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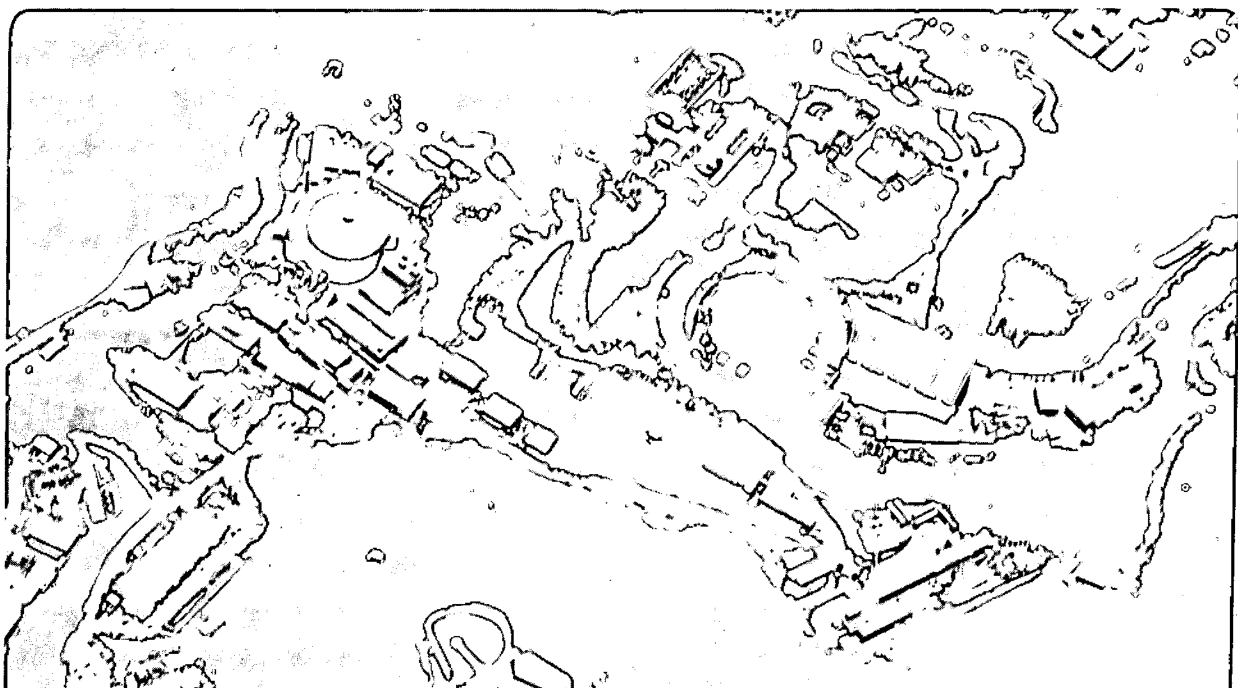

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Quantum Measurement and the Mind–Brain Connection *

Invited paper at the Symposium for Modern Physics
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Abstract

It is argued that quantum measurements do pose a problem, within the context created by the fundamental aim of science, which is identified as the construction of a cohesive, comprehensive, and rationally coherent idea of the nature of the world in which we live. Models of nature are divided into two classes: (1), those in which there is a selection process that, for any possible measurement, would, if that measurement were to be performed, pick out one single outcome, and, (2), all others. It is proved that any model of class (1) that reproduces the predictions of quantum theory must violate the condition that there be no faster-than-light influences of any kind. This result is used to motivate the study of models in which unitary evolution is maintained and there is no selection of unique outcomes. A consideration of ontic probabilities, historical records, and the form of the mind-brain connection leads to an elaboration of the Everett many-worlds interpretation that appears to provide the basis of satisfactory solution of the measurement problem.

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1. The Problem

An essential part of the problem of quantum measurements is to correctly identify the problem. Indeed, many scientists believe that quantum measurements pose no scientific problem at all, and that the subject of this conference lies, therefore, outside the realm of science. Even among scientists who profess to see a problem there is considerable divergence about precisely what this problem is: certainly many of the differences of opinion expressed at this conference stem directly from differing perceptions of the nature of the problem.

van Fraassen[1] has identified the problem as the reconciliation of the truism that quantum theory describes an indeterministic world with the fact that quantum theory describes the evolution of an isolated system deterministically. This comes close to the mark, but needs elaboration.

The basic work in this field is that of von Neumann.[2] Within von Neumann's framework the problem, if there be one, is connected to his postulate that the quantum system evolves in two fundamentally different ways, either normally in accordance with a unitary transformation (type II process), or, during the course of a measurement process, in accordance with a (type I) process of the form

$$\rho \rightarrow \sum_i P_i \rho P_i Tr P_i \rho, \tag{1.1}$$

where the set of P_i are a set of disjoint projectors ($P_i P_j = P_i \delta_{ij}$) that sum to unity ($\sum P_i = I$).

A projector P_i might be, for example, the operator defined by the requirement that it take the value *one* when acting on states in which the position of the center of mass of a certain pointer of some measuring devices lies within some specified domain, say to the right of the resting point, and takes the value *zero* otherwise. Or P_i might project onto the "yes" state of a memory unit on a magnetic tape, or onto the states of a laboratory notebook in which appear the statement "the pointer moved to the right".

The von Neumann reduction is compatible with an ignorance interpretation. It is logically completely different from the similar–looking reductions that can occur in the *reduced* density matrices that can be formed by performing partial traces over selected degrees of freedom: the von Neumann reduction is a reduction of the density matrix of the entire universe, or of the largest system that can be described as a quantum system.

Zeh[3], Zurek[4], and Joos[5] have examined the reductions that can occur in the reduced matrices formed by taking partial traces over unobserved environmental degrees of freedom. As those authors have repeatedly emphasized, such considerations leave essentially untouched the basic problem associated with the von Neumann reduction. Various contributions[6,7] to this conference have examined reductions associated with certain other reduced density matrices, and have arrived at the similar conclusion that the problem of the von Neumann reduction is left untouched.

But what is this problem? In fact, there is no problem if von Neumann's quantum formalism is ascribed the significance specified by the Copenhagen interpretation. According to this interpretation the sole correct use of the quantum formalism is merely to make calculations of expectations pertaining to observations obtained under classically described conditions.[8,9] Within this framework the "measurement process" of the von Neumann description must be identified as part of a process whereby some human observer is trying to acquire knowledge about a quantum system: "measurements" do not occur in the physical world considered alone; they are tied specifically to the acquisition of knowledge by human observers, and the reduction postulate is simple part of the computations scheme by which those observers calculate expectations pertaining to their observations.

Within this orthodox framework a question of *consistency* can arise in a situation involving a chain of measuring devices linking the quantum system to the brain of the observer. This question concerns the dependence of the calculated expectation upon *which* of the devices in this chain are considered to be "classically describable", i.e., upon *which* of the devices the operator P_i act.

von Neumann's analysis shows that for good (nondemolition) measurements the calculated results will not depend significantly upon where one places the 'Heisenberg cut' that divides the classically described world from the part of the world that is described quantum mechanically.

