PHYSICAL REVIEW A VOLUME 46, NUMBER 11 1 DECEMBER 1992

Noise-induced reduction of wave packets and faster-than-light influences

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(Received 7 November 1991)

A simple proof is given of a recent claim [P. Pearle, Phys. Rev. A **39**, 2277 (1989)] that appropriately coupled classical white noise reduces wave packets of macroscopic objects. Three difficulties with the classical mechanism are noted. All three are resolved by passing to the quantum analog. The 2.7-K microwave background is effective in some cases. Quantum noise reduces the density matrix of observables, not the wave function itself. The relative merits and liabilities of these two kinds of reduction, called von Neumann reduction and Heisenberg reduction, respectively, are discussed. In this connection a new type of correlation experiment, devised by Hardy [Phys. Rev. Lett. **68**, 2981 (1992)] is used to prove a theorem that says, essentially, that any ontological solution of the quantum measurement problem must admit either parallel worlds of the Everett kind or faster-than-light influences of some kind.

PACS number(s): 03.65.Bz, 02.50.+s

I. INTRODUCTION

The founders of quantum theory held that the mathematical formalism should be interpreted pragmatically as merely a tool for calculating expectations about observations obtained under conditions specified in terms of classical physical concepts [1]. This way of interpreting quantum theory resolves the problem of measurement. The pragmatic rules assert that if A is a description in terms of classical concepts of specifications on the dispositions of the devices that prepare a quantum system and if B is a description in terms of classical concepts of specifications on the dispositions of the devices that characterize a particular result of a measurement on that system, then there is a density matrix ρ_A and a response matrix ρ_B such that the probability that a response meeting specifications B will occur under conditions meeting specifications A is the trace of the product $\rho_A\rho_B$. No mention is made here of any reduction of wave packets. The two translations $A\rightarrow\rho_A$ and $B\rightarrow\rho_B$ from the language of classical descriptions to the language of the quantum formalism must, in the final analysis, be determined by empirical calibration of the devices.

This formalism was originally intended to cover quantum systems of atomic size, and there was an important condition that the quantum system must, in principle, not act upon its environment, including the preparing and measuring devices, during the interval between its preparation and measurement. Any such interaction would produce phase leakage and cause a breakdown in the quantum-mechanical description of the quantum system.

Over the years the domain of applicability of quantum theory has grown, and efforts are now being made to treat as quantum systems, in place of the originally considered atomic systems, suitably prepared by laboratory devices, rather the entire universe at the big bang, and stellar bodies as they collapse into black holes [2]. This increase in the envisaged scope of quantum theory has given urgency to the task of conceiving quantum theory more broadly, in a way that extends it beyond the anthropocentric conception that served so well in more limited domains of science.

The extreme accuracy of certain predictions of quantum theory suggests that the formalism corresponds to certain aspects of Nature herself—that the theory is more than merely a man-made tool for calculating expectations. Yet, if one tries to pursue the idea of an "objective" wave function, then a certain well-known puzzle arises. Quantum theory allows for superpositions of states, and one immediately finds [3] that the wave function of the pointer on a measuring device, even if originally represented by a localized pure-state wave function, will often evolve into a superposition of, for example, two distinct states, one representing the pointer having swung to the right and the other representing this same pointer having swung to the left. Or a "cat" will evolve into a superposition of two states, one representing a dead cat, the other representing a live cat.

A variation of this puzzle occurs, at least in principle, even in the pragmatically interpreted theory: *If* one could devise an experiment that would measure the interference between the two alternative possible pointer positions, then, according to the pragmatic rules, one must expect to observe this interference. The practical difficulties are so great that an actual test of such an interference seems out of the question [4]. Yet, conceptually at least, even the pragmatically interpreted theory seems to demand that the universe itself must in some sense be continually evolving into a superposition of all possibilities, even on the macroscopic level.

Faced with this puzzle, Heisenberg [5] suggested that, "If we want to describe what happens in an atomic event," then one should think that a "transition from the possible to actual takes place as soon as the interaction of the object with the measuring device, and thereby with the rest of the world, has come into play." He speaks of a world of "actual events," and of an underlying structure of "objective tendencies" for these events to occur. He then draws a parallel between the objective actual event occurring at the level of the device and the related mental event of the subjective reduction of the wave packet that occurs when new information is recognized.

