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Theoretical model of a purported empirical violation of the predictions of quantum theory

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A generalization of Weinberg's nonlinear quantum theory is used to model a reported violation of the predictions of orthodox quantum theory.

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I. INTRODUCTION

This work concerns the possibility of causal anomalies. By a causal anomaly I mean a theoretical or empirical situation in which the occurrence or nonoccurrence of an observable event at one time must apparently depend upon a *subsequently* generated (pseudo) random number, or willful human act.

Considerations of the Einstein-Podolsky-Rosen [1] and Bell's-Theorem [2] type entail [3]—if many-world's interpretations are excluded—the occurrence of causal anomalies on the theoretical level, provided certain predictions of quantum theory are at least approximately valid. However, those anomalies cannot manifest on the empirical level if the quantum predictions hold exactly [4]. On the other hand, slight departures from the exact validity of the quantum predictions [5] could lead to small but observable causal anomalies [6].

Empirical causal anomalies have been reported in the past in experiments that appear, at least superficially, to have been conducted in accordance with scientific procedures [7], and the protocols are becoming ever more stringent [8]. I do not enter into the difficult question of assessing the reliability of these reports. The scientific community generally looks upon them with skepticism. But at least part of this skepticism originates not from specific challenges to the protocols and procedures of the works of, for example, Jahn, Dobyns, and Dunne [7], but from the belief that such results are not compatible with well-established principles of physics, and hence to be excluded on theoretical grounds. However, it turns out that small modifications of the standard quantum principles would allow some of the most impossible sounding of the reported phenomena to be accommodated. According to the report in Ref. [8], it would appear that in certain experimental situations willfull human acts, selected by pseudorandom numbers generated at one time, can shift, relative to the randomness predicted by normal quantum theory, the timings of radioactive decays that were detected and recorded months earlier on floppy discs, but that were not observed at that time by any human observer. Such an influence of an observer backward in time on atomic events seems completely at odds with physical theory. However, a slight modification of normal quantum theory can accommodate the reported data. In the scientific study of any reported phenomena it is hard to make progress without a theoretical description that ties them in a coherent way into the rest of physics.

The purpose of the present work is to construct, on the basis of an extension of Weinberg's nonlinear generalization of quantum theory [5], a theoretical model that would accommodate causal anomalies of the kind described above. Specifically, the present work shows that the reported phenomena, although incompatible with the main currents of contemporary scientific thought, can be theoretically modeled in a coherent and relatively simple way by combining certain ideas of von Neumann and Pauli about the interpretation of quantum theory with Weinberg's nonlinear generalization of the quantum formalism.

II. THE THEORETICAL MODEL

To retain the mathematical structure of quantum theory *almost* intact, I shall exploit the ideas of von Neumann [9] and Pauli [10], according to which the von Neumann process number 1 (reduction of the wave packet) is physically associated with the mental process of the observer. It is interesting that two of our most rigorous-minded mathematical physicists should both be inclined to favor an idea that is so contrary to our normal idea of the nature of the physical world. Most physicists have, I think, preferred to accept the common-sense idea that the world of *macroscopic* material properties is factual: e.g., that the Geiger counter either fires or does not fire, independently of whether any observer has witnessed it; and that the mark on the photographic plate is either there or not there, whether anyone observes it or not. Yet it is difficult to reconcile this common-sense intuition with the mathematical formalism of quantum theory. For there is in that structure no natural breakpoint in the chain of events that leads from an atomic event that initiates the chain to the brain event associated with the resulting observational experience. From the perspective of the mathematical physicist the imposition of a breakpoint

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at any purely physical level is arbitrary and awkward: it would break the close connection between mathematics and the physical world in a way that is mathematically unnatural, and moreover lacks any empirical or scientific justification. From a purely logical perspective it seems preferable to accept the uniformity of nature's link between the mathematical and physical worlds, rather than to inject, without any logical or empirical reason, our notoriously fallible intuitions about the nature of physical reality.