The clarity of von Neumann's presentation invites one to consider von Neumann's reduction process to be a process that occurs physically within nature herself, rather than in the computations of scientists. Indeed, Ghirardi, Rimini, and Weber,[10] and Pearle[11] have accepted this invitation to construe the von Neumann process as a real physical process. However, the orthodox way to solve the problem of the reduction is to accept the Copenhagen view that the quantum formalism is merely a set of rules for calculating expectations pertaining to our observations. These rules are considered to be adequately justified by their practical success: their origin, or physical basis, is asserted to be in no need of explanation.

There are, in my opinion, two major objections to this pragmatic approach. The first is that it is overly restrictive. Most physical systems have properties that can be understood as consequences of the quantum nature of these systems, in spite of the fact that no one has ever prepared these systems, or will ever assigned a wave function to then. The stability of planets and rocks, and the physical properties of metals, inorganic compounds, and organic compounds, have presumably existed long before any quantum physicist assigned a wave function to them. Thus there is evidently some element of truth in the quantum description that is independent of the mental acts of quantum physicists: the mental acts of quantum physicists depend upon the existence of quantum properties, not vice versa. Hence the pragmatically construed theory is, in some sense, incomplete.

The second objection is related to the first. The task of science is not simply to provide a foundation for engineering practice, or to make predictions about how laboratory experiments will turn out. We do laboratory experiments in order to find out something about the nature of the world, not merely to perfect and test prescriptions about how to compute expectations pertaining to the results of laboratory experiments. To restrict the aims of science in the way suggested by a narrowly construed Copenhagen interpretation is to confuse the means of science with its ends. The proper goal of science is to provide, by means of empirical investigations and theoretical analysis, a cohesive, comprehensive, and rationally coherent idea of the nature of the world in which we live. To be diverted from this goal by philosophy is to become confused by philosophy, not illuminated by it. From this perspective the EPR-Bell analysis establishes not the futility of pursuing the real, but rather the inadequacy of classical conceptions of the real.

The possible models of nature are of two fundamentally different kinds: (1), those in which nature would, in any measurement situation that we might set up, make some absolute selection between the alternative possible observable outcomes, and, (2), those in which this property does not hold. The models of Ghirardi, Rimini, Weber, and Pearle lie in the first class, as does the pilot-wave model of Bohm.[12] The many-minds model of Everett,[13] to the extent that it can be formulated as a truly coherent, rational, and well-defined model of nature, lies in the second class. Section two of this paper gives a proof that models in the first class must necessarily involve some kind of faster-than-light influence. Certain earlier proofs of similar results have involved auxiliary assumptions such as determinism, counterfactual definiteness, the EPR criterion of physical reality, or hidden-variable factorization. The proof given in section 2 employs no such assumption, but is based, rather, on the assumption that if a measurement were to be performed then the outcome would be determinate. The proof is based on predictions of quantum theory pertaining to the outcomes of the three-particle spin-correlation experiments discussed by Greenberger, Horne, and Zeilinger.[14]

The result obtained in section two is used to motivate the work of section three, in which an effort is made to meet the objection to the many-minds approach that it is not sufficiently well formulated to be regarded as a rationally coherent model of nature.

2. Significance of Bell's Theorem: Local Selection Entails Superluminal Influence

Bell's original theorem[15] is usually formulated as the assertion that 'No local deterministic hidden-variable theory is compatible with the predictions of quantum theory'. This result is useful in the context of an effort to construct a rationally coherent model of nature that is compatible with the predictions of quantum theory: it rules out a large class of theories. This class consists of theories that satisfy the following two premises:

1. *Reality Premise.* The outcomes that a certain set of mutually exclusive alternative possible measurements 'would have if they were to be performed' is determined by a set of simultaneously well-defined functions of a set of hidden variables.

2. *Locality Premise.* The outcome that 'would appear' in any spacetime re-

gion R_i, under any condition that might be set up there, is independent of which measurement is chosen and performed in any region R_j that is spacelike separated from the first.

This reality premise contradicts two basic quantum precepts, namely the precept that nature is indeterministic, and the precept that observables corresponding to mutually exclusive alternative possible measurements cannot have simultaneously determinate values. Hence the theorem appears merely to confirm the inadequacy, in the quantum domain, of classical ideas about reality.

The theorem can, however, be reformulated so that: (1), the reality premise expresses ideas widely accepted among quantum physicists, principally the idea of *macroscopic* physical realism; and, (2), the locality premise is a clean expression of the condition that there be no faster-than-light influence of any kind. Then the theorem no longer simply reaffirms the inadequacy of classical concepts. Rather, it allows the no-faster-than-light-influence condition to discriminate between two fundamentally different conceptions of nature that are both compatible with the usual quantum precepts.

The reformulated version is this: 'No general selection process compatible with the predictions of quantum theory can be local.'

A *selection process* is a process that will, for any local measurement, under the condition that this measurement be performed, select a single outcome that, in principle, will appear to all observers who examine the result of this measurement.

A selection process is operative in both the collapse model of Ghirardi, Rimini, and Weber,[10] and the pilot-wave model of Bohm[12]: in both models nature selects a single outcome for any performed measurement, and this outcome will, in principle, appear to all observers who examine the result of this measurement. However, no selection process is operative in the many–minds model of Everett[13]: in this model *each* of the alternative possible outcomes will, in principle, appear in the consciousness of some corresponding observer.

A *general* selection process is a selection process in which: (1), the decisions as to which measurements are to be performed in each of several spacetime regions are indeterminate until the moment that these choices are made; and, (2), for each of these regions the selection process will act no matter which of the alternative possible measurements is chosen and performed there.

The collapse model of Ghirardi, Rimini, and Weber and the pilot-wave model of Bohm are both deterministic, as originally formulated. However, the choices among possible measurements can be made indeterministic without disturbing these models in any essential way. One way to do this is simply to imbed the quantum world described in these models in a classical external field that acts only in certain small spacetime regions, and that can shift the choices of measurements in arbitrary ways. Alternatively, one can, for each such choice, add a small quantum mechanical 'choice system' that is dynamically isolated from the rest of the system until the moment of choice. The extra classical variables that are, according to these models, associated with these choice systems can be kept indeterminate until the moment of choice. At this moment of choice one particular set of values for the set of classical choice parameters is chosen; and one particular measurement will consequently be chosen. But there are an infinite number of possible values that were not chosen. Thus 'what would have happened in the other cases' remains indeterminate.

This construction allows the theories of Ghirardi, Rimini, and Weber, and of Bohm, to provide models of general selection processes.