Heisenberg did not develop this idea mathematically: The pragmatic interpretation rendered any such development superfluous. However, the aforementioned extreme accuracy of quantum predictions suggests trying to represent mathematically these "objective tendencies" of Heisenberg's ontology by an *objective* wave function, satisfying the Schrödinger equation. The actual events in Heisenberg's ontology would then be represented by sudden stochastic jumps in this objective wave function. The probability of such a jump could be governed by the probabilities naturally associated with the wave function, thereby incorporating the basic idea that the objective wave function controls the "objective tendencies" for events to occur.

This idea has recently been cast into a particular mathematical form by Ghirardi, Rimini, and Weber (GRW) [6]. Their proposal is that there are spontaneous stochastic reductions of the objective coordinate-space wave function: The coordinate-space wave function of each particle in the universe has a certain innate chance to spontaneously collapse to a new form. This new form is obtained by first multiplying the old wave function by a certain Gaussian function centered at a random point, and then renormalizing. This Gaussian function is taken to have a width of roughly 10^{-5} cm, and the probability distribution associated with the random center point of this Gaussian is assumed to be governed by the square of the norm of the wave function after multiplication by the Gaussian. This biasing of the probable location of the reduction allows the wave function to be interpreted in terms of an "objective tendency" for an event to occur. The chance for a single particle to spontaneously collapse is taken to be 10^{-8} per year: Then the induced probability that the "pointer" will spontaneously collapse to either its left or right position is $\sim 10^{23-8}$ per year.

This "spontaneous stochastic localization" mechanism of GRW brings the physical character of the wave function at the macroscopic level into accord with our sense impressions. However, the mechanism is *ad hoc:* It is not connected to anything else in physics.

An apparent improvement has been introduced by Pearle [7]. In Pearle's version, the quantum system is coupled weakly to a "white-noise" function $W_\Omega(x,t)$, which has the property

$$\langle\langle W_\Omega(x',t')W_\Omega(x''t'')\rangle\rangle=\lambda\Phi(x'-x'')\delta(t'-t'') . \quad (1)$$

Here,

$$\Phi(x'-x'')=\exp[-(x'-x'')^2/2\sigma]$$

is the Gaussian function of GRW, and λ is their time constant. The symbol Ω designates a particular white-noise function $W_\Omega(x,t)$, which is associated with a probability function $P(\Omega)$, and $\langle\langle\ \rangle\rangle$ represents the weighted sum over all Ω.

The δ function $\delta(t'-t'')$ occurring in (1) is characteristic of white noise, which has a flat spectral distribution in energy. The function $\Phi(x'-x'')$ characterizes the correlation of the noise at neighboring points. Pearle's version is less *ad hoc* than that of GRW by virtue of the ubiquitous presence of noise in all physical systems.

Using a very particular form for the coupling of this classical white noise into the quantum system, and a very peculiar assumption relating to statistical weights, Pearle obtains a remarkable result. He finds that for most elements Ω in the classical ensemble of white-noise functions, the effect of the noise is to cause the wave function to drop nearly to zero, whereas for a few elements there will be a huge localized buildup. Furthermore, if $\psi_\Omega(x,t)$ is the wave function that evolves under the action of the white-noise function $W_\Omega(x',t')$, then the single-particle coordinate-space density matrix defined by

$$D(x',t,x'')\equiv\langle\langle \psi_\Omega(x't)\psi^*_\Omega(x'',t)\rangle\rangle \quad (2)$$

evolves in the presence of this noise (with the normal Hamiltonian set to zero, in order to display more clearly the effect of the noise) according to the equation

$$\frac{d}{dt}D(x,t,x'')=-\lambda(1-\Phi(x'-x''))D(x',t,x'') .$$

By virtue of this equation, the coordinate-space probability density

$$P(x,t)\equiv D(x,t,x)$$

is constant, since $\Phi(0)=1$. Thus any pure state, or mixture, will evolve under the action of the noise alone into a statistical mixture of states that has the same coordinate-space probability density. On the other hand, if $x'\neq x''$, then the density-matrix element $D(x',t,x'')$ decays exponentially. More detailed considerations show that the noise converts any one-particle state represented by a broad coordinate-space wave packet into a classical statistical mixture of wave packets, each of which is largely confined to a narrow region in coordinate space. This change is achieved without disturbing the coordinate-space probability density obtained by averaging over the various functions.

