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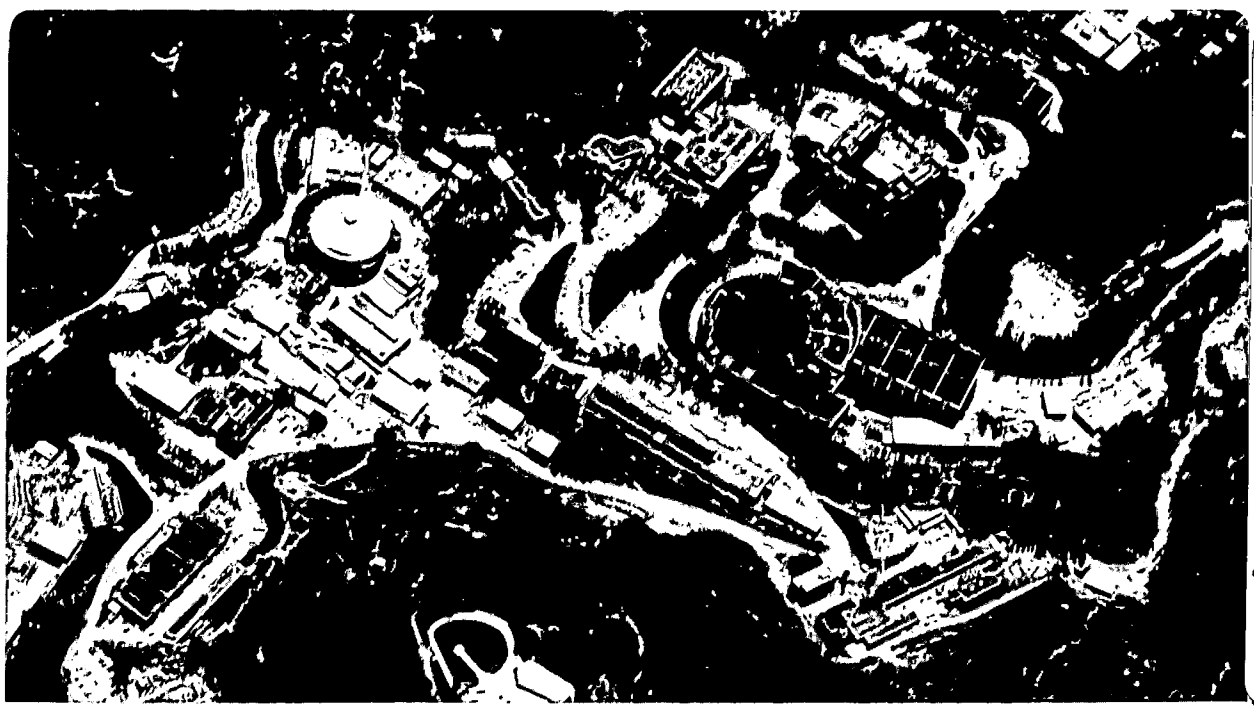

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Chance, Choice, and Consciousness: The Role of Mind in the Quantum Brain *

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Abstract

Contemporary quantum mechanical description of nature involves two processes. The first is a dynamical process governed by the equations of local quantum field theory. This process is local and deterministic, but it generates a structure that is not compatible with observed reality. A second process is therefore invoked. This second process somehow analyzes the structure generated by the first process into a collection of possible observable realities, and selects one of these as the actually appearing reality. This selection process is not well understood. It is necessarily nonlocal and, according to orthodox thinking, is governed by an irreducible element of chance. The occurrence of this irreducible element of chance means that the theory is not naturalistic: the dynamics is controlled in part by something that is not part of the physical universe. The present work describes a quantum mechanical model of brain dynamics in which the quantum selection process is a causal process governed not by pure chance but rather by a mathematically specified nonlocal physical process identifiable as the conscious process.

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1. Introduction.

The orthodox Copenhagen interpretation of quantum theory, as promulgated by Niels Bohr, is pragmatic: the quantum formalism is regarded as merely a set of useful rules for predicting what our classically describable experiences will be under conditions specified by classically describable experiences. The entry of chance into the theory is regarded as an expression of the brute empirical fact that atomic systems prepared and measured identically—to the best of our experimental capabilities— give nonidentical results that have statistical regularities. The question of the origin of the element of chance is left unanswered. Einstein rejected the idea that God plays dice with the universe, and Bohr concurred in rejecting the idea of "a choice on the part of 'nature' "[1]. Yet the notion that a definite choice is fixed by nothing at all is even more repugnant to rational thought.

Bohr's interpretation does not cover biological and cosmological systems. The possibility therefore arises that what appears as pure chance in the restricted domain of atomic phenomena has its roots in a more complete description of nature.

The element of chance normally enters into quantum theory in connection with our observations. In the absence of observations the evolution of the universe is governed by local laws that are natural generalizations of the laws of classical mechanics: the universe is conceived to be an aggregate of localized properties, and the rate of change in each such property is governed exclusively by nearby properties. Observations, however, are associated with a "second process" that is logically required to be highly nonlocal [2], and therefore fundamentally different from the first process.

The aim of the present work is to provide a logical and mathematical framework for a causal theory of brain dynamics in which the controlling element of chance in the quantum selection process is replaced by a nonlocal physical process identifiable with the conscious aspect of brain process.

In this formulation of quantum dynamics conscious experiences exercise genuine control over brain activity. Analogous elements should occur in all biological systems, due to the enormous survival advantage they can confer. But in lower life forms, and also in the inanimate part of nature, these elements

will, because of the absence in them of the intentional and attentional structure supplied by our brains, be very different from human conscious experiences.

2. Quantum Searching and Survival.

Survival, at least in the animal kingdom, depends on rapidly finding and executing appropriate behaviors. Options are generally available, and the organism must reject those not appropriate in the specific situation in which it finds itself, and pursue one that is appropriate. The process of searching for an appropriate behavior can be likened to a search for the way out of a maze. The classical search procedure is essentially to try, at some mental level, each of the possibilities until a blockage is encountered, and then to back off and try another. This can be very time consuming, and an organism that uses it is likely to be devoured by one that employs a faster process. Massive parallel (and interconnected) processing may offer advantages, but it introduces the compensating problem of keeping the whole system operating in a coherently coordinated way.

For rapid searching the exploitation of the quantum character of brains can confer a huge advantage. Quantum dynamics is essentially hydrodynamics [3]. The contrast between classical and quantum search procedures can be likened to the contrast between the particle and hydrodynamical solutions to the problem of getting out of a maze: in the particle solution the particle bounces randomly around the maze in the hope of finding the small opening; in the hydrodynamical solution the maze is filled with water, which then rushes out through the opening. The essential point is that in classical-particle dynamics what the particle does is completely unaffected by what it would have done if it had been on a nearby trajectory, whereas the flow of water is affected by what is happening nearby: if water rushes out at one place, leaving a void, then nearby water rushes in to fill the void, sucking in water from further away.