Following, then, the mathematics, instead of intuition, I shall adopt the assumption that the Schrödinger equation holds uniformly in the *physical* world. That is, I shall adopt the view that the physical universe, represented by the quantum state of the universe, consists merely of a set of tendencies that entail statistical links between mental events.

In fact, this point of view is not incompatible with the Copenhagen interpretation, which, although epistemological rather than ontological in character [11], rests on the central fact that in science we deal, perforce, with connections between human observations: the rest of science is a theoretical imagery whose connection to reality must remain forever uncertain.

According to this point of view, expressed however in ontological terms, the various possibilities in regard to the detection of a radioactive decay remain in a state of "possibility" or "potentiality," even after the results are recorded on magnetic tape: no reduction of the wave packet occurs until some pertinent mental event occurs.

By adopting this non-common-sense point of view, we shift the problem raised by the reported results from that of accounting for an influence of willful thoughts occurring at one time upon radioactive decays occurring months earlier to the simpler problem of accounting for the biasing of the probabilities for the occurrence of the thoughts themselves, i.e., a biasing relative to the probabilities predicted by orthodox quantum theory.

This latter problem is manageable: Weinberg [5] has devised a nonlinear quantum mechanics that is very similar to quantum theory, but that can produce probabilities that are biased, relative to the probabilities predicted by linear quantum mechanics. Gisin [6] has already pointed out that Weinberg's theory can lead to causal anomalies.

According to the interpretation of quantum theory adopted here, the mechanical recording of the detection of the products of a radioactive decay generates a separation of the physical world into a collection of superposed "channels" or "branches": the physical world, as represented by the wave function of the universe, divides into a superposition of channels, one for each of the different possible recorded (but unobserved) results. Contrary to common sense the recorded but unobserved numbers remain in a state of superposed "potentia," to use the word of Heisenberg. Later, when the human observer looks at the device, the state of his brain will separate into a superposition of channels corresponding to the various alternative macroscopic possibilities, in the way described by von Neumann [9]. Finally, when the *psychological* event of observation occurs, the state of the universe will be reduced by a projection onto those brain states that are singled out by the conscious experience of the observer [12].

If the probabilities associated with the various alternative possibilities for the brain state are those given by orthodox quantum theory, then there can be no systematic positive bias of the kind reported: the probabilities associated with the alternative possible brain events will necessarily, according to the orthodox theory, as explained by von Neumann, agree with those that were determined earlier from the probabilities of the alternative possible detections of radioactive decays: there could be no biasing of those probabilities due to a subsequent willful intent of an observer. However, a generalization of Weinberg's nonlinear quantum mechanics allows the probabilities for the possible reductions of the state of the brain of the observer to be biased, relative to those predicted by orthodox quantum theory, by features of the state of the brain of the conscious observer. If such a feature were the activity of the brain that is associated with "intent," then the effect of the anomalous term in the Hamiltonian would be to shift the quantum probabilities corresponding to the various alternative possible conscious events toward the possibilities linked to his positive intent.

We turn, therefore, to a description of Weinberg's theory, in the context of the problem of the shifting of the probabilities away from those predicted by orthodox quantum theory, and toward those defined by an "intent" represented by particular features of the state of the brain of the observer.

Weinberg's nonlinear quantum theory is rooted in the fact that the quantum-mechanical equations of motion for a general quantum system are just the classical equations of motion for a very simple kind of classical system, namely a collection of classical simple harmonic oscillators. Thus a natural way to generalize quantum theory is to generalize this simple classical system.