The *reality premise* of the reformulated theorem is simply that a general selection process is operative. This premise is essentially the demand that macroscopic physical realism hold: the active presence of a general selection process entails that those observable properties of measuring devices that characterize outcomes of measurements become determinate whether or not they are observed by someone; these macroscopic observable properties are not fundamentally observer dependant, as they are in the many–minds model.

It is this close connection to macroscopic physical realism that provides the motivation for the study of general selection processes. Interest in the possibility of reconciling quantum theory with physical realism motivated also another generalization of Bell's theorem, namely the one formulated as the assertion that 'No theory can be compatible with both local realism and the predictions of quantum theory'. However, the reality premise of that theorem[16] is far stronger than macroscopic physical realism.[17]

The locality premise of the reformulated theorem will be defined in due course. First, however, a model of a general selection process more general than either of the two models described above will be constructed. To make this model concrete, and closely connected to the proof of the theorem, it will be formulated within the context of an experimental arrangement discussed by Greenberger Horne, and Zeilinger.[14] This GHZ experiment is a generalization of the EPR-Bohm spin-correlation experiment considered by Bell. It has certain advantages, which will soon become evident.

The GHZ experiment involves three spin-$\frac{1}{2}$ particles, which are measured in three mutually spacelike separated spacetime regions $R_i, i\epsilon\{1,2,3\}$. The initial spin state is

$$\psi = \frac{1}{\sqrt{2}}\left(\begin{pmatrix}1\\0\end{pmatrix}_1\begin{pmatrix}1\\0\end{pmatrix}_2\begin{pmatrix}1\\0\end{pmatrix}_3 - \begin{pmatrix}0\\1\end{pmatrix}_1\begin{pmatrix}0\\1\end{pmatrix}_2\begin{pmatrix}0\\1\end{pmatrix}_3\right), \tag{2.1}$$

where the eigenstates of σ_z^i are used. In region R_i a choice is to be made to measure either σ_x^i or σ_y^i, and the chosen measurement is then to be performed in R_i.

Let X_i represent the condition that a measurement of σ_x^i be chosen and performed in region R_i, and let Y_i represent the condition that a measurement of σ_y^i be chosen and performed in region R_i. Let $x_i = +1$ and $x_i = -1$ represent the two alternative possible outcomes that might appear under condition X_i, and let $y_i = +1$ and $y_i = -1$ represent the two alternative possible outcomes that might appear under condition Y_i. Then quantum theory makes the following predictions:

$$\text{If } X_1X_2X_3 \text{ then } x_1x_2x_3 = -1, \tag{2.2}$$

$$\text{If } X_1Y_2Y_3 \text{ then } x_1y_2y_3 = +1, \tag{2.3}$$

$$\text{If } Y_1X_2Y_3 \text{ then } y_1x_2y_3 = +1, \tag{2.4}$$

and

$$\text{If } Y_1Y_2X_3 \text{ then } y_1y_2x_3 = +1. \tag{2.5}$$

The first prediction is that if the measurements of σ_x^1, σ_x^2, and σ_x^3 were to be chosen and performed in the regions R_1, R_2, and R_3, respectively, then the appearing triad of values x_1, x_2, and x_3 would have product minus one. The three other predictions are defined analogously.

A random-variable model of a general selection process, operating in the GHZ context, is constructed in the following way. Let the six functions

$$x_i(\rho(X_i;...),...) \qquad i\epsilon\{1,2,3\} \tag{2.6}$$

and

$$y_i(\rho(Y_i;...),...) \qquad i\epsilon\{1,2,3\} \tag{2.7}$$

be defined. The quantity $\rho(X_1;...)$ is, in general, a random variable (i.e., a *set* of values with a weight assigned to each value) that will, however, if σ_x^1 is measured, be transformed into a determinate value. The five other ρ's are defined analogously.

These six quantities ρ are six among a host of similar quantities. The basic selection process of the universe is described in terms of these quantities ρ. Initially these ρ's are all indeterminate (e.g., random variables), but some of them will eventually become, under the action of the fundamental process of the universe, transformed into determinate values.

This fundamental process, which is the generation of determinate properties, consists of a sequence of events, each of which is a transformation of some ρ from its original indeterminate status into a determinate value. Each ρ is associated with a spacetime point, called its location.

The dots in $\rho(X_1;...)$ represent the set of ρ's upon which it might depend. In principle these ρ's could be located at points scattered over all of spacetime. But this sort of scattering would create the danger of a 'gridlock', in which no ρ could become determinate because it would depend functionally upon other ρ's that are indeterminate.

A gridlock can be prevented by, for example, introducing a preferred co-ordinate system, and hence a preferred temporal ordering, and requiring each ρ to be functionally independent of all ρ's having temporally later locations, and specifying also that the sequence of events be ordered in accordance with this same temporal ordering. This latter condition would yield a fundamental process that acts in accordance with the intuitive idea that what happens today becomes fixed prior to the fixing of what happens tomorrow.

An alternative possibility, more in line with ideas from the theory of relativity, is to introduce no preferred coordinate system, but to allow no ρ to depend upon any ρ that is not located in its own backward light cone, which is the backward light cone whose apex lies at its own location.

The final three dots in the expression $x_1(\rho(X_1;...),...)$ represent the other ρ's upon which this function can depend. One demand imposed by the requirement that a general selection process be operative is that if the measurement of σ_x^1 were to be chosen and performed in R_1 then expression $x_1(\rho(X_1;...),...)$ would yield some determinate value, +1 or −1. One way to ensure this property would be to demand: (1), that *both* triads of dots in this expression be restricted to sets of ρ's whose locations lie in the backward light cone of $\rho(X_i;...)$; and, (2), that all of these ρ's become transformed into determinate values *prior* to the event at which $\rho(X_i;...)$ becomes determinate. (The word 'prior' used here refers to *process time*, which is the time variable associated with the fundamental selection process: it increases by one unit at the occurrence of each event in the fundamental sequence of selection events.)

The quantity $\rho(X_i;...)$ is directly associated with the selection of the outcome of the measurement of σ_x^1, and its location lies in R_1. Another important ρ whose location lies in R_1 is the quantity ρ_1; it is the becoming determinate of ρ_1 that fixes which measurement will be performed in R_1. The location of ρ_1 lies in the backward light-cone of $\rho(X_i;...)$. The quantities ρ_2 and ρ_3 are defined analogously.

Within this random-variable model the locality (i.e., no-faster-than-light-influence) premise is expressed as the set of conditions: "Under any condition X_1,

$$\begin{aligned}
&[x_1(\rho(X_i;..),...)]_{X_2X_3} \\
&= [x_1(\rho(X_i;...),...)]_{Y_2Y_3} \\
&= [x_1(\rho(X_i;...),...]_{X_2Y_3} \\
&= [x_1(\rho(X_i;...),...)]_{Y_2X_3},
\end{aligned} \tag{2.8a}$$

together with the analogous conditions for x_2, x_3, y_1, y_2 and y_3. The subscript X_2X_3 represents the condition that ρ_2 and ρ_3 are assigned determinate values, and these values are allowed to be *any* values such that σ_x^2 is chosen and performed in R_2 and σ_x^3 is chosen and performed in R_3. The other subscripts are defined analogously.