This point can be illustrated by considering a circular trough that has also a circular cross section in each radial plane. Suppose this trough is filled with a statistical ensemble representing alternative possibilities for the position and velocity of one particle. Each element of the ensemble oscillates in a radial plane, with no angular motion. Suppose we open a small angular section of the trough so that the particles in that section flow out. The remaining particles, which represent the alternative possibilities, will continue to oscillate forever. But if

one fills the trough with water and opens the section then all the water runs out. The quantum probability function for one particle behaves like water, not like the statistical ensemble of independent particles.

A physicist who wants to see this in the equations can consider a wave function for a particle confined to a circle. The time-dependent Schroedinger has on the left the operator i times the derivative with respect to t, and on the right the kinetic energy term. To represent the opening in the maze (i.e., the solution that is not blocked by negative feed-back) add on the right the term b times minus i times a Dirac delta function of the (cyclic) argument x(mod 1). Then the rate of loss of probability in the ring is 2b times the square of the magnitude of the wave function at x=0. This is non-negative, and more detailed calculations show that the probability is rapidly sucked to the point x=0, where it disappears.

A more realistic model would have in place of the Dirac delta function a function with a flat central plateau bounded on each side by a sharp gaussian fall-off. The rate of flow of probability from the surrounding region into the region of probability loss is controlled by the sharpness of the gaussian walls.

This way of searching for an appropriate response should be particularly rapid and effective in a brain organized in the way described in [4], because in that system the unblocked flow out of the maze (of alternatives, most of which are blocked by negative feed-back) creates a template for action, which then automatically evolves into the corresponding action itself. There is no need to convert the solution represented by the unblocked flow into a plan of action, and then to create the corresponding sets of instructions to muscles etc.: the unimpeded flow produces a template for action that, if not blocked, automatically evolves into the appropriate action itself. So the basic problem of rapidly producing an appropriate action is precisely that of rapidly getting all of the probability into an unblocked channel, i.e., of keeping the search process from getting hung up exploring the blocked channels. The hydrodynamical character of the quantum law of evolution provides an efficient way to solve this problem.

Notice also that the quantum mechanism does not involve a sudden 'all or nothing' leap in phylogenetic development: even a little bit of sucking of the probabilities into unblocked channels will aid survival, and the organism can gradually evolve in a way that tends to enhance the process.

3. Decoherence

It has often been observed that the coupling of a system to its environment has a tendency to make interference phenomena that are present in principle within quantum systems difficult to observe in practice. Phase relationships, which are essential to interference phenomena, get diffused into the environment, and are difficult to retrieve. The net effect of this is to make a large part of the observable phenomena in a quantum universe similar to what would be observed in a world in which certain collective (i.e., macroscopic) variables are governed by classical mechanics. This greatly diminishes the realm of phenomena that require for their understanding the explicit use of quantum theory.

These decoherence effects will have a tendency to reduce, in a system such as the brain, the distances over which the idea of a simple single quantum system holds. This will reduce the distances over which the simple hydrodynamical considerations described above will hold. However, the following points must be considered.

a) A calcium ion entering a bouton through a microchannel of diameter x must, by Heisenberg's indeterminacy principle, have a momentum spread of $\hbar/x$, and hence a velocity spread of $(\hbar/x)/m$, and hence a spatial spread in time t, if the particle were freely moving, of $t(\hbar/x)/m$. Taking t to be 200 microseconds, the typical time for the ion to diffuse from the microchannel opening to a triggering site for the release of a vesicle of neurotransmitter, and taking x to be one nanometer, one finds the diameter of the wave function to be about 0.04 centimeters, which is huge compared to the 1/100000000 centimeter size of the calcium ion. There is, therefore, in brain dynamics a powerful counterforce to the mechanisms that tend to diminish quantum coherence effects.

b) The normal process that induces decoherence arises from the fact that a collision of a state represented by a broad wave function with a state represented by a narrow wave packet effectively reduces the coherence length in the first state to a distance proportional to the width of the second state. But in an aqueous medium in which all the states of the individual systems have broad packets this mechanism is no longer effective: coherence lengths can remain long.

c) Even if the coherence length were only a factor of ten times the diameter of the atom or ion involved in some process, the cross section involved would be

a hundred times larger. The search processes under consideration here involves huge numbers of atoms and ions acting together, and the cross-section factors multiply. Thus even a small effect at the level of the individual atoms and ions could give, by virtue of the hydrodynamical effect, a large quantum enhancement of the efficiency of an essentially aqueous macroscopic search process.

4. Quantum Theory and Experience

The core problem in quantum theory is perhaps best illustrated by Einstein's example [5] of a radioactive atom placed in a Geiger counter that is hooked up to a pen that is drawing a line on a moving strip of paper: when the atom decays the Geiger counter fires, and this causes a blip to be drawn on the moving strip of paper. Since all the parts of the apparatus are made up of atoms and electrons, etc., one should be able to apply quantum theory. But if one simply applies the Schroedinger equation, or the equations of local field theory, one finds that the moving strip will evolve into a continuous superposition of possibilities, with every possible time of decay represented by a correspondingly placed blip. No single decay time is singled out as the actual decay time. But what is observed if one looks at the strip is a blip appearing in one place, rather than a smeared out superposition of all the possibilities. So quantum theory, if left in this stage where only the Schroedinger equation (or the corresponding equation of local quantum field theory) is considered, is incomplete: some explanation of the mismatch between what we experience and what is generated by the Schroedinger equation is needed. Some account is needed for the process that selects, from the continuum of possibilities generated by Schroedinger equation , the particular thing that we actually see.

Physicists have proposed a number of possible ways of completing the theory. I do not wish to describe them here in detail. The chief contenders can be tied to the names of Bohr, Bohm, Everett, Heisenberg, and Wigner. Very briefly, the essence of each position is as follows:

Bohr [6]: Quantum theory is a set of useful rules that scientists can use to compute statistical prediction about whether or not certain conceivable classically describable experiences will appear under various conditions specified by classical describable experiences. Defect: The theory formulated in this way admittedly does not cover biological and cosmological systems, hence a putative theoretical description of nature herself might be useful for the further develop-

ment of science.