To describe this connection of quantum theory to classical simple harmonic oscillators, let p_n and q_n, for $n=1,2,\ldots,$ be the classical canonical variables for a collection of simply harmonic oscillators. Define the dimensionless parameters

$$x_n = q_n \left[\frac{m\omega}{2\hbar} \right]^{1/2} \tag{1a}$$

and

$$y_n = p_n \left[\frac{1}{2\hbar m\omega} \right]^{1/2} . \tag{1b}$$

Then the collection of pairs

$$z_n = x_n + i y_n \tag{2a}$$

and

$$z_n^* = x_n - i y_n \tag{2b}$$

is an equivalent set of variables, and the classical Hamiltonian can be written (with $\hbar = 1$) as

$$h(z,z^*)=z_n^* H_{nm} z_m$$
$$\equiv (z|n)(n|H|m)(m|z)$$
$$\equiv (z|H|z) \ . \tag{3}$$

Here, as throughout this paper, repeated indices are to be summed. The function $h(z,z^*)$ is bilinear: it is a linear function of each of its two (vector) arguments z and z^*. The matrix H_{nm} is independent of z and z^*: it is a diagonal matrix with positive elements, in the original basis. However, (3) is written in a basis-independent way, and in the general representation H_{nm} is Hermitian, $H_{nm}=(H_{mn})^*$. The basis-independent quantity h is real:

$$h(z,z^*)=(h(z,z^*))^*=h^*(z^*,z) \ . \tag{4}$$

The canonical classical equation of motion for a function $f(z,z^*)$ is

$$\frac{df}{dt}=\{f,h\} \ . \tag{5}$$

Here the right-hand side is the Poisson bracket, which can be written in the form

$$\{f,h\}=-i\left[\frac{\partial f}{\partial z_n}\frac{\partial h}{\partial z_n^*}-\frac{\partial h}{\partial z_n}\frac{\partial f}{\partial z_n^*}\right] \ . \tag{6}$$

To obtain quantum mechanics as a special case, one restricts the observables to bilinear forms:

$$f(z,z^*)=z_n^* F_{nm} z_m$$
$$\equiv (z|F|z) \ , \tag{7}$$

where F is independent of z and z^*. Then

$$\frac{df(z,z^*)}{dt}=\frac{d(z|F|z)}{dt}$$
$$=\{f,h\}$$
$$=-i(z|[F,H]|z) \ , \tag{8}$$

where $[F,H]$ is the commutator. The variables z_n and z_n^* can then be identified with the components $\psi_n \equiv \langle n|\psi\rangle$ and $\psi_n^* \equiv \langle \psi|n\rangle$ of the general quantum system.

To pass to Weinberg's nonlinear quantum theory one allows the observables, including the Hamiltonian, to be real *nonbilinear* functions of z and z^*, i.e., of ψ and ψ^*, but imposes the condition that every observable be homogeneous of degree one in each of the variables z and z^*:

$$z_n\frac{\partial f}{\partial z_n}=z_n^*\frac{\partial f}{\partial z_n^*}=f \ . \tag{9}$$

This condition allows one to write

$$f(z,z^*)=z_n^*\frac{\partial^2 f(z,z^*)}{\partial z_n^*\partial z_m}z_m$$
$$\equiv z_n^* F_{nm} z_m$$
$$\equiv (z|F|z) \ , \tag{10}$$

where the F_{nm} are now no longer necessarily independent of z and z^*. The reality condition $f(z,z^*)=f(z,z^*)^*$ is equivalent to

$$F_{nm}=(F_{mn})^* \ . \tag{11}$$

The matrix elements H_{nm} are defined in an analogous way, and

$$\frac{df}{dt}=\frac{d(z|F|z)}{dt}$$
$$=\{f,h\}$$
$$=-i(z|[F,H]|z) \ . \tag{12}$$

This equation looks the same as the orthodox equation (3). Now, however, the operator parts cannot be separated from the state-vector parts z and z^*, because F and H can depend upon z and z^*.

We now apply this formalism to our situation. Let the general wave function ψ be written as

$$\psi=\sum_i a_i\varphi_i\chi_i \ , \tag{13}$$

where the χ_i denote states of the brain, and the φ_i are a set of mutually orthogonal states of the rest of the universe. Suppose, for simplicity, that at $t=0$ the state ψ has the form

$$\psi=a\varphi_+\chi_0+b\varphi_-\chi_0 \ , \tag{14}$$

where φ_+ and φ_- are two macroscopically different states: suppose φ_+ corresponds to a world in which the recorded numbers have a positive bias, and φ_- corresponds to a state in which the recorded numbers have a negative bias. Suppose the state χ_0 is represented, for simplicity, by a compactly supported wave function in momentum space (say in one variable p), and that the interaction Hamiltonian is

