to arrange different interactions between microscopic objects, measuring apparatus, and the human observer, then the question of the intrinsic properties of these entities must be considered. These intrinsic properties may be far from familiar and commonsensical: there may be limitations on spatiotemporal localizability, or it may be that composite systems have an intrinsic wholeness and unanalyzability into parts which was not found in classical physics, or it may be that the superposition principle applies to the states of macroscopic objects and even to states of mind. The point is that whatever these intrinsic properties may be, they must suffice to account for the transitions which occur in quantum mechanical measurement as natural processes. The shifting of the separation between subject and object postpones for an arbitrary but finite number of steps the necessity for explaining these transitions in terms of the intrinsic characteristics of natural entities, but in principle it must finally be possible to provide such an explanation.

VI. CONCLUSIONS

The foregoing study has examined, in detail, two of the many accounts of observation in quantum mechanics—that of von Neumann, London, and Bauer, and that of Bohr. Both of these accounts maintain that the current formulation of quantum mechanics provides a rigorous description of physical reality, but they differ in their epistemological proposals and, therefore, the difficulties which they encounter are quite different. von Neumann, London, and Bauer propose that objective changes of the state of physical system occur when certain measurements are performed, and they explain these changes by referring to the subjective experience of an observer. This mutual involvement of physical and mental phenomena is counterintuitive in the extreme, though without apparent inconsistency. However, there is no empirical evidence that the mind is endowed with the power, which they attribute to it, of reducing superpositions; and furthermore, there is no obvious way of explaining the agreement among different observers who independently observe physical systems. Thus, their interpretation of quantum mechanics rests upon psychological presuppositions which are almost certainly false. In Bohr's account, the change of state of a microphysical object under measurement is due to the change of the experimental arrangement for observing the object. Since the experimental arrangement can be described in physical terms, Bohr does not need to postulate an intrusion of consciousness into the course of physical phenomena. However, his explanation implies the renunciation of an intrinsic characterization of objects in favor of complementary descriptions from alternative points of view, and the flexibility which this conceptual device provides is excessive, for ultimately it requires the abandonment of any definite ontology. Some variant interpretations of quantum mechanics were also noted and criticized in the course of studying these two major accounts. Even though this survey of interpretations was not exhaustive, it did cast strong doubt upon the possibility of giving a coherent discussion of observation in quantum mechanics without modifying the theory itself.[33] It should be emphasized again

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[33] Among the interpretations which have not been explicitly discussed above, that of Hugh Everett, III, Rev. Mod. Phys. **29**, 454 (1957) (accompanied by J. A. Wheeler's assessment) should be specially mentioned. According to Everett, quantum theory is complete without the postulate that changes of state of type 1 occur. He eliminates the problem of accounting for the reduction of superpositions by denying that a reduction occurs at *any* stage in a measurement. Furthermore, he accepts the radical ontological consequences of his premisses: ". . . *all* elements of a superposition (all 'branches') are 'actual', none any more 'real' than the rest. It is unnecessary to suppose that all but one are somehow destroyed, since all the separate elements of a superposition individually obey the wave equation with complete indifference to the presence or absence ('actuality' or not) of any other elements. This total lack of effect of one branch on another also implies that no observer will ever be aware of any 'splitting' process." Everett's interpretation, and particularly his treatment of the relation between appearance and reality, deserves a more detailed analysis than is given here, but

that the psychological and philosophical problems concerning observation which must be clarified do not arise from considerations external to physics—for instance, from an attempt to relate physics to other disciplines—but from an attempt to understand the conceptual apparatus of the current formulation of quantum theory.

It is possible that the conceptual problems of quantum mechanics will be resolved by discovering corrections to the physical theory itself, for example, by finding that the time-dependent Schrödinger equation is only an approximation to an exact nonlinear equation governing the evolution of the state of a system. If this proves to be true, then the reduction of a superposition could perhaps occur when the microscopic system interacts with the macroscopic apparatus, and no appeal to the consciousness of an observer for this purpose would be required.[34] The ontological problem of the relation between mind and matter would remain, but it would be posed in essentially the same way as in the period of classical physics and with no more urgency. Such a solution would be welcome to many physicists, for it would perpetuate the convenience of the "bifurcation of nature." Nevertheless, there may be reasons for regret if such a solution proves to be successful. "Small clouds" in an otherwise highly successful theory have often been precursors of great illumination—e.g., the difficulties in explaining blackbody radiation led to Planck's discovery of the quantum of action. The conceptual problem of the reduction of a superposition is a "small cloud" in contemporary physical theory, in which the laws of physics are otherwise completely independent of the existence of minds. If this difficulty should eventually provide some insight into the mysterious coexistence and interaction of mind and matter, our present intellectual discomfort would be overwhelmingly compensated.

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its essential weakness, I believe, is the following. From the standpoint of any observer (or more accurately, from the standpoint of any "branch" of an observer) the branch of the world which he sees evolves stochastically. Since all other branches are observationally inaccessible to the observer, the empirical content (in the broadest sense possible) of Everett's interpretation is precisely the same as the empirical content of a modified quantum theory in which isolated systems of suitable kinds occasionally undergo "quantum jumps" in violation of the Schrödinger equation. Thus the continuous evolution of the total quantum state is obtained by Everett at the price of an extreme violation of Ockham's principle, the entities multiplied being entire universes.

[34] E. P. Wigner, Am. J. Phys. **31**, 6 (1963); also the second of the two works by G. Ludwig cited in Ref. 15; and A. Komar, Phys. Rev. **126**, 365 (1962).