Bohm [7]: There is in addition to the quantum wave function also a real classical world whose motion is controlled by the wave function. As in classical mechanics the entire course of history is fixed at the moment of the creation of the universe. Defects: This formulation is very nonparsimonious because the Schroedinger equation must grind out forever the infinitudes of "empty branches" of the wave function that will never have any effect on the the classical world, which is the only part of reality that we experience. Also, the statistical aspects of quantum theory enter though the obscure idea of a preferred statistical ensemble of universes. Finally, consciousness can play no causal role in the dynamics.

Everett [8]: The wave function of the universe is continually separating into "branches" that are "decoherent" in the sense that if one restricts the set observables to certain localizable collective (macroscopic) properties then the state of the universe is approximately equivalent to a statistical mixture of these branches. It is assumed that there are separate mental states associated with these separate branches, and that they can be treated as members of a statistical ensemble with weights specified by the weights of the corresponding statistical ensemble of branches. All of the mental states in this ensemble are assumed to really exist, even though each such state contains no awareness of the others. Defects: This formulation is very nonparsimonious: only one of the infinitude of mental universes is ever experienced by us. Also, the treatment of the mental states does not follow from the physics: the state of the universe is a "conjunction" of the branches (it consists of branch 1 and branch 2 and ...) whereas in order to apply statistics the set of mental worlds must be "disjunctive" (it consists of mind 1 or mind 2 or ...). The notion that a single mental state can evolve into either mental state 1 or mental state 2, with specified probabilities, seems incompatible with the idea that the two alternatives are simultaneously present and really existing. At the very least, these ideas constitute a radical departure from normal ideas about the relationship between conjunctions and disjunctions. Furthermore, the notion that the wave function separates into well defined distinct "branches" is not always applicable: the normal evolution of a wave is an amorphous spreading out. This creates a serious technical problem, not yet resolved, of how to define the decomposition of an amorphous quantum

structure into a disjunction of classically describable observable realities in such a way that a probability can be coherently assigned to each of the associated overlapping mind/brain states, if there is no physical process that picks out and actualizes one of these overlapping states, and rejects the others. Finally, consciousness can play no causal role in the dynamics.

Heisenberg [9]: Heisenberg is a co-creator of the Copenhagen interpretation that I have associated with Bohr. But he also proposed a picture of nature herself in which there are to kinds of realities: potentialities and actualities. It is possible to regard the wave function as a representation of "potentialities" for "actual events": the potentialities evolve according to the Schroedinger equation until the conditions for a possible 'event' are created, and then this event either occurs or does not occur, according to a prescribed statistical rule. If the event occurs then the wave function changes to a new form that reflects the fact that this event has occurred, and then it (the new wave function) proceeds again to evolve according to the Schroedinger equation. The events are supposed to occur in connection with "measuring devices". Defects: The definition of "measuring device" is not specified, and hence the theory is not well defined. And, again, mind plays no role in the dynamics

Wigner [10]: Wigner, giving credit to von Neumann, suggests that what characterizes a "measuring device" is the occurrence of an "experience" in connection with the measurement. Specifically, the "measuring devices" of the Heisenberg interpretation are identified with the aspects of brain dynamics directly associated with the occurrence of a conscious experience.

Each of these general approaches has its contemporary proponents. Thus the works of Ghirardi, Rimini, Weber, and Pearle [11] are in the Heisenberg spirit. The works of Gell-mann and Hartle [12] are in the Everett framework. The works of Omnes [13] are, apparently, in the Bohr spirit. The present work is in the Heisenberg-Wigner-von Neumann spirit: I accept the general idea of Heisenberg that the wave function specifies propensities for events to occur, and the idea of Wigner (or von Neumann) that these events are associated with experiential qualities, in some very generic sense, but allow events to occur in both inanimate and animate systems. However, I focus first on those particular events that are identifiable with human conscious events, since we have direct information about these.

5. Choice and Consciousness

William James concludes from a study "of the particulars of the distribution of consciousness" (as contrasted with our perhaps misleading intuition) that "consciousness is at all times primarily a selecting agency". He says also: "It is to my mind utterly inconceivable that consciousness should have nothing to do with a business to which it so fathfully attends".

But why should he, or anyone else, even imagine that consciousness has nothing to do with the choices we make? The reason, of course, is that this is what classical physics tells us.

Let me explain. The infant learns, early on, through concordance of impressions gleaned from the five senses, including reports of others, to think that things like apples and toys, etc. continue to exist even when no one is sensing or actively thinking about them. Classical physics extends this idea of objective existence to the whole world of inanimate objects: all such things, large and small, are conceived to be mere aggregates of simple localizable properties that evolve according to local deterministic laws. Functional structures, such as pistons and drive shafts, though usefully conceived by us as whole functional entities, are considered to be fundamentally nothing but the aggregates of the interacting local parts of which they are formed. According to classical thinking, no extra property not explainable in terms of the aggregrate of simple localized properties is needed to explain, at least in principle, the behavior of even the most complex physical structure. This is the basic idea of classical physics. If we extend that idea to the bodies of human beings then their behaviors should, in principle, be completely explainable in terms of their localizable components. Conscious thoughts do not appear in the classical-physics description, and hence, in principle, no reference to such things should be needed to explain human behaviour. Any notion that certain functional features or aspects of brain dynamics have an experiential "beingness as a whole" that goes beyond the elemental beingness of the interacting local properties is alien to classical thinking, and directly contradicts it if any dynamical role is given to such entities that is not completely reducible to the local dynamics of the local parts. Thus, according to the ideas of classical mechanics, our conscious thoughts are excess baggage: all physical behavior would be just the same if the functional structure of the brain were just what it is, but no conscious thoughts were present.

It is difficult to believe that thoughts do nothing: that they are pure excess baggage. Yet how is one to make sense of the alternative idea that they, themselves, do something that their parts are not doing? How can a "whole" have an effect that is not ultimately just the effect of its parts acting in unison?

Our point of departure is the fact that in (Heisenberg-von Neumann-Wigner) quantum field theory there are two distinct dynamical processes. They are most clearly displayed in the so-called Heisenberg picture, or representation. There the local operators of the theory evolve according to the Heisenberg equations of motion, which are the Heisenberg-picture counterparts of the Schroedinger equation. These equations generate from the operators located along any space-like surface (or constant-time slice) the operators at all spacetime points, i.e., at all points, from the infinite past to the infinite future. This is analogous to the situation in classical mechanics, where the classical equations of motion generate, from values on one space-like surface, the values of all quantities at all times and places. But this part of the dynamics is, in the quantum case, only half the story, and the relatively trivial kinematic part at that. The nontrivial part of the dynamics is the part that controls the evolution of the (Heisenberg picture) state of the universe. This part consists of selections that are not determined by the local deterministic aspects of the quantum dynamics. Orthodox quantum theory says that these selections are determined by pure chance, but the simplest naturalistic possibility is that they are controlled by some nonlocal aspect of the physical universe. If, in the case of brain process, this aspect can be identified with our conscious thoughts, then consciousness would be a bona fide selecting agency. Because the selection events are events they do not have separate parts: each quantum event is a selection and actualization, all at once, of a spatially extended structure of propensities.