$$H=(|\varphi_+\rangle\langle\varphi_+|-|\varphi_-\rangle\langle\varphi_-|)X_{\rm op} \ , \tag{15}$$

where $X_{\rm op}$ is the generator of translations in the variable p. Under the action of this Hamiltonian the state (14) evolves into

$$\psi(t)=a\varphi_+\chi_+(t)+b\varphi_-\chi_-(t) \ , \tag{16}$$

where the states $\chi_+(t)$ and $\chi_-(t)$, expressed in momentum space, are displaced in opposite directions by an amount proportional to t.

Note that if $F_+=|\varphi_+\rangle\langle\varphi_+|$ and $F_-=|\varphi_-\rangle\langle\varphi_1|$ then

$$f_+(t)=\langle\psi(t)|F_+|\psi(t)\rangle$$

and

$$f_-(t)=\langle\psi(t)|F_-|\psi(t)\rangle$$

are both independent of t: the probability of finding the system in the positively (or negatively) biased state is not influenced by the action of the "measurement" process generated by the H specified in (15).

This constancy of $f_+(t)$ and $f_-(t)$ is a general consequence of the fact that the evolution is generated by a Hermitian H that has no matrix elements connecting the states $|\varphi_+\rangle$ and $|\varphi_-\rangle$. More generally, if the F_i,

$i=1,\ldots,N$, are a set of projection operators onto orthogonal states $|\varphi_i\rangle$ in φ space, and H has no elements connecting any two different states $|\varphi_i\rangle$, and if

$$\psi=\sum_{i=1}^{N} a_i\varphi_i\chi_i \ ,$$

then

$$df_i(t)=\frac{d}{dt}\langle\psi(t)|F_i|\psi(t)\rangle$$
$$=\langle\psi(t)|[F,H]|\psi(t)\rangle$$
$$=0:$$

the probabilities $f_i(t)$ remain constant.

If the different states $|\varphi_i\rangle$ represent macroscopically different configurations (e.g., states in which different numbers are typed onto cardboard sheets) then it would be unreasonable to allow H to have any (significantly) nonzero matrix elements connecting them.

This argument is not altered by passing over to the nonlinear version of the equation of motion represented by (12). As long as H has no matrix elements connecting the macroscopically distinct states $|\varphi_i\rangle$, there will be no transitions between these states, and hence no change in the associated probabilities $f_i(t)$.

This argument apparently shows that Weinberg's theory by itself is not sufficient to produce the reported phenomena. To model this effect we take $h(z,z^*) =h'(z,z^*)+ih''(z,z^*)$, with h' and h'' real. This generalization of Weinberg's theory is examined next.

From the homogeneity condition (9) one obtains, as before [see (10)],

$$h(z,z^*)=z_n^* H_{nm} z_m \ , \tag{17}$$

but now with

$$H_{nm}=H'_{nm}+iH''_{nm} \ ,$$

where

$$H'_{nm}=(H'_{mn})^* \tag{18a}$$

and

$$H''_{nm}=(H''_{mn})^* \ . \tag{18b}$$

Weinberg's equation of motion for z_n is

$$\frac{dz_n}{dt}=-i\frac{\partial}{\partial z_n^*}h$$
$$=-i\left[\frac{\partial^2 h}{\partial z_n^*\partial z_m}\right]z_m$$
$$=-iH_{nm}z_m \ . \tag{19}$$

Hence

$$\frac{dz_n^*}{dt}=iH_{nm}^* z_m^*$$
$$=iz_m^*(H'_{mn}-iH''_{mn}) \ . \tag{20}$$

Consequently, the equation of motion for a real function $f(z,z^*)$ becomes

$$\frac{df}{dt}=\frac{d(z|f|z)}{dt}$$
$$=-i(z|[F,H']|z)+(z|[F,H'']_+|z) \ , \tag{21}$$

where

$$[F,H'']_+=(FH''+H''F) \tag{22}$$

is the anticommunicator. This anticommutator term can contribute to df/dt even if H'' is diagonal in (φ^+,φ^-).