It is interesting that noise can produce such an effect, which would resolve the measurement problem in quantum mechanics in an objective way. However, Pearle's derivation of this result is lengthy and is based on the machinery of the Ito stochastic differential equations, which is unfamiliar to most physicists. As a point of departure, I shall first give a simple derivation of Pearle's result. This derivation will be the basis of the subsequent developments.

II. A SIMPLE DERIVATION OF PEARLE'S RESULT

Let the operator that generates the evolution of the second-quantized state vector $|\Psi(t)\rangle$ from time t'' to time t' in the presence of the particular white noise $W_\Omega(x,t)$ be

$$T_\Omega(t',t'')=T\left[\exp\left\{\int_{t''}^{t'}dt_1\int dx_1 J(x_1,t_1)W_\Omega(x_1,t_1)\right.\right.$$
$$\left.\left.-\int_{t''}^{t'}dt_1\int_{t''}^{t'}dt_2\int dx_1\int dx_2 J(x_1,t_1)J(x_2,t_2)\langle\langle W_{\Omega'}(x_1,t_1)W_{\Omega'}(x_2,t_2)\rangle\rangle\right\}\right], \tag{3}$$

where T is the usual time-ordering operator.

If the function $W_\Omega(x,t)$ in the first term in the braces were replaced by $-ieA(x,t)$, then this contribution would look familiar. But, as written, the evolution operator is Hermitian rather than unitary. Moreover, there is a second *ad hoc* counterterm, which is added simply to make the result come out right.

The operator

$$J(x,t)=a^*(x,t)a(x,t) \tag{4}$$

is the particle-density operator, and

$$[a(x',t),a^*(x'',t)]=\delta^3(x'-x'') . \tag{5}$$

Thus the second-quantized state representing a single particle with wave function $\psi(x,t)$ is

$$|\Psi(t;\psi(x,t))\rangle=\int d^3x_1 a^*(x_1,t)\psi(x_1,t)|0\rangle , \tag{6}$$

and the matrix element

$$\langle 0|a(x,t)\Psi(t;\psi(x,t))\rangle=\psi(x,t) \tag{7}$$

is the one-particle wave function.

The full density-matrix operator is

$$D(t)=\langle\langle\, |\Psi(t)\rangle\langle\Psi(t)|\,\rangle\rangle , \tag{8}$$

and the one-particle coordinate-space density matrix is

$$D(x',t,x'')=\langle 0|a(x',t)D(t)a^*(x'',t)|0\rangle . \tag{9}$$

We are interested here only in the evolution generated by the white noise itself. So we may take $a(x,t)=a(x)$. The quantity of interest is then

$$\frac{d}{dt}D(x',t,x'')$$
$$=\lim_{\epsilon\to 0}\frac{1}{\epsilon}\langle 0|a(x',t)$$
$$\times\left\langle\!\!\left\langle T\left[1+\int_t^{t+\epsilon}dt_1\int dx_1 J(x_1,t_1)W_\Omega(x_1,t_1)\right.\right.\right.$$
$$+\tfrac{1}{2}\int_t^{t+\epsilon}dt_1\int_t^{t+\epsilon}dt_2\int dx_1\int dx_2 J(x_1,t_1)J(x_2,t_2)$$
$$\left.\times\{W_\Omega(x_1,t_1)W_\Omega(x_2,t_2)-2\langle\langle W_{\Omega'}(x_1,t_1)W_{\Omega'}(x_2,t_2)\rangle\rangle\}\right]$$
$$\times|\Psi(t)\rangle\langle\Psi(t)|T\left[1+\int_t^{t+\epsilon}dt_3\int dx_3 J(x_3,t_3)W_\Omega(x_3,t_3)\right.$$
$$+\tfrac{1}{2}\int_t^{t+\epsilon}dt_3\int_t^{t+\epsilon}dt_4\int dx_3\int dx_4 J(x_3,t_3)J(x_4,t_4)$$
$$\times\{W_\Omega(x_3,t_3)W_\Omega(x_4,t_4)$$
$$\left.-2\langle\langle W_{\Omega'}(x_3,t_3)W_{\Omega'}(x_4,t_4)\rangle\rangle\}\right]$$
$$\left.\left.-|\Psi(t)\rangle\langle\Psi(t)|\right\rangle\!\!\right\rangle a^*(x'',t)|0\rangle . \tag{10}$$