Conditions (2.8a) would be satisfied if the light–cone conditions mentioned above were to be satisfied: the determinate value appearing under condition X_1 would then be independent of whether X_2 or Y_2 would be chosen by the becoming determinate of ρ_2, and of whether X_3 or Y_3 would be chosen by the becoming determinate of ρ_3.

The locality premise of the reformulated theorem is similar to (2.8a). It asserts that: "Under any condition X_1

$$[x_1]_{X_2X_3} = [x_1]_{Y_2Y_3} = [x_1]_{X_2Y_3} = [x_1]_{Y_2X_3}." \tag{2.8b}$$

The analogs for $x_2, ..., y_3$ are also demanded. The meaning and rationale of these conditions will now be described.

What is under consideration here is one single experimental situation in which choices are about to be made that will determine which measurements are to be performed in the three regions. The condition "Under any condition X_1" stands for: "If an experimental procedure for measuring σ_x^1 were to be chosen in R_1, and this procedure were to be carried out". Under this condition, according to our reality premise, some determinate outcome, either +1 or −1, must be selected in R_1. This outcome is not predetermined, and it could logically depend upon which measurements will later, in some frame of reference, be chosen and performed in the other two regions. However, the condition that there be no faster-than-light influence of any kind can be taken to mean that, as far as processes in R_1 are concerned, it is as if these choices to be made in R_2 and R_3 do not exist. Thus, in the realm of theoretically allowed possibilities, there are not several alternative possible selections in R_1, corresponding to the various alternative possible choices that might later be made in R_2 and R_3, and hence a logical possibility that these various selections could be different. There is, logically, insofar as these differences in future choices are concerned, just one selection of one outcome.

The subscript X_2X_3 on the first term in (2.8b) represent the conditions: "If a procedure for measuring σ_x^2 were to be chosen and carried out in R_2, and if a procedure for measuring σ_x^3 were to be chosen and carried out in R_3". The other subscripts have analogous meanings.The various subscripts in (2.8b) refer, therefore, to alternative possible measurments that cannot be simultaneously performed.

Quantum theory warns us to be wary of such situations. However, it does not inveigh against the idea that if a measurement of σ_x^1 were to be performed then some determinate outcome would be selected, and that this selection cannot depend upon choices that have not yet been made, and hence do not yet exist.

Deterministic theories often entail rigid connections among outcomes associated with alternative possible future conditions. Thus the logical situation engendered by the no–faster–than–light influence assumption is somewhat similar to the one encountered in deterministic theories. However, there is a crucial difference: the demand (2.8b) specifies that the outcomes selected under the various alternative possible conditions indicated there must be the *same* outcome, without entailing that this single outcome be predetermined.

To formalize the conditions represented by (2.8b) we shall appropriate the machinery normally employed within the context of deterministic theories, where one can contemplate rigid theoretical connections among outcomes associated with alternative possible measurements. But we will use this machinery in a way that does not entail predetermined outcomes. Thus the first part of (2.8b) will be expressed, in part, by the assertion:

"Under any condition X_1, if $[(X_2 X_3)$ and $(x_1 = +1]$ then [if $(Y_2 Y_3)$ then

$$(x_1 = +1)]" \tag{2.8c}$$

In words this says: "If X_1 were to be chosen then: if [X_2 and X_3 were to be chosen and x_1 were to be +1] then [if, *instead*, Y_2 and Y_3 were to be chosen then x_1 would be +1]".

This assertion imposes the theoretical demand that the outcomes selected in R_1 under the alternative possible conditions in $R_2 \cup R_3$ be the *same* outcome, without implying that this single outcome be predetermined. The word "would" that occurs in the verbal equivalent of (2.8c) is not a consequence of any use of physical determinism. It imposes the no–faster–than–light–influence condition that the selection in R_1 be made without reference to future free choices. The *lack of dependence* of a stochastically made selection upon future free choices is not determinism.

A compact expression of (2.8c), generalized to include also the possible outcome -1, is this:

$$((X_1 X_2 X_3)\text{and}(x_1 = p)) \Rightarrow ((X_1 Y_2 Y_3) \Rightarrow (x_1 = p)). \tag{2.8d}$$

Some other parts of (2.8b) that will be used in the ensuing proof are, in this compact notation,

$$((Y_1X_2X_3)\text{and}(x_2x_3 = -p)) \Rightarrow ((X_1X_2X_3) \Rightarrow (x_2x_3 = -p)) \qquad (2.8e)$$

and

$$((X_1Y_2Y_3)\text{and}(y_2y_3 = p)) \Rightarrow ((Y_1Y_2Y_3) \Rightarrow (y_2y_3 = p)). \qquad (2.8f)$$

We turn now to the proof. The first two predictions of quantum theory, (2.2) and (2.3), assert that

$$(X_1X_2X_3) \Rightarrow (x_1x_2x_3 = -1) \qquad (2.9)$$

and

$$(X_1Y_2Y_3) \Rightarrow (x_1y_2y_3 = +1). \qquad (2.10)$$

Accepting these two conditions, and also (2.8d), we obtain the following sequence of syllogisms:

$$\begin{aligned}
&((\ X_1X_2X_3) \text{ and } (x_2x_3 = -p))\\
&\quad \Rightarrow ((X_1X_2X_3) \text{ and } (x_1x_2x_3 = -1) \text{ and } (x_2x_3 = -p))\\
&\quad \Rightarrow ((X_1X_2X_3) \text{ and } (x_1 = p))\\
&\quad \Rightarrow ((X_1Y_2Y_3) \Rightarrow ((x_1y_2y_3 = 1) \text{ and } (x_1 = p)))\\
&\quad \Rightarrow ((X_1Y_2Y_3) \Rightarrow (y_2y_3 = p)). \qquad (2.11)
\end{aligned}$$

Thus our premises (2.9), (2.10), and (2.8d) entail that

$$((X_1X_2X_3) \text{ and } (x_2x_3 = -p)) \Rightarrow ((X_1Y_2Y_3) \Rightarrow (y_2y_3 = p)). \qquad (2.12)$$

In words, this result asserts that:

Under any condition X_1, if X_2 and X_3 were to be chosen and the product of the then-determinate values x_2 and x_3 were to be $-p$ then, if, *instead*, Y_2 and Y_3 were to be chosen, the product of the then-determinate values y_2 and y_3 would be p.

This theoretical condition, which relates outcomes allowed under alternative possible conditions, is *directly entailed* by our premises: if it were to fail then the determinate value x_1 would be *forced to depend* upon which measurements are later to be chosen in $R_2 \cup R_3$.