How could such a quantum process of selection and actualization work?

6. General Description of Brain/Mind Dynamics

Before going into the mathematical details of the model, I give a brief general description of my conception of how the quantum brain/mind works. For a more detailed description see reference [4].

Each conscious event is the felt event that actualizes a certain "executive" pattern of brain activity. This pattern endures long enough for it to become

"facilitated": i.e., to become etched into the physical structure of the neurons in such a way that a subsequent excitation of part of the pattern tends to spread to the whole pattern. The sequence of conscious thoughts associated with a given brain is represented by a sequence of actualizations of such patterns. The patterns in such a sequences have, in general, a large carry-over of components from one pattern to the next. Thus the sequence of executive patterns has the structure of a "marching band" that marches into and out of existence, with new parts coming into being at each step, and older parts fading out. The "feel" of each thought expresses the intentional and attentional content of the associated actualized executive pattern. The pervading experience of the presence of an enduring "I" is the felt process of continually re-actualizing the slowly changing peripheral part of the executive pattern. This part provides the over-all orientation for the executively controlled part of the mind/brain process. The sequence of felt events that actualize the executive patterns constitutes a tiny part of the brain activity: it rides on a vast substrate of unconscious brain activity that is controlled by the local deterministic process governed by the equations of local quantum field theory. Each executive pattern consists of a template for action that is constructed largely from components of earlier templates, and it issues its directives to the lower-level processes simply by the automatic spreading of the neural patterns of excitations that comprise it. The processing is analog, not digital, with a continual inflow of information from the environment, to which the body and brain adapt. Although the analog process can be simulated, at great expense, by a digital computer, the issue here pertains to how real brain tissues and aqueous ionic solutions, etc. function in real time.

Due to the quantum nature of the brain, and in particular to point a) mentioned in section 3 above, the brain state must evolve, via the local deterministic process determined by the equations of local quantum field theory, into a superposition of states each of which contains at the executive level a different alternative possible template for action. Each alternative is represented, during some brief time interval, by a relative stable enduring pattern of neural activity, and this stability constitutes the condition required for an event to occur. The "second process" now enters. It is represented in the physical realm (i.e., in Hilbert space) by a selection of one of these alternative possible states, each of which specifies a distinct template for action.

According to orthodox quantum ideas, this selection event is controlled by pure chance. The use of "pure chance" in a pragmatic context is completely acceptable. But it is not acceptable at the level of ontology. In the context of a naturalistic science some explanation in terms of physical quantities is needed, at least in principle, for how the particular reality that actually appears is picked out from the collection of alternative possibilities that are created by the local deterministic part of the dynamics.

The simplest naturalistic possibility is that the selection is controlled by the state vector itself, since this vector, and its changes, represent the physical reality. A most natural possibility would be for the choice to be controlled by the aspect of the state vector that specifies the environment that defines the possible states between which the selection event must choose. In our case that aspect would be the state of the brain itself, or, perhaps, even the aspect of the brain associated with the "I" mentioned above. In this latter case it would be the "I", as it is represented in the quantum dynamics, that selects the sequence of templates for action that controls the behavior of the organism.

But how could such a quantum process work?

7. Mathematical Formulation

My aim here to provide a mathematical model of causal quantum brain dynamics in which the quantum selection process is governed by our conscious thoughts, rather than by pure chance; i.e., where the notorious stochastic selection process of quantum mechanics, called the "irrational" element by Pauli, is replaced by a causal process in which our conscious thoughts, acting as whole entities not reducible to aggregates of local properties, become the bona fide selecting agents.

Quantum electrodynamics (extended to cover the magnetic properties of nuclei) is the theory that controls, as far as we know, the properties of the tissues and the aqueous (ionic) solutions that constitute our brains. This theory is our paradigm basic physical theory, and the one best understood by physicists. It describes accurately, as far as we know, the huge range of actual physical phenomema involving the materials encountered in daily life. It is also related to classical electrodynamics in a particularly beautiful and useful way. I take it as the basis of this work.

In this section I assume the reader to have some knowledge of the principles of quantum electrodynamics, and the notations used to describe it. I draw particularly on references [14] and [15], which describe in detail the natural connection between quantum electrodynamics and classical electrodynamics.

In the low-energy regime of interest here it should be sufficient to consider just the classical part of the photon interaction defined in [14]. Then the explicit expression for the unitary operator that describes the evolution from time t_1 to time t_2 of the quantum elecromagnetic field in the presence of a set $L = \{L_i\}$ of specified classical charged-particle trajectories, with trajectory L_i specified by the function $x_i(t)$ and carrying charge e_i, is

$$U[L; t_2, t_1] = \exp < a^* \cdot J(L) > \exp < -J^*(L) \cdot a > \exp[-(J^*(L) \cdot J(L)/2)],$$

where, for any X and Y,

$$< X \cdot Y > \equiv \int d^4k (2\pi)^{-4} 2\pi \delta^+(k^2) X(k) \cdot Y(k),$$

$$(X \cdot Y) \equiv \int d^4k (2\pi)^{-4} i(k^2 + i\epsilon)^{-1} X(k) \cdot Y(k),$$

and $X \cdot Y = X_\mu Y^\mu = X^\mu Y_\mu$. Also,

$$J_\mu(L; k) \equiv \sum_i -ie_i \int_{L_i} dx_\mu \exp(ikx).$$

The integral along the trajectory L_i is

$$\int_{L_i} dx_\mu \exp(ikx) \equiv \int_{t_1}^{t_2} dt (dx_{i\mu}(t)/dt) \exp(ikx).$$

The $a^*(k)$ and $a(k)$ are the photon creation and annihilation operators:

$$[a(k), a^*(k')] = (2\pi)^3 \delta^3(k - k') 2k_0.$$

The operator $U[L; t_2, t_1]$ acting on the photon vacuum state creates the coherent photon state that is the quantum-theoretic analog of the classical electromagnetic field generated by classical point particles moving on the set of trajectories $L = \{L_i\}$ between times t_1 and t_2.