Insertion of

$$\langle\langle W_\Omega(x',t')W_\Omega(x'',t'')\rangle\rangle=\lambda\Phi(x'-x'')\delta(t'-t'') \tag{11}$$

and of the equation

$$\langle 0|a(x',t)\int d^3x\, J(x,t)f(x,t)=f(x',t)\langle 0|a(x',t) \tag{12}$$

and its Hermitian conjugate, together with the white-noise properties [8]

$$\langle\langle W_\Omega(x_1,t_1)\cdots W_\Omega(x_n,t_n)\rangle\rangle=\begin{cases}0, & n \text{ odd} \qquad (13a)\\ \sum_{\text{all pairs}}\langle\langle W_\Omega(x_i,t_i)W_\Omega(x_j,t_j)\rangle\rangle\cdots\langle\langle W_\Omega(x_k,t_k)W_\Omega(x_l,t_l)\rangle\rangle\ , & n \text{ even} \qquad (13b)\end{cases}$$

immediately gives

$$\frac{d}{dt}D(x',t,x'')=-\lambda(1-\Phi(x'-x''))D(x',t,x'')\ . \tag{14}$$

III. THREE PROBLEMS WITH THE CLASSICAL MECHANISM

The evolution operator $T_\Omega(t_1,t_2)$ is not unitary. Consequently, the norm of the state vector generally changes under the action of $T_\Omega(t_1,t_2)$. This creates a problem. Each element Ω of the ensemble $\{W_\Omega(x,t)\}$ of white-noise functions has a fixed weight $P(\Omega)$, and this weight refers to the entire space-time "path" $W_\Omega(x,t)$. But the norm of the wave function $\psi_\Omega(x,t)$ associated with this path changes with t. In the density matrix $D(x',t,x'')$ the weight given to $\psi_\Omega(x,t)$ is $P(\Omega)$ times the norm squared of $\psi_\Omega(x,t)$. This means that the statistical mixture of noise functions is not treated exactly as a classical statistical mixture of noise functions. Rather, at each time t one can imagine a branching of a noise function into a set of different subsequent possibilities, and a postulated redistribution of probabilities that depends upon the wave function of the quantum system. This injects a hidden nonlinearity into the Schrödinger equation and makes the system not understandable as simply a quantum system in a background of classical noise: The normal classical probability concept is replaced by a peculiar *ad hoc* new concept in which the probabilities become redistributed over the elements of the ensemble with the passage of time.

A second problematic feature of the proposal is that it requires a classical source. Any ordinary noise should, in a quantum world, be treated quantum mechanically. Adding a classical part to the universe is *ad hoc* and encounters the problem that although we know how to imbed a quantum system in a prescribed classical background, we do not know how to describe consistently the reaction of the classical system to the quantum system. A third problem is the *ad hoc* counter term. This term is simply added to make the result come out right. These three problems are automatically resolved by going over to the quantum version of the same idea.

IV. THE QUANTUM VERSION

In the quantum version the Hermitian transition operator $T_\Omega(t_1,t_2)$ is replaced by the unitary operator

$$U(t_1,t_2)=T\left[\exp\left[-ie\int_{t_2}^{t_1}dt\int d^3xJ(x,t)\times A(x,t)\hbar^{-1}\right]\right]\ , \tag{15}$$

where

$$\left[\frac{e}{\hbar}\right]^2\langle\langle A(x',t')A(x'',t'')\rangle\rangle=\lambda\Phi(x'-x'')\delta(t'-t'')\ , \tag{16}$$

the analogs of (13) hold, and $\langle\langle\ \rangle\rangle$ now represents the expectation value in the space of the operator $A(x,t)$. Then adaptation of the earlier calculation gives immediately the same result (14). The essential point is that now the crucial factor of $-\frac{1}{2}$ in the terms of (10) that contain the double time integrals come directly from the expansion of the exponential, which brings in two factors of i, whereas before one had to add the negative *ad hoc* counterterm to get the sign of this term to come out right.