The no-faster-than-light influence conditions entail that the condition X_1 can be omitted from (2.12). Indeed, by using (2.8e), (2.12), and (2.8f) one obtains the sequence of syllogisms

$$\begin{aligned}
&((Y_1 X_2 X_3) \text{ and } (x_2 x_3 = -p)) \\
&\quad \Rightarrow ((X_1 X_2 X_3) \Rightarrow (x_2 x_3 = -p)) \\
&\quad \Rightarrow ((X_1 X_2 X_3) \Rightarrow ((X_1 X_2 X_3) \text{ and } (x_2 x_3 = -p))) \\
&\quad \Rightarrow ((X_1 X_2 X_3) \Rightarrow ((X_1 Y_2 Y_3) \Rightarrow (y_2 y_3 = p))) \\
&\quad \Rightarrow ((X_1 X_2 X_3) \Rightarrow ((X_1 Y_2 Y_3) \Rightarrow ((X_1 Y_2 Y_3) \text{ and } (y_2 y_3 = p)))) \\
&\quad \Rightarrow ((X_1 X_2 X_3) \Rightarrow ((X_1 Y_2 Y_3) \Rightarrow ((Y_1' Y_2 Y_3) \Rightarrow (y_2 y_3 = p)))). \qquad (2.13)
\end{aligned}$$

The sequence, in the last line, "then if X_1 were to be chosen instead of Y_1, then if $Y_2 Y_3$ were to be chosen instead of $X_2 X_3$, then if Y_1' were to be chosen instead of X_1" can be shortened to "then if $Y_1' Y_2 Y_3$ were to be chosen instead of $Y_1 X_2 X_3$". One special case is that in which Y_1' is the same as the original Y_1. In this case (2.13) becomes

$$((Y_1 X_2 X_3) \text{ and } (x_2 x_3 = -p)) \Rightarrow ((Y_1 Y_2 Y_3) \Rightarrow (y_2 y_3 = p)), \qquad (2.14)$$

which is (2.12) with X_1 replaced by Y_1. Thus the two results together have the precondition "If (X_1 or Y_1)". But X_1 and Y_1 are the only possibilities considered in R_1. Thus this precondition can be omitted. This yields

$$((X_2 X_3) \text{ and } (x_2 x_3 = -p)) \Rightarrow ((Y_2 Y_3) \Rightarrow (y_2 y_3 = p)). \qquad (2.15)$$

The second two predictions of quantum theory, (2.4) and (2.5), yield, in the same way,

$$((Y_2 X_3) \text{ and } (y_2 x_3 = q)) \Rightarrow ((X_2 Y_3) \Rightarrow (x_2 y_3 = q)). \qquad (2.16)$$

Condition (2.15) entails that

$$\begin{aligned}
&[(X_2 \text{ and } (x_2 = m)) \text{ and } (X_3 \text{ and } (x_3 = n))] \\
&\quad \Rightarrow [(Y_2 Y_3) \Rightarrow (y_2 y_3 = -mn)] \\
&\quad \Rightarrow [(Y_2 \text{ and } (y_2 = r)) \Rightarrow (Y_3 \Rightarrow (y_3 = -mnr)). \qquad (2.17)
\end{aligned}$$

This entails that

$$[X_2 \text{ and } (x_2 = m))] \Rightarrow [((X_3 \text{ and } (x_3 = n)) \text{ and } (Y_2 \text{ and } (y_2 = r))) \Rightarrow (Y_3 \Rightarrow (y_3 = -mnr))] \quad (2.18)$$

On the other hand, (2.16) entails that

$$[(X_3 \text{ and}(x_3 = n)) \text{ and } (Y_2 \text{ and } (y_2 = r))] \Rightarrow [(Y_3 \text{ and } (y_3 = -mnr)) \Rightarrow (X_2 \Rightarrow (x_2 = -m))]. \quad (2.19)$$

Insertion of this relationship into (2.18) entails that

$$[X_2 \text{ and } (x_2 = m)] \Rightarrow [((X_3 \text{ and } (x_3 = n)) \text{ and } (Y_2 \text{ and } (y_2 = r))) \Rightarrow (Y_3 \Rightarrow (X_2' \Rightarrow (x_2' = -m)))]. \quad (2.20)$$

The numbers n and r are arbitrary, and do not appear elsewhere. Thus, by virtue of our reality premise, which demands that if X_3 were to be chosen then some outcome $x_2 = \pm 1$ must be selected, and that if Y_2 were to be chosen then some outcome $y_2 = \pm 1$ must be selected, we may omit the conditions "and $(x_3 = n)$" and " and $(y_2 = r)$". This simplification reduces (2.20) to

$$[X_2 \text{ and } (x_2 = m)] \Rightarrow [(X_3 Y_2) \Rightarrow (X_2' \Rightarrow (x_2' = -m))] \quad (2.21a)$$

In words, this asserts that:

"If some X_2 were to be chosen and the selected outcome were to be $x_2 = m$, then if some X_3 were to be chosen, and if, instead of X_2, *any* Y_2 were to be chosen, then if, instead of X_3, *any* Y_3 were to be chosen, then if, instead of Y_2, *any* X_2' were to be chosen then the selected outcome must be $x_2' = -m$" (2.21b)

The primes on the final X_2' and x_2' are inserted to distinguish them from the original X_2 and x_2. The words "*any*" have been inserted to emphasize that this result is required to hold no matter which of the conceivable alternative possible procedures for measuring the indicated quantity is chosen. For example, in our models, different determinate values of ρ_i, or its analogs in the GRW and Bohm models, could create nonidentical experimental conditions corresponding to a measurement of, say, σ_y^i, and these nonidentical conditions might lead to different outcomes: this is allowed, *a priori.*

The construct "if *any* Y_2 were to be chosen instead of X_2", and the other similar ones in (2.21b), were introduced as parts of a formalization of the delicate concept that certain outcomes are nonpredetermined yet independent of choices to be made later. This purely logical construct involves no physical sequence of choices of alternative possibilities: the alternative possibilities all exist on a par. No possibility can be destroyed by drawing from it a conclusion about what would, by virtue of a certain relationship of sameness, hold if, instead, some other possibility were to be chosen. Consequently, the fact that under some condition X_2 the outcome $x_2 = m$ could appear, which is ensured by the initial condition in (2.21), cannot be destroyed by the logical acts of considering some alternative measurements. Thus the *possibility* that X_2' *could be* the same as X_2, and that x_2' *could be* the same as x_2, cannot be destroyed by the intermediate logical steps in (2.21).