The $U[L; t_2, t_1]$ can be decomposed into commuting contributions from the various values of k. The general coherent state can be written

$$|q, p > \equiv \exp i(< q \cdot P > - < p \cdot Q >)|0 >,$$

where $|0>$ is the photon vacuum state and

$$Q(k) = (a_k + a_k^*)/\sqrt{2}$$

and

$$P(k) = i(a_k - a_k^*)/\sqrt{2},$$

and $q(k)$ and $p(k)$ are two functions defined (and square integrable) on the mass shell $k^2 = 0$, $k_0 \geq 0$. The inner product of two coherent states is

$$< q,p|q',p' >= \exp -(< q-q' \cdot q-q' > + < p-p' \cdot p-p' > +2i < p-p' \cdot q+q' >)/4.$$

There is a decomposition of unity

$$I = \prod d^4k(2\pi)^{-4} 2\pi\delta^+(k^2) \int dq_k dp_k/\pi$$

$$\times \exp(iq_k P_k - ip_k Q_k)|0_k >< 0_k| \exp -(iq_k P_k - ip_k Q_k).$$

Here meaning can be given by quantizing in a box, so that that the variable k is discretized. Equivalently,

$$I = \int d\mu(q,p)|q,p >< q,p|,$$

where $\mu(q,p)$ is the appropriate measure on the functions q(k) and p(k). Then if the state $|\Psi >< \Psi|$ were to jump to $|q,p >< q,p|$ with probability density $< q,p|\Psi >< \Psi|q,p >$, the resulting mixture would be

$$\int d\mu(q,p)|q,p >< q,p|\Psi >< \Psi|q,p >< q,p|,$$

whose trace is

$$\int d\mu(q,p) < q,p|\Psi >< \Psi|q,p >=< \Psi|\Psi > .$$

To represent the limited capacity of consciousness let us assume, in this model, that the states of consciousness associated with a brain can be expressed in terms of a relatively small subset of the modes of the electromagnetic field in the brain cavity. Let us assume that events occurring outside the brain are keeping the state of the universe outside the brain cavity in a single state, so that the state of the brain can also be represented by a single state. The brain is represented, in the method of Feynman, by a superposition of the trajectories

of the particles in it, with each element of the superposition accompanied by the coherent-state electromagnetic field that this set of trajectories generates. Let the state of the electromagnetic field restricted to the modes that represent consciousness be called $|\Psi(t)>$. Using the decomposition of unity one can write

$$|\Psi(t)>=\int d\mu(q,p)|q,p><q,p|\Psi(t)> .$$

Hence the state at time t can be represented by the function $<q,p|\Psi(t)>$, which is a complex-valued function over the set of arguments $\{q_1,p_1,q_2,p_2,...,q_n,p_n\}$, where n is the number of modes associated with $|\Psi>$. Thus in this model the contents of the consciousness associated with a brain is represented in terms of this function defined over a $2n-$dimensional space: the ith conscious event is represented by the transition

$$|\Psi_i(t_{i+1})>\longrightarrow|\Psi_{i+1}(t_{i+1})>=P_i|\Psi_i(t_{i+1})>,$$

where P_i is a projection operator.

For each allowed value of k the pair of numbers (q_k,p_k) represents the state of motion of the kth mode of the electromagnetic field. Each of these modes is defined by a particular wave pattern that extends over the whole brain cavity. This pattern is an oscillating structure something like a sine wave or a cosine wave. Each mode is fed by the motions of all of the charged particles in the brain. Thus each mode is a representation of a certain integrated aspect of the activity of the brain, and the collection of values $q_1,p_1,...,p_n$ is a compact representation of certain aspects the over-all activity of the brain.

The state $|q,p>$ represents the conjunction, or collection over the set of all allowed values of k, of the various states $|q_k,p_k>$. The function

$$V(q,p,t)=<q,p|\Psi(t)><\Psi(t)|q,p>$$

satisfies $0\leq V(q,p,t)\leq 1$, and it represents, according to orthodox thinking, the "probability" that a system that is represented by a general state $|\Psi(t)>$ just before the time t will be observed to be in the classically describable state $|q,p>$ if the observation occurs at time t. The coherent states $|q,p>$ can, for various mathematical and physical reasons, be regarded as the "most classical" of the possible states of the electromagnetic quantum field.

To contruct a causal dynamics in which the state of consciousness itself controls the selection of the next state of consciousness one must specify a rule that determines, in terms of the evolving state $|\Psi_i(t)>$ up to time t_{i+1}, both the time t_{i+1} when the next selection event occurs, and the state $|\Psi_{i+1}(t_{i+1})>$ that is selected and actualized by that event.

In the absence of interactions, and under certain ideal conditions of confinement, the deterministic normal law of evolution entails that in each mode k there is an independent rotation in the (q_k, p_k) plane with a characteristic angular velocity $\omega_k = k_0$. Due to the effects of the motions of the particles there will be, added to this, a flow of probability that will tend to concentrate the probability in the neighborhoods of a certain set of "optimal" classical states $|q, p>$. The reason is that the function of brain dynamics is to produce some single template for action, and to be effective this template must be a "classical" state, because, according to orthodox ideas, only these can be dynamically robust in the room temperature brain [16]. According to the semi-classical description of the brain dynamics, only one of these classical-type states will be present, but according to quantum theory there must be a superposition of many such classical-type states, unless collapses occurs at lower (i.e., microscopic) levels. The assumption here is that no collapses occur at the lower brain levels: there is absolutely no empirical evidence, or theoretical reason, for the occurrence of such lower-level brain events.

So in this model the probability will begin to concentrate around various locally optimal coherent states, and hence around the various (generally) isolated points (q, p) in the $2n-$dimensional space at which the quantity

$$V(q, p, t) =< q, p|\Psi_i(t) >< \Psi_i(t)|q, p >$$

reaches a local maximum. Each of these points (q, p) represents a "locally-optimal solution" (at time t) to the search problem: as far as the myopic local mechanical process can see the state $|q, p>$ specifies an analog-computed "best" template for action in the circumstances in which the organism finds itself. This action can be either intentional (it tends to create in the future a certain state of the body/brain/environment complex) or attentional (it tends to gather information), and the latter action is a special case of the former. As discussed in [4], the intentional and attentional character of these actions is a consequence

of the fact that the template for action actualized by the quantum brain event is represented as a projected body-world schema, i.e., as the brains projected representation of the body that it is controlling and the environment in which it is situated.