In the quantum version, just as in the classical version, and also as in Brownian motion, the back reaction of observable degrees of freedom upon the noise is neglected: the noise is represented purely statistically by a collection of stationary (i.e., invariant under translations in time) expectation values.

Consider, as an example, a particle moving in the 2.7-K microwave background. The effect of the part of the expectation value

$$\langle\langle A_\mu(x_1,t_1)A_\nu(x_2,t_2)\rangle\rangle$$

arising from the pure vacuum fluctuations is exactly canceled by the mass-renormalization counter term [9], whereas the part corresponding to blackbody background radiation is [10]

$$\langle\langle A_\mu(x_1,t_1)A_\nu(x_2,t_2)\rangle\rangle=\frac{-g_{\mu\nu}}{2\pi^2}\frac{\hbar}{c}\int_0^\infty\frac{k\,dk}{(e^{\beta k}-1)}\cos(kct)\frac{\sin(k\Delta)}{k\Delta}\ ,$$

where $t=t_1-t_2$, $\Delta=|x_1-x_2|$, $\beta=(k_BT/\hbar c)^{-1}$, $T=2.7$

K, and k_B is the Boltzmann constant.

Because of the Boltzmann exponential, only very soft photons ($k \approx \mathrm{cm}^{-1}$) contribute appreciably. Thus to first approximation we neglect the direct effect of the photon interaction upon the motion of the particle. Our interest is in the regime $\Delta \approx \mathrm{cm}$. The velocity of light is assumed to be large compared to all other velocities in the problem. Then the factor $\cos kct$ becomes rapidly oscillating in the integrations over time that occur in our equation of motion,

$$D(x',t',x'')=\langle 0|a(x',t')\left[T\exp\left[\int_{t''}^{t'}dt_1\int dx_1[-ieJ_\mu(x_1,t_1)A_\mu(x_1,t_1)\hbar^{-1}]\right]\right]$$
$$\times D(t'')\left[T\exp\left[\int_{t''}^{t'}dt_2\int dx_2[-ieJ_\nu(x_2,t_2)A_\nu(x_2,t_2)\hbar^{-1}]\right]\right]^\dagger ,$$

and the slowly varying factors can in first approximation be fixed at the average value $k \approx 10\ \mathrm{cm}^{-1}$. This yields the white-noise approximation

$$\langle\langle A_\mu(x_1,t_1)A_\nu(x_2,t_2)\rangle\rangle \approx \frac{-g_{\mu\nu}}{2\pi}\delta(t)\frac{\hbar k/c^2}{e^{\beta k}-1}\frac{\sin(k\Delta)}{k\Delta} .$$

Then the earlier argument again gives Eq. (14) with

$$\Phi(x'-x'')=\frac{\sin k|x'-x''|}{k|x'-x''|}$$

and, for a free electron,

$$\lambda=\frac{1}{\hbar^2}e^2|v|^2\frac{2}{2\pi}\frac{\hbar k/c^2}{e^{\beta k}-1}=\frac{e^2}{\hbar c}\left|\frac{v}{c}\right|^2\frac{1}{\pi}\frac{kc}{e^{\beta k}-1}\quad \mathrm{sec}^{-1} .$$

For a thermal (300-K) electron, the factor $|v/c|^2$ becomes $\approx 10^{-7}$ and hence (for $k\approx 10\ \mathrm{cm}^{-1}$, $\beta \approx 10^{-1}$ cm),

$$\lambda \approx \frac{1}{137}\quad \mathrm{sec}^{-1} .$$

The effect is therefore small. On the other hand, for a small conducting particle of radius a ($ka \ll 1$), the parameter λ becomes approximately (see the Appendix)

$$\lambda \approx \left[\frac{4\pi\omega^4 a^3}{3\sigma\hbar}\right]\left[\frac{\hbar k/c^2}{\pi(e^{\beta k}-1)}\right] .$$

For $k=10\ \mathrm{cm}^{-1}$ and $a=10^{-4}$ cm, this gives

$$\lambda \approx 10^{18}\quad \mathrm{sec}^{-1} .$$

Hence the damping factor in Eq. (14) becomes, for $\Delta = 10^{-4}$ cm,

$$\lambda\frac{\sin(k\Delta)}{k\Delta}\approx 10^{18}\times 10^{-6}/6$$
$$\approx 10^{11}\quad \mathrm{sec}^{-1} .$$

Thus the cosmic background radiation can produce large noise-induced reductions of the off-diagonal elements of $D(x',t,x'')$ even for small objects.