We now make explicit the final assumption, which is that the choices of which measurement are to be performed are fixed by variables that are initially indeterminate, so that all of the alternative possibilities are allowed. This assumption was, in fact, part of the requirement for a general selection process. This assumption means that the initial assumption in (2.21) can be satisfied for some m, and that the intermediate conditions can be satisfied. But then (2.21) yields a contradiction. For the logical acts of considering the alternative possibilities cannot destroy the possibility, that the final X_2' could be the same as the initial X_2, and that the outcome selected under that final condition X_2' could be $x_2' = m$. This contradicts the conclusion, asserted by (2.21), that x_2' must be $-m$.

The conclusion is that the following four conditions cannot be simultaneously enforced:

1. Indeterminate Choices
2. Macroscopic Physical Realism

3. No Faster-Than-Light Influence of any Kind.

4. Validity of the Predictions of Quantum Theory

The first and second assumptions provide the variable causes and determinate effects need to formulate clearly the no-faster-than-light- influence assumption. The operative parts of these first two assumptions, in the context of the proof, are contained in the premise that a general selection process is acting.

This conclusion is fundamentally different from the conclusion of either Bell's original theorem, or arguments based on the EPR criterion of physical reality. Those conclusions are essentially that certain classical conceptions of reality must fail. The present conclusion is that some property that is not contrary to the quantum precepts, and that is widely accepted by quantum physicists, must fail

The result derived here is completely understandable. The proof merely confirms a fact that could have been anticipated from the beginning, namely that one cannot mutilate the integrity of the basic mathematical structure of quantum theory, as represented in its unitary covariant law of evolution, by superposing the alien "collapse of the wave function", without disrupting the property of no faster–that–light influence. To retain this property one must retain the parallel observers demanded by the unitary law of evolution. If this is done, and attention is paid to the central fact of the interpretation of quantum theory, which is that the probabilities it defines are probabilities for the formation of *combined records* of all the facts being correlated, and that these combined records can be formed only by bringing the records of the separate facts together in the intersection of the forward light–cones of the regions in which these facts are generated, then the predictions of quantum theory are readily seen to arise from superposition of amplitudes without recourse to faster–than–light influences.

In particular, if one writes x_i^+ and x_i^- as normalized solutions of $\sigma_x^i x_i^\pm = \pm x_i^\pm$, and expresses the spin state ψ in the forms appropriate to the four experiments, namely as

$$\frac{1}{4}\Big[(x_1^+ + x_1^-)(x_2^+ + x_2^-)(x_3^+ + x_3^-)$$

$$- (x_1^+ - x_1^-)(x_2^+ - x_2^-)(x_3^+ - x_3^-)\Big]$$

$$= \frac{1}{2}\Big[x_1^- x_2^+ x_3^+ + x_1^+ x_2^- x_3^+ + x_1^+ x_2^+ x_3^-$$

$$+ x_1^- x_2^- x_3^-\Big]$$

and

$$\frac{1}{4}\Big[(x_1^+ + x_1^-)(y_2^+ + y_2^-)(y_3^+ + y_3^-)$$

$$+ (x_1^+ - x_1^-)(y_2^+ - y_2^-)(y_3^+ - y_3^-)\Big]$$

$$= \frac{1}{2}\Big[x_1^+ y_2^+ y_3^+ + x_1^+ y_2^- y_3^-$$

$$+ x_1^- y_2^+ y_3^- + x_1^- y_2^- y_3^+\Big],$$

and its two cyclic counterparts, and recognizes that in the unitary evolution each spin state will be converted into the corresponding macroscopic state of the observer, then one sees that the quantum predictions arise from a superposition–principle cancellation, completely incomprehensible from the classical point of view, between certain combinations of the *macroscopic* states of the parallel observers. Even though these states are macroscopic their cancellations will not be disrupted by the uncontrollable phases associated with macroscopic states, for these phases, though uncontrolled, are common.

3. Ontic Probabilities, Historical Records, and Many–Minds

The conclusion of the foregoing section is that, within an indeterministic setting in which choices among possible measurements are indeterminate, one cannot reconcile the idea that the predictions of quantum theory are valid with the ideas that: (1), there are no faster-than-light influences of any kind; and, (2), the outcome of any local measurement would become determinate if the measurement were to be performed. Any rationally coherent model of nature must violate at least one of these four conditions. Each of the four options contradicts an intuition derived either from our direct experience of the world, or from our experience with earlier partially successful theories. The intuitions derived from earlier partially successful theories are probably the more likely to prevail: much of the history of philosophy is a warning to be wary of our direct intuitions, whereas in the progression of physical theories, from classical theory, to relativity theory, to quantum theory, each successive theory is partially incorporated into its successors, and hence presumably captures certain essential features of an eventual full scientific understanding of nature. This consideration suggests that a cohesive, comprehensive, and rationally coherent model of nature is more likely to emerge from adherence to the basic principle of relativistic quantum theory, namely covariant unitary evolution, than from adherence to the principle of macroscopic physical realism.

Relativistic quantum theory is fundamentally probabilistic: it has probabilities built into its basic structure. This elevation, by quantum theory, of probability to fundamental status highlights the severe difficulties that have plagued the efforts of mathematicians and philosophers to make the concept of probability absolutely clear within the context of classical ideas about nature.

What does it mean to say that the outcome of coin flip has a 51% probability to be heads and a 49% probability to be tails? It means, of course, that, if one were to do a large number, n, of identical coin flips, then the probability that there would be m heads and $n-m$ tails would be $(.51)^m(.49)^{n-m}n!/m!(n-m)!$. But this answer just shifts the question to that of the meaning of this latter probability.

One can assign *epistic* meanings in these cases of large numbers of identical processes by introducing the vague idea that if the relative probability of some possibility in a situation that will occur only once is "almost zero" then we can be "almost certain" that this possibility will not occur. Alternatively, one can define an epistic probability by *imagining* the unrealizable possibility of an infinite number of repetitions of the stochastic process. But the question is then: What is the *ontic*, or ontological, basis of the concordance of our usual experiences with these epistic concepts?

One approach to this question is illustrated by the Bohm pilot-wave model. At some initial time, the beginning of the universe, the wave function is suppose to have some definite form, and then *the single classical world* (which in this model is assumed to exist) is supposed to be fixed at some *single initial position* in accordance with the probability density specified by the wave function. But it makes no sense, ontologically, to say that the one single world is placed at one single position in accordance with a smeared-out probability distribution. To make ontic sense of this idea one would have to introduce an infinite number of alternative possible worlds, and distribute them in accordance with this rule. But that would bring back the many worlds that the theory was supposed to eliminate. The GRW model is faced with a similar difficulty.

The logical situation, therefore, is that quantum theory itself, to the extent that the quantum state is assigned ontic status, has ontic probabilities built into it. But if one disrupts the theory by introducing a selection process, in order to bring the model into line with our intuitions about macroscopic physical realism, then, although epistic meanings can be introduced by contemplating, in our imagination, an infinite number of copies of the system, the ontic foundation of probability becomes lost: the original indeterministic-probabilistic theory is replaced by a quasi-classical deterministic theory, supplemented by an irrational probability idea in which the ontic probabilities are expressed in terms of things that do not exist. However, if one foregoes macroscopic physical realism then one can retain a rational concept of ontic probability, and, at the same time, exclude the need for faster-than-light influences.