Let a certain time $t_{i+1} > t_i$ be defined by an (urgency) energy factor $E(t) = \hbar(t_{i+1} - t_i)^{-1}$. Let the value of (q, p) at the largest of the local-maxima of $V(q, p, t_{i+1})$ be called $(q(t_{i+1}), p(t_{i+1}))_{max}$. Then the simplest possible reasonable selection rule would be given by the formula

$$P_i = |(q(t_{i+1}), p(t_{i+1}))_{max} >< (q(t_{i+1}), p(t_{i+1}))_{max}|,$$

which entails that

$$|\Psi_{i+1} >< \Psi_{i+1}| / < \Psi_{i+1}|\Psi_{i+1} >= |(q(t_{i+1}), p(t_{i+1}))_{max} >< (q(t_{i+1}), p(t_{i+1}))_{max}|.$$

This rule could produce a tremendous speed up of the search process. Instead of waiting until all the probability gets concentrated in one state $|q, p >$, or into a set of isolated states $|q_i, p_i >$ [or choosing the state randomly, in accordance with the probability function $V(q, p, t_{i+1})$, which could often lead to a disastrous result], this simplest selection process would pick the state $|q, p >$ with the largest value of $V(q, p, t)$ at the time $t = t_{i+1}$. This process does not involve the complex notion of picking a random number, which is a physically impossible feat that is difficult even to define.

One important feature of this selection process is that it involves the state $\Psi(t)$ as a whole: the whole function $V(q, p, t_{i+1})$ must be known in order to determine where its maximum lies. This kind of selection process is not available in the semi-classical ontology, in which only one classically describable state exists at the macroscopic level. That is because this single classically describable macro-state state (e.g., some one actual state $|q, p, t_{i+1} >$) contains no information about what the probabilities associated either with itself or with the other alternative possibilities would have been if the collapse had not occurred earlier, at some micro-level, and reduced the earlier state to some single classically describable state, in which, for example, the action potential along each nerve is specified by a well defined classically describable electromagnetic field. There is no rational reason in quantum mechanics for such a micro-level event to occur. Indeed, the only reason to postulate the occurrence of such premature reductions

is to assuage the classical intuition that the action-potential pulse along each nerve "ought to be classically describable even when it is not observed", instead of being controlled, when unobserved, by the local deterministic equations of quantum field theory. But the validity of this classical intuition is questionable if it severely curtails the ability of the brain to function optimally.

A second important feature of this selection process is that the actualized state Ψ_{i+1} is the state of the entire aspect of the brain that is connected to consciousness. So the feel of the conscious event will involve that aspect of the brain, taken as a whole. The "I" part of the state $\Psi(t)$ is its slowly changing part. This part is being continually re-actualized by the sequence of events, and hence specifies the slowly changing background part of the felt experience. It is this persisting stable background part of the sequence of templates for action that is providing the over-all guidance for the entire sequence of selection events that is controlling the on-going brain process itself.

A somewhat more sophisticated search procedure would be to find the state $|(q,p)_{max}>$, as before, but to identify it as merely a candidate that is to be examined for its concordance with the objectives imbedded in the current template. This is what a good search procedure ought to do: first pick out the top candidate by means of a mechanical process, but then evaluate this candidate by a more refined procedure that could block its acceptance if it does not meet specified criteria.

It may at first seem strange to imagine that nature could operate in such a sophisticated way. But it must be remembered that the generation of a truly random sequence is itself a very sophisticated (and indeed physically impossible) process, and that what the physical sciences have understood, so far, is only the mechanical part of nature's two-part process. Here it is the not-well-understood selection process that is under consideration. I have imposed on this attempt to understand the selection process the naturalistic requirement that the whole process be expressible in natural terms, i.e., that the universal process be a causal self-controlling evolution of the Hilbert-space state vector in which all aspects of nature, including our conscious experiences, are efficacious.

No attempt is made here to show that the quantum statistical laws will hold for the aspects of the brain's internal dynamics controlled by conscious thoughts. No such result has been empirically verified. The validity of the statistical laws

for events in the inanimate world is regarded as a consequence of our ignorance of the actual causes, and of certain a priori probability distributions. This is discussed in section 9.

It may be useful to describe the main features of this model in simple terms. If we imagine the brain to be, for example, a uniform rectangular box then each mode k would correspond to wave form that is periodic in all three directions: it would be formed as a combination of products of sine waves and cosine waves, and would cover the whole box-shaped brain. (More realistic conditions are needed, but this is a simple proto-type.) Classically there would be an amplitude for this wave, and in the absence of interactions with the charged particles this amplitude would undergo a simple periodic motion in time. In analogy with the coordinate and momentum variables of an oscillating pendulum there are two variables, q_k and p_k, that describe the motion of the amplitude of the mode k. With a proper choice of scales for the variables q_k and p_k the motion of the amplitude of mode k if it were not coupled to the charges would be a circular motion in the (q_k, p_k)-plane. The classical theory would say that the physical system, mode k, would be represented by a point in q_k, p_k space. But quantum theory says that the physical system, mode k, must be represnted by a wave (i.e., by a wave function) in (q_k, p_k) space. The reason is that interference effects between the values of this wave (function) at different points (q_k, p_k) can be exhibited, and therefore it is not possible to say the full reality is represented by any single value of (q_k, p_k): one must acknowledge the reality of the whole wave. It is possible to associate something like a "probability density" with this wave, but the corresponding probability cannot be concentrated at a point: in units where Planck's constant is unity the bulk of the probability cannot be squeezed into a region of the (q_k, p_k) plane of area less that unity.

The mode k has certain natural states called "coherent states", $|q_k, p_k >$. Each of these is represented in (q_k, p_k)-space by a wave function that has a "probability density" that falls off exponentially as one moves in any direction away from the centerpoint (q_k, p_k) at which the probability density is maximum. These coherent states are in many ways the "most classical" wave functions allowed by quantum theory [17], and a central idea of the present model is to specify that it is to one of these "most classical" states that the mode-k component of the electromagnetic field will jump, or collapse, when an observation

occurs. This specification represents a certain "maximal" principle: the second process, which is supposed to pick out and actualize some classically describable reality, is required to pick out and actualize one of these "most classical" of the quantum states. If this selection/actualization process really exists in nature then the classically describable states that are actualized by this process should be "natural classical states" from some point of view. The coherent states satisfy this requirement. This strong, specific postulate should be easier to disprove, if it is incorrect, than a vague or loosely defined one.

If we consider a system consisting of a collection of modes k, then the generalization of the single coherent state $|q_k, p_k >$ is the product of these states, $|q, p >$. Classically this system would be described by specifying the values all of the classical variables q_k and p_k as functions of time. But the "best" that can be done quantum mechanically is to specify that at certain times t_i the system is in one of the coherent states $|q, p >$. However, the equations of local quantum field theory (here quantum electrodynamics) entail that if the system starts in such a state then the system will, if no "observation" occurs, soon evolve into a superposition (i.e., a linear combination) of many such states. But the next "observation" will then reduce it again to some classically describable state. In the present model each a human observation is identified as a human conscious experience. Indeed, these are the same observations that the pragmatic Copenhagen interpretation of Bohr refers to, basically. The 'happening' in a human brain that corresponds to such an observation is, according to the present model, the selection and actualization of the corresponding coherent state $|q, p >$.