V. COMPARISON TO OTHER TREATMENTS

In this field a fundamental distinction must be drawn between two kinds of reductions. These I shall call Heisenberg and von Neumann reductions, respectively. A Heisenberg reduction picks out a particular result of the experiment, whereas a von Neumann reduction merely reduces a density matrix to diagonal form, in some particular basis. Each of these reductions can occur at either the objective or the subjective level.

A *subjective* Heisenberg reduction occurs when a scientist recognizes new information—perhaps that the pointer has swung to the right and not to the left—and uses this information to construct a new density matrix to represent his new state of knowledge. An *objective* Heisenberg reduction is an analogous change in a density matrix that is interpreted objectively as a representation of (certain aspects of) Nature herself, rather than as merely a tool for making predictions about observations. Thus an objective Heisenberg reduction is a theoretical representation of an "actual event" occurring in Nature herself.

Reductions of the von Neumann type were called "processes of type 1" by von Neumann in his analysis of the process of measurement. From the von Neumann point of view, quantum theory is a purely statistical theory that is supposed to make only statistical predictions such as "the pointer is equally likely to swing to the right as to the left": The theory is not supposed to determine, or pick out, which of these two possibilities will actually appear. This statistical point of view accords with that of the Copenhagen interpretation of Bohr and Heisenberg.

The GRW mechanism generates objective Heisenberg reductions. Other ways of obtaining such reductions have been proposed. Maxwell [11] suggests that every inelastic-scattering event is an actual event; Bussey [12] suggests that every scattering event is an actual event. Some earlier proposals by Pearle [13] discuss possible (nonlinear) modifications of the Schrödinger equation that would produce objective Heisenberg reductions, but those proposals do not unambiguously fix the precise conditions under which these reductions occur.

Pearle's newest proposal [7] is a specific continuous version of the GRW mechanism, and it also gives objective Heisenberg reductions. The quantum version, on the other hand, gives only von Neumann reductions of the reduced density matrix corresponding to observable quantities.

There are various other ways to get von Neumann reductions of this latter kind. Indeed, one may simply note that (1) there are soft photons, gas molecules, and perhaps other invisible things, that interact locally with the macroscopic pointer; (2) the states of these invisible things will, by virtue of the local interactions, become correlated to the position of the pointer in accordance with

$$(\alpha\psi_{PL}+\beta\psi_{PR})\psi_I \rightarrow \alpha\psi'_{PL}\psi_{IL}+\beta\psi'_{PR}\psi_{IR} ,$$

where R, L, P, and I stand for right, left, pointer, and invisible, respectively; and (3) the states ψ_{IL} and ψ_{IR} will be orthogonal if even one invisible particle is represented orthogonally in these two states. These facts immediately entail that the reduced density matrix in the observable (e.g., pointer) degrees of freedom, which is obtained by averaging (taking a trace) over the invisible degrees of freedom, will quickly tend to become diagonal in position space.

This sort of reduction, which I called environmental-separation-induced (ESI) reduction, is induced by the orthogonalities produced in the invisible degrees of freedom by the action upon them of the observable degrees of freedom. The existence and importance of this kind of reduction was manifest in the work of von Neumann. Numerical estimates of the effects have recently been made by Joos and Zeh [14].

The noise-induced reduction described in Sec. IV is not an ESI reduction. It is not computed by keeping track of the action of the observed system upon the invisible degrees of freedom. It is controlled by the statistical character of the noise source itself, as represented by the expectation value

$$\langle\langle A(x',t')A(x'',t'')\rangle\rangle .$$

In this approximation the action of the source upon the noise is neglected: the expectation values are taken to be stationary (invariant under time translation) and independent of the source, just as in the simple treatments of Brownian motion.

Joos and Zeh stress the difference between the ESI reductions and the conceivable possible noise-induced reductions, which they say are suggested by some words of Heisenberg. The noise-induced reductions described in Sec. IV constitute a realization of Heisenberg's suggestion.