In quantum theory the natural carriers of ontic probabilities are historical records. To explain the meaning of this statement we begin by considering the concept of a record. The importance of records to the understanding of quantum theory has often been emphasized.

A proto-type record is a magnetic tape with a sequence of locations, labelled by an index i, such that each location is either magnetized or unmagnetized; or a book with a sequence of locations, specified by an index i, such that each location is either blank, or contains a symbol 1. Naturally occurring records can also be considered, but we focus on these man-made ones.

Let P_i be the projection operator that projects onto states of the universe in which:

1. A record, say a tape or book, is present in a nondestructive environment, and
2. Location i is magnetized, or contains the symbol 1.

The operator $\overline{P}_i$ projects onto states where this same tape or book is present in the nondestruative environment, but the location i is unmagnatized, or does not contain the symbol 1. Thus $P_i\overline{P}_i = 0$, and $[P_i, \overline{P}_i] = 0$. The symbol R_i will stand for either P_i or $\overline{P}_i$.

We employ the Heisenberg representation in which the state of the universe is a fixed state Ψ, and each operator P_i refers to some particular time.

The defining properties of records are:

A. Quasi-Stability:

$$P_i\Psi = P_i'\Psi$$

B. Copiability:

$$P_i\Psi = P_{j(i)}'\Psi$$

C. Combinability:

$$P_i'\Psi = P_{k(i)}\Psi$$

$$P_i''\Psi = P_{j(i)}\Psi.$$

In the quasi-stability property the operators P_i and P_i' are supposed to refer to perceptibly different times, and to be, at those different times, projectors onto the states in which the specified physical property (e.g., a symbol 1 in position i) holds.

The copiability property specifies that there are physical mechanisms that can create new records that are the same, insofar as information content is concerned, as the original record.

The combinability property specifies that there are physical mechanisms that can combine the information content of the two records into a single record.

An essential point, here, is that, due to interactions with the environment, the projector P_{12}^S onto a superposition $\varphi_1 + e^{i\psi}\varphi_2$ of eigenstates of two projectors P_1 and P_2 of the proto-type kind would not specify a record: the quasi-stability property of such a projector would be violated. However, the sum $P_{12} = P_1 + P_2$ satisfies the defining characteristics of the projection operators that define records.

An *historical record* is a record existing at one time that is a combination of records created at different times. An example is a history book, or a scientist's laboratory notebook, containing replications of records made at different times during the course of an experiment, and containing, therefore, information about preparations and outcomes originally represented by records that may no longer exist.

The ontic probability postulate is this:

Suppose P_I is a projector such that $P_I\Psi \neq 0$ represents a part of the universe in which there is an historical record R that records the fact that some system was prepared in a certain way, and that a certain measurement was subsequently performed upon it, and that a record of the experiment and its outcome would be formed regardless of which outcome of the measurement eventually turns up. Let P_F be the projector on the record of one of the possible outcomes of the measurement. Then

$$\mathrm{Prob}(P_F : P_I) = \langle P_F P_I \rangle / \langle P_I \rangle$$

is the probability that, under the conditions specified by $P_I = 1$, the historical record R contains the record of the outcome specified by $P_F = 1$. Here $\langle\ \rangle$ represents expectation value in the state Ψ.

This postulate refers to nothing that does not exist: it refers only to existing historical records; it refers to nothing existing only earlier, or only later, or in anyone's imagination. It refers to an *ontic* probability.

In accordance with the meaning of probability, if $\mathrm{Prob}(P_F : P_I) = 0$ then the historical record R cannot contain a record of the result specified by $P_F = 1$.

To develop the meaning of ontic probability we examine some of its further properties.

Consider a typical Stern-Gerlach type of measurement. Suppose the preparation corresponds to preparing the spin in the plus x direction. Then the condition on the associated historical record is

$$P_I\Psi = \frac{1}{2}(\sigma_x + 1)P_I\Psi.$$

The operator P_I acts directly on the historical record, but the operator $\frac{1}{2}(\sigma_x+1)$ acts on the spin state of the particle just after the preparation. The above equation represents the fact that the historical record records the fact that the initial spin state was the one for which $\sigma_x = +1$.

Let P_I represent also the condition that the component in the z direction was later measured, but no assertion about the outcome of that later measurement. Then the two possibilities for the record of this outcome are specified by projectors P_1 and P_2, where

$$P_1 P_I \Psi = \frac{1}{2}(\sigma_z + 1) P_I \Psi \qquad P_1 \epsilon \{R_i\}$$

and

$$P_2 P_I \Psi = \frac{1}{2}(\sigma_z - 1) P_I \Psi \qquad P_2 \epsilon \{R_i\}$$

One may then compute

$$\begin{aligned}
&\text{Prob}(P_1 : P_I) \\
&= \langle P_1 P_I \rangle / \langle P_I \rangle \\
&= \langle P_I P_1 P_1 P_I \rangle / \langle P_I \rangle \\
&= \frac{\langle P_I \frac{1}{2}(\sigma_x + 1) \frac{1}{2}(\sigma_z + 1) \frac{1}{2}(\sigma_z + 1) \frac{1}{2}(\sigma_x + 1) P_I \rangle}{\langle P_I \frac{1}{2}(\sigma_x + 1) P_I \rangle} \\
&= \frac{1}{2}
\end{aligned}$$

and, likewise,

$$\text{Prob}(P_2 : P_I) = \tfrac{1}{2}.$$

One may also compute

$$\begin{aligned}
&\text{Prob}(P_1 P_2 : P_I) \\
&= \langle P_1 P_2 P_I \rangle / \langle P_I \rangle \\
&= \langle \frac{1}{2}(\sigma_z + 1)) \frac{1}{2}(\sigma_z - 1) P_I \rangle / \langle P_I \rangle \\
&= 0
\end{aligned}$$

This result implies that the historical record cannot contain both the record that affirms that the outcome of the σ_z measurement was $+1$ and the record that affirms that the outcome of the σ_z measurement was -1.

The results obtained above show that the historical record of the experiment has the following three properties: (1), the historical record does not contain both a record of the fact that outcome $\sigma_z = +1$ occurred and a record of the fact that the outcome $\sigma_z = -1$ occurred; (2), the probability is $\frac{1}{2}$ that the historical record contains a record of the fact that outcome $\sigma_z = +1$ occurred; and (3), the probability is $\frac{1}{2}$ that the historical record contains a record of the fact that the outcome $\sigma_z = -1$ occurred.