The quantity $V(q, p, t_{i+1})$ defined above is, according to orthodox quantum theory, the predicted probability that a system that is in the state $\Psi(t_{i+1})$ at time t_{i+1} will be observed to be in state $|q, p >$ if the observation occurs at time t_{i+1}. In the present model the function $V(q, p, t_{i+1})$ is used to specify not a fundamentally stochastic (i.e., random or chance-controlled) process but rather the causal process of the selection and actualization of some particular state $|q, p >$. And this causal process is controlled by features of the quantum brain that are specified by the Hilbert space representation of the conscious process itself. This process is a nonlocal process that rides on the local brain process, and it is the nonlocal selection process that, according to the principles of quantum theory, is required to enter whenever an observation occurs.

8. Qualia: The Feel Of An Actualization

According to the theory described here, a human conscious event is the reality that is represented in the model as a felt event that actualizes an executive template for action in a human brain, and the flow of consciousness is the reality that is represented as the sequence of felt events that actualize a sequence of executive templates for action in a human brain. The conscious "I" is the reality that is represented as the sequence of felt re-actualizations of the slowly changing background structure in these templates for action. This background structure provides the over-all orientation for the ongoing mind/brain process. Since the whole quantum process takes place in the realm of potentialities, or probabilities, or propensities, which are mind-like in character, and these quantities pertain only to felt events, which are just the actualizations of other potentialities, probabilities, and propensities, the whole quantum ontology has an essentially mind-like character: ontologically speaking, everything is mind like. Yet all of these mind-like things are represented mathematically in terms of Hilbert-space vectors, which is what represents, in quantum mechanics, the physical aspect of nature. Thus this model integrates into one mathematical structure the mental and physical aspects of nature. The conflation of mind and matter by quantum theory was, of course, a feature well appreciated its founders.

9. Quantum Statistics

If the process of selection and actualization of "the actual" in human brains is governed by a nonlocal causal process, rather than by pure chance, then one must naturally expect analogous causal processes to be occurring elsewhere in nature. If we assume that the selection process is in all cases controlled by a causal process then it must be explained why the statistical rules of quantum theory hold in those cases where they have been tested and validated.

An explanation can be constructed as follows. Consider an n-dimensional Hilbert space of points $(z_1, z_2, ..., z_n)$, where, each for each i,

$$z_i = x_i + iy_i = r_i \exp i\theta_i$$

is a complex number, and $r_i \geq 0$. This space can be imbedded in a 2n-dimensional real space of points $(x_1, y_1, x_2, y_2, ..., x_n, y_n)$, and each unitary transformation in the Hilbert space generates an orthogonal transformation in the real space. The volume in the real space defined by the intersection of the

unit ball centered at the origin with the collection of rays from the origin that pass through a region R on the unit sphere is invariant under any orthogonal transformation, and hence also under the image in real space of any unitary transformation in the Hilbert space. Thus the volume (=surface area) of any region R of the unit sphere in the real space is invariant under the image of any unitary transformation in the Hilbert space.

Since dynamical evolution, and most symmetry operations in the the Hilbert space, are generated by unitary transformations, the a priori probability density of unit vectors in Hilbert space should be invariant under unitary transformations. Thus it is reasonable to assign to any region R on the surface of the real unit sphere an a priori probability equal to the volume (=surface area) of that region R.

This a priori probability rule can be used in the following way. Suppose that, as in our brain case, there is, for a given state Ψ_i, a rule that specifies a candidate projection operator P_i, and that if the passage from state Ψ_i to state $P_i\Psi_i$ is not "blocked" then the transition proceeds. If $P_i = I$, where I is the identity operator, then the passage is not blocked, since a change into itself is no change at all, and if $P_i = 0$ then the passage must be blocked, since a transition to the null state is not allowed.

But then what is the rule that determines whether the passage is blocked?

According to the idea behind the present theory everything that enters into the dynamics is represented in Hilbert space: nothing dynamically significant stands outside the Hilbert space of the universe! And the dynamics is to be specified in terms of the state of the universe, or perhaps in terms of the full history of states

$$(\ldots, \Psi_{i-2}, \Psi_{i-1}, \Psi_i).$$

The simplest form for the "blocking rule" is that the states Ψ_i and $P_i\Psi_i$ determine a state Φ of unit norm that lies in the complex 2-dimensional subspace generated by Ψ_i and $P_i\Psi_i$, and that the transition from the state Ψ_i to the state $P_i\Psi_i$ proceeds unless for some representative of the state Ψ_i, which is defined only up to a phase factor, the direct path from Ψ_i to some representative of $P_i\Psi_i$ intersects the ray Φ

The geometric situation is this. The state Ψ_i can be represented in the 2-

dimensional Hilbert space generated by Ψ_i and $P_i\Psi_i$ by the continuum of pairs of complex numbers

$$(z_1, z_2) = (\exp i\phi, 0); 0 \leq \phi \leq 1,$$

and the state $P_i\Psi_i$ can then be represented by the continuum of pairs

$$(\cos^2\theta \exp i\phi, \sin\theta\cos\theta \exp i\phi \exp i\chi)$$

with $0 \leq \phi \leq 2\pi$ and $0 \leq \chi \leq 2\pi$. The overall phase factor $\exp i\phi$ drops out of all computations and can be set to unity. The phase factor χ reflects an arbitrary choice of the phase of the basis vector associated with the component z_2, and it is assumed that there is a representative of $P_i\Psi_i$ for each value of χ. The "direct path" from a representative of Ψ_i to a representative of $P_i\Psi_i$ can be traced out by allowing the value of θ to run from zero to its actual value. Allowing θ to run from zero to $\pi/2$ and χ to run from zero to 2π generates a 2-dimensional spherical surface $S_{1/2}$ of radius $1/2$ centered at $z_1 = 1/2$. The vectors Φ are defined as the set of unit-normed vectors from the origin $z_1 = z_2 = 0$, or as the equivalent parallel vectors of norm $1/2$ from the center of $S_{1/2}$. A uniform distribution of the unit-normed vectors Φ on the unit 2-sphere is equivalent to a uniform distribution of points on the spherical surface $S_{1/2}$. Notice that a point

$$(\cos^2\theta', 0, \sin\theta'\cos\theta'\cos\chi', \sin\theta'\cos\theta'\sin\chi')$$

on $S_{1/2}$ blocks some direct path in $S_{1/2}$ from the representative $(1,0,0,0)$ of Ψ_i to some representative of $P_i\Psi_i$ if and only if θ' satisfies $0 \leq \theta' \leq \theta$