Reductions of the ESI type have been considered also by Zurek [15], but in a more general context that does not highlight the importance of the local character of the interaction. The general principles of quantum theory are often stated in ways that emphasize the similarities between different kinds of variables, such as position and momentum. It then becomes difficult to see what makes the position variables so unique. It is, in fact, the local form of the interaction, within the context of relativistic quantum-field theories, that makes the position variables of macroscopic objects stand out. The local form of the interactions with quantum-noise sources forces the density matrix in the observable degrees of freedom to tend to diagonal form in the position variables.

VI. REMARKS

(1) Normally we think that noise tends only to disorganize things. But the quantum noise, and the similar ESI reductions, act to inject classical structure into the amorphous quantum world. They convert the "one-quantum-world" ontology into a "one-quantum-world, many-classical-worlds" ontology. These classical worlds exist, however, only in a very thin veneer of degrees of freedom that are associated with large mass, and are therefore, like the particles in Brownian motion, sluggish in the background of the chaotic noise. The background noise acts upon the classical ensemble of classical worlds in two ways: It tends to break up each classical world in this ensemble into an ensemble of worlds, and it causes each of these new worlds to be classical.

(2) Scientists who argue for the need to go beyond pure quantum theory often cite Einstein's dissatisfaction with quantum theory. However, Einstein's principal objection was to the subjective character of the theory: he held that basic physical theory should represent the physical world itself, not merely connections between human observations [16]. More specifically, he believed that quantum theory "constitutes an optimum formulation of (certain) connections, $\cdots$ [but] offers no useful point of departure for future developments" [17]. However, a theory with an objective universal wave function evolving in accordance with the Schrödinger equation meets Einstein's demand for objectivity, and the recent cosmological applications constitute "future developments" in a regime of physics far removed from the original domain of laboratory experiments on atomic systems, yet close to Einstein's own interest in cosmology. Even the statistical features that Einstein disliked become not fundamental elements in Nature taken as a whole, but merely artifacts of the use we make of the theory "God does not play dice," because the universe evolves deterministically. It is simply that populations of appropriately defined ensembles enjoy statistical properties.

VII. ADDED REMARKS

The foregoing discussion is based on a laboratory report by the author [18]. Several works on the subject have recently appeared, in particular, the work of Ghirardi, Pearle, and Rimini [19], where similarities between the original GRW work and the newer noise-based theory are noted.

It is of interest to discuss the relative merits of, on the one hand, mechanisms such as those of Pearle and GRW that give objective Heisenberg reduction and, on the other hand, those like the quantum noise that give only objective von Neumann reductions.

Two deep and important issues are involved in the evaluation of these alternatives. The first is the question of the viability of the Everett approach; the second is the question of the acceptability of the faster-than-light influences. Such influences are entailed by Heisenberg collapse theories, but do not occur in Everett-type collapses.

The viability of the Everett approach has not yet been demonstrated. Such a demonstration would entail explaining, in a satisfactory way, the emergence of multiple discrete realms of human experience, each conforming to classical concepts, from the amorphous tangled soup of quantum amplitudes, and the unambiguous assignments of correct statistical weights to these discrete worlds. If, on the basis of the Schrödinger equation alone, one can actually deduce the emergence of these properly weighted discrete classical worlds from the quantum continuum, then it would be unreasonable from the scientific point of view to accept some needless and arbitrary additional process in nature, particularly a process that entails instantaneous action at a distance. On the other hand, if the Everett approach cannot be sustained, then science must ask: What conditions or requirements should be used to guide the search for a satisfactory objective collapse mechanism? Without stringent aesthetic or empirical conditions, the possibilities for collapse mechanisms are boundless. These questions have been addressed in two recent publications of mine [20,21] and need not be further discussed here.

Finally, it is appropriate to mention the recent attempts of Pearle and others [22] to obtain a relativistic generalization of the dynamical reduction mechanism. These attempts have not yet succeeded because it was confirmed that the function $\Phi(x-x')$ must, as expected, be replaced by a Dirac δ function. In the nonrelativistic theory this function $\Phi(x-x')$ was explicitly required to be slowly varying enough to make the energy introduced into the universe at each "hit" small enough to be consistent with observation. The change to a δ function makes this energy increment infinite.

Putting aside this energy problem the authors of the first Ref. [22], examine the problem of nonlocality, and say that "No objective local property can emerge as a consequence of a measurement occurring in a spacelike separated region . . ., no faster-than-light physical effect can occur."