By deriving these properties we have, for our simple example, *derived the von Neumann reduction postulate* in an ontic, or ontological, framework in which the unitary law of evolution is strictly maintained. In particular, even though the unitary law of evolution is maintained, the historical record contains a record of the fact that either one *or* the other outcome occurred, *not both*, and each of the two alternative possibilities has probability $\frac{1}{2}$.

How is this result connected to our experience? To answer this question one needs a theory of the mind-brain connection, since the theory presented above deals only with the physical aspects of nature.

A quantum theory of the mind-brain connection has been developed elsewhere.[18] The essential point of that theory is the feature that conscious mental process is an *isomorphic image* of the process in the brain that creates the physical basis of memory. That brain process consists precisely of the creation of a sequence of historical records, and each conscious experience is an isomorphic image within the psychological domain of an historical record created in the brain.

Given this theory of the mind-brain connection, the relationship of the foregoing physical theory to experience is direct: the perception by the human observer of the external historical record creates within the brain an historical record that is an image of the external historical record. This brain process is accompanied by an experience that is an isomorphic image of that latter historical record. But in this case the results obtained earlier at the physical level carry directly over to experience: the experience will correspond to a recording of one or the other of the two alternative possible outcomes, not both, and each possibility will have weight $\frac{1}{2}$.

The unitary law of evolution is retained here. Thus there will be two historical records generated, one with a recording of the outcome $\sigma_z = +1$, and the other with a recording of the outcome $\sigma_z = -1$. But what does it mean to say that each of these two alternatives has probability $\frac{1}{2}$ if both alternatives "occur", in an absolute sense.

Actually, the real logical problem is with the "classical" case, in which only one of the two alternatives occurs: in that classical case there are severe logical difficulties. But if *both* of the alternatives have ontic status then it is no longer necessary to explain what *does* exist in terms of what *does not exist*, and the question of the meaning of ontic probably becomes tractable.

Major problems in science are often resolved together. There was already in classical physics a problem with "time": the existing world was conceived to occupy a zero–duration time slice separating a nonexistent past from a nonexistent future. This ontology was troubling to philosophers: Bergson, for example, upheld the idea that the existing present moment has finite "duration". Classical relativity theory went to the other extreme: it had no natural place at all for the present "now"; the contents of entire spacetime continuum was spread out in an ontologically uniform way.

Relativistic quantum theory, as described in the Heisenberg representation, again laid out they contents of the entire spacetime continuum in a uniform way: there was no special place "now".

This difficulty was resolved in the Copenhagen epistemological interpretation by bringing in the experiences of observers, and, in models having a selection process, by bringing in the sequence of selection events, each of which is represented within the theory by a change in the otherwise–fixed Heisenberg state of the universe. Here, however, we seek an ontic solution with no selection of unique determinate outcome.

In the context of the probability issue there is the related question of "occurrences" or "happenings": probabilities are generally probabilities for something to "occur". But in relativistic quantum theory, without the Copenhagen addendum, or a selection process of some sort, there is no notion of any occurrence: the whole spacetime structure of probabilities is simply laid out in a uniform way, with no indication of what the probabilities are probabilities *of*.

There is a further related problem: a comprehensive model of nature must have counterparts of all things that are known to exist. But the only things really known to exist are human experiences. This aspect of reality is left out of the wave function of quantum theory, but cannot be left out of a comprehensive model of nature.

These various problems are resolved together if one identifies "occurrences" or "happenings" with mental events, and specifies that it is *these* occurrences that are governed by the ontic probabilities. In this case, if unitary evolution is maintained, there will be a mental event corresponding to the formation in the brain of each of the alternative possible memory–type historical records, and the relative probabilities that quantum theory assigns to these alternative possible historical records can be interpreted in terms of the idea of a splitting of experiential reality into separately experienced branches. Indeed, as described and explained in detail in ref. 18, each "present experience" is directly experienced as a temporal process imbedded in a context that can cover long periods of time, and there is an intuitive feeling that the occurring experience is picked from among many alternative possibilities . This intuition is, from the point of view of unitary quantum theory, valid: any experienced succession of events is just one experienced succession from among many that co–exist with it in an absolute sense. The relative probability that quantum theory ascribes to any specified one of these alternative experiential sucessions, within a specified collection of such successions, is just the relative probability that a single experiential succession, picked randomly from this collection, will be that specified one.

The above remarks are, in my opinion, completely in line with the views set forth by Everett, and constitute merely a slight elaboration upon them. I have sought, here, by providing philosophic perspective, and focus on key points, to defend the thesis that those ideas, taken in conjunction with the description of the mind-brain connection set forth in ref. 18, provide a natural and reasonable basis for both a satisfactory resolution of the measurement problem in quantum theory and a cohesive, comprehensive, and rationally coherent conception of the nature of the world in which we live.

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References

1. B.C. van Fraassen, *The model interpretation of quantum theory*, in this volume.

2. J. von Neumann, *Mathematical Foundations of Quantum Mechanics*, (Princeton U.P., Princeton N.J., 1955) Ch. V and VI.

3. H.D. Zeh, *Foundations of Physics* **1** (1970) 69.

4. W.H. Zurek, *Annals of the New York Academy of Sciences* **480** (1986) 89.

5. E. Joos, *Annals of the New York Academy of Sciences 480* (1986) 6, and (with H.D. Zeh), *Z. Phys.* **B59** (1985) 223.

6. P. Mittelstaedt, *The objectification in the measuring process and the many-worlds interpretation*, in this volume.

7. P. Busch, *Macroscopic quantum systems and the objectification problem*, in this volume.

8. N. Bohr, *Atomic Physics and Human Knowledge*, (Wiley, New York, 1958) pp.64, 71, 90; *Essays 1958-1962 on Atomic Physics and Human Knowledge*, (Wiley, New York, 1963) p.60.

9. H.P. Stapp, *Amer. J. Phys.* **40** (1972) 1098.

10. G. Ghirardi, A. Rimini, and T. Weber, *Phys. Rev.* **D 34** (1986) 470.

11. P. Pearle, *Phys. Rev.* **A39** (1989) 2277.

12. D. Bohm, *Phys. Rev.* **85** (1952) 166.

13. H. Everett, *Rev. Mod. Phys.* **29** (1957) 452.

14. D.M. Greenberger, M. Horne, and A. Zeilinger, in *Bell's Theorem, Quantum Theory, and Conceptions of the Universe*, ed. M. Kafatos, (Klumer Academic Press, Dordrecht, 1989). N. David Mermin, *Physics Today*, June 1990, p.9.

15. J.S. Bell, *Physics* **1** (1964) 195.

16. J.F. Clauser and A. Shimony, *Rept. Prog. Phys.* **41** (1978) 1881.

17. J.P. Jarrett, *Nous, 18* (1984) 569.

18. H.P. Stapp, *A Quantum Theory of the Mind-Brain Interface*, Lawrence Berkeley Laboratory Report LBL-28574 EXPANDED.

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