In some situations, namely those in which the realities that are governing the second process are human conscious experiences, we have direct knowledge of what the governing realities are: they are exactly the conscious experiences that are controlling the second process. But in cases where the collapse of the wave function is associated with, say, an event in a Geiger counter, we are not privy to the form of the controlling realities. So in these cases we must fall back to statistical considerations. According to the model described above, there is a vector Φ that determines whether or not the collapse will occur, but we are ignorant of what it is. But the a priori probability distribution for the location of the vector Φ corresponds to a uniform distribution over the spherical surface $S_{1/2}$. The probability that the transition from Ψ_i to $P_i\Psi_i$ will be blocked is then

equal to the fraction of the surface area of $S_{1/2}$ that is covered as θ' runs from zero to θ. This probability is $1 - \cos^2\theta$. Hence the a priori probability that the transition will occur is $\cos^2\theta$. This is the same as $|P_i\Psi_i|^2/|\Psi_i|^2$, which is what quantum theory predicts. So in this model the statistical predictions of quantum theory would arise from a combination of our ignorance of the true causes, with an a priori uniform probability distribution over an appropriate 2-sphere of the real image of a Hilbert space vector Φ that determines whether the transition to a specified state occurs or not.

10. Remarks

1. Quantum brain theory has been characterized as "A solution in search of a problem". A first question, in this connection, is whether a semi-classical model of the brain—e.g., a model in which the action potential on every neuron is regarded as a well-defined classically describable electromagnetic pulse—is capable of generating solutions to search problems as quickly as the brain actually does it, or whether a quantum mechanism such as the hydrodynamic effect, or the picking of the most likely solution mentioned above, is needed. The way in which a classical brain could search for suitable templates for action (or recognize patterns) is not known at present in enough detail to make an estimate of the claasically allowed rapidities possible . But it seems reasonable that nature would make use of the quantum possibilities for speeding up the search processes.

2. This question of speed is, however, not the only relevant consideration. Even if a semi-classical model were fast enough the question would arise why a dynamically inert psychical element is present at all in nature. Wigner emphasized that in the rest of physics every action of one thing upon another is accompanied by a reaction of the second back on the first. A dynamically inert psychic reality could have no survival value, hence no physical reason to exist. Yet it seems absurd to think that something so different from its supposedly classical physical foundation could arise just by accident.

3. The model described here is heretical in attempting to replace the irreducible element of chance in quantum theory by a nonlocal causal process in Hilbert space. Indeed, in my earlier works on the subject I adhered to the orthodox idea that the statistical predictions are inviolate. Even adhering to that stricture, the evident mentalistic character of basic elements in quantum me-

chanics (i.e., the existence of nothing material or substantive; but merely probabilities, nonlocal selection events, and the experiences of observers) suggested that the experiential aspects of nature were closely tied to its fundamentally quantum nature. But if mental entities are really entering into the ontology in a basic way, it seems unnatural not to give them a genuine dynamical role, rather than the illusory one that they would have if an irreducible element of chance were really controlling the selection process. In any case, perhaps this spelling out of a simple mathematical model may convey better than words the fact that quantum theory naturally accomodates a conception of nature in which there is, in the human brain, a nonlocal physical process of selection and actualization that: (1), supervenes over the local process that is the quantum anologue of the local process of classical physics; (2), is not reducible to any local process; and (3), plays a bona fide executive role in the determination of our mental and physical actions.

4. The events in this second process have an ontological character that differs greatly from that of the local process: the events abruptly select and actualize, via a global process, new states of the physical system, whereas the local process merely evolves in a continous mechanical way the potentialities for these actual events. It is therefore natural that the events should be endowed with a different kind of beingness: i.e., with a certain "actualness" that goes beyond the mere "tendency" character of what is generated by the local process. Since this actualization event is, in the case of brain events, simultaneously both an actualization of a template for action and an implanting of the form of this template into a memory structure, in the form of its projected functional effects on the body and its enviroment, it is not unnatural that the beingness of this brain event should be an embodiment or representation of the functional character of this event.

References

1. N. Bohr, See ref.4 p. 63/64.

2. D. Bedford and H.P. Stapp, Synthese 102, 139-164, 1995; H.P. Stapp, Phys. Rev. A49, 4257, 1994; Ref.4, p.6.

3. R.P. Feynman, Feynman Lectures, Chapter 21.

4. H.P.Stapp, Mind, Matter, and Quantum Mechanics, Spinger-Verlag,

Heidelberg, 1993. Chapter 6.

5. A. Einstein, in A. Einstein: Philosopher-Scientist, ed. P.A. Schilpp, Tudor, New York, 1951. p.667-673.

6. N. Bohr, See ref. 4, Chapter 3

7. D. Bohm and B.J. Hiley, The Undivided Universe: An Ontological Interpretation of Quantum Theory, Routledge, London, New York, 1993.

8. H. Everett III, Rev. Mod. Phys. 29, 463, (1957).

9. W. Heisenberg, Physics and Philosophy, Harper Row, New York, 1958, Chapter III. 10. E. Wigner, in The Scientist Speculates, ed.I.J. Good, Basic Books, New York, 1962.

11. G.C.Ghirardi, A. Rimini, and Weber, Phys. Rev. D34, 470 (1986); G.C.Ghirardi, P.Pearle, and A.Rimini, A42, 78 (1990)

12. M. Gell-Mann and J. B. Hartle, in Proc. 3rd Int. Sympos. on Quantum Mechanics in the Light of New Technology, eds. S. Kobayashi, H. Ezawa, Y. Murayama, and S. Nomura, Phys. Soc. of Japan.

13. R. Omnes, The Interpretation of Quantum Mechanics, Princeton Univ. Press, Princeton NJ, 1994.

14. H.P.Stapp, Phys. Rev. D28, 1386 (1983)

15. T. Kawai and H.P. Stapp, Phys. Rev. D52, 2484-2532, (1995)

16. H.P. Stapp, in Symposium on the Foundations of Modern Physics 1990, P.Lahti and P. Mittelstaedt eds., World Scientific, Singapore. Sec. 3; and in ref.[4] p. 130.

17. R.J. Glauber, in Quantum Optics, S.M. Kay and A. Maitland, eds. Academic Press, London and New York, 1970; T. W. B. Kibble in ibid;
H.P. Stapp, in Quantum Implications: Essays in Honour of David Bohm, B.J. Hiley and F.David Peats eds., Routledge and Paul Kegan Ltd., London and New York, 1987.

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