Suppose, for example, that

$$h(\psi,\psi^*)=\langle\psi|F_+X_{\rm op}|\psi\rangle e^{i\epsilon\langle\psi|\chi_+\rangle\langle\chi_+|\psi\rangle/\langle\psi|\psi\rangle} \ , \tag{23}$$

with a small positive ϵ, where

$$F_+=|\varphi_+\rangle\langle\varphi_+|$$

and

$$|\chi_+\rangle=e^{-iX_{\rm op}}|\chi_0\rangle \ .$$

Then at $t=1$ the state $\psi(t)$ [originally $(a\varphi_+ + b\varphi_-)|\chi_0\rangle$] will have evolved, by virtue of the real part of h, to approximately

$$a\varphi_+\chi_+ + b\varphi_-\chi_0 \ . \tag{24}$$

But then the exponent in (23) will become nonzero (if $a\neq 0$), and the resulting imaginary part of h will cause df_+/dt to be positive. Hence the probability associated with the state $|\varphi_+\rangle$ will build up, relative to the value $|a|^2$ prescribed by orthodox quantum theory.

This example shows that the reported phenomena, although contrary to orthodox ideas about causality, can be model within a Weinberg-type of nonlinear quantum theory if the Hamiltonian function $h(\psi,\psi^*)$ is allowed to be nonreal.

If there are in nature nonlinear contributions of the kind indicated in Eq. (23), then it seems likely that biological systems would develop in such a way as to exploit the biasing action. The biasing states, illustrated in the model by the state $|\chi_+\rangle$, could become tied, in the course of biological evolution, to biological desiderata, so that the statistical tendencies specified by the basic dynamics would be shifted in a way that would enhance the survival of the organism.

The Weinberg nonlinearities were initially introduced in the present context because of Gisin's result, which showed that these nonlinearities could lead to causal anomalies of the Einstein-Podolsky-Rosen (EPR) kind. However, the considerations given above indicate that those nonlinearities alone cannot produce anomalies of the kind reported in Ref. [8]: a nonreal h is apparently needed to obtain an effect of that kind.

Because the nonlinear aspect is not obviously needed, one could try to revert to a linear theory. Yet it is important to recognize that in the modeling of acausal effects one has available the more general nonlinear framework.

If the purported acausal phenomena is a real physical effect and is explainable in terms of a nonreal h that arises solely in conjunction with nonlinear terms, as in the model given above, then orthodox quantum theory could become simply the linear approximation to a more adequate nonlinear theory.

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[1] A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. **47**, 777 (1935).
[2] J. S. Bell, Physics **1**, 195 (1964).
[3] H. P. Stapp, Phys. Rev. A **47**, 847 (1993); **46**, 6860 (1992); H. P. Stapp and D. Bedford, Synthese (to be published).
[4] P. Eberhard, Nuovo Cimento **46B**, 392 (1978).
[5] S. Weinberg, Ann. Phys. (N.Y.) **194**, 336 (1989).
[6] N. Gisin, Phys. Lett. A **143**, 1 (1990).
[7] R. Jahn, Y. Dobyns, and B. Dunne, J. Sci. Expl. **5**, 205 (1991); B. J. Dunne and R. G. Jahn, *ibid.* **6**, 311 (1992).
[8] H. Schmidt, J. Parapsychol. **57**, 351 (1993).
[9] J. von Neumann, *Mathematical Foundations of Quantum Mechanics* (Princeton University Press, Princeton, 1955), Chap. VI.
[10] W. Pauli, quoted in *Mind, Matter, and Quantum Mechanics* (Springer-Verlag, Berlin, 1993), Chap. 7.
[11] H. P. Stapp, Am. J. Phys. **40**, 1098 (1972).
[12] H. P. Stapp, *Mind, Matter, and Quantum Mechanics* (Ref. [10]).