This claim might appear to assert that the theory is local; i.e., that no faster-than-light influences of any kind are needed. Actually, the established result is much less: the result is essentially an expression of a convention about how the word "objective" is to be used. As for faster-than-light influences, one of the authors (P. Pearle) confirms that he and his colleagues are quite aware of the presence and necessity of such influences in their model.

In view of the necessity in this model of faster-than-light influences a critical issue arises here, and, indeed, in the whole field: Is it possible to escape the two horns of the dilemma? Must one choose between faster-than-light influences and parallel worlds? If, in an ontological context, it is really necessary to choose one or the other of these two alternative possibilities, then, in view of the difficulties that face the parallel-worlds option, a tentative acceptance of the only available alternative is not unreasonable. But can there be a third way?

There have been, in the wake of Bell's seminal work, many proofs of the necessity of faster-than-light influences in quantum theory. However, most of these proofs make, in addition to a no-faster-than-light-influence assumption, some strong reality assumption that is completely alien to the precepts of quantum philosophy. For example, some proofs introduce *hidden variables,* and require a factorization property that entails that, for any fixed values of these hidden variables, the result of a measurement in one of two spacelike-separated regions must be independent of the *result* of the measurement in the other region. Other proofs invoke the Einstein locality condition, which asserts that if by performing some measurement in one of two spacelike-separated regions a scientist would become able to predict with certainty the result of a measurement of some quantity in the other region, then this quantity has a well-defined value, even if neither one of the two measurements is ever performed. Each of these reality assumptions contravenes the basic precepts of quantum philosophy. Hence the entailed conflict with the predictions of quantum theory is not too surprising. The need to invoke such reality assumptions means that the resulting theorems do not display the two-horned dilemma.

Actually, the dilemma is four-horned. One of the remaining two options is to reject the presumed validity of at least one of the four predictions of quantum theory that are needed for the proof. I have discounted that possibility because the needed predictions arise directly from the most basic quantum principles, and because the empirical evidence supporting similar predictions, although not absolutely air-tight, is exceedingly strong. The second of the remaining two options is to challenge the assumption that in a Bell-type theoretical analysis one can treat the two binary choices of the two experimenters as two independent free variables; i.e., to reject the possibility that one can conduct the logical analysis of quantum theory from a standpoint in time just prior to the making of these two choices, and can consider each of the four available pairs of choices to be at that time an open possibility.

The four-horned dilemma is displayed clearly in the following theorem, which refers to an EPR-type experiment contrived recently by Hardy [23]. The conditions of the theorem are the following:

(i) The four needed predictions of quantum theory are valid.

(ii) For each of the two spacelike-separated spacetime regions, A and B, the choice between the two alternative possible measurements that might be performed in that region can be treated as an independent random variable: each of the two choices is indeterminate at the time of the analysis, which is taken to be just prior to any fixing of these two choices.

(iii) For each of the two regions, A and B, and for each of the two alternative possible local measurements that might be chosen in that region, *if that measurement were to be chosen and performed* then some single result for that measurement, either "yes" or "no," must be selected by nature. (This condition precludes parallel worlds.)

(iv) No selection by nature of a result in one region can depend upon a choice that does not yet exist, in the sense that it will become determinate only at some future time, as measured in *some* frame of reference. (This is the no-faster-than-light influence condition. It asserts that nature's selection in one region cannot be affected in any way by a far-away experimenter's choice that "has not yet been made.")

In Hardy's experiment there are in each of the two spacelike separated regions A and B two alternative possible measurement, 1 and 2. Let:

$A_1 \equiv$ the condition that measurement 1_A be performed in region A.

$A_2 \equiv$ the condition that measurement 2_A be performed in region A.

$B_1 \equiv$ the condition that measurement 1_B be performed in region B.

$B_2 \equiv$ the condition that measurement 2_B be performed in region B.

$y_A \equiv$ the condition that the result "yes" appears in region A.

$n_A \equiv$ the condition that the result "no" appears in region A.

$y_B \equiv$ the condition that the result "yes" appears in region B.

$n_B \equiv$ the condition that the result "no" appears in region B.

Then the pertinent predictions of quantum theory in Hardy's experiment are [where $\rightarrow$ means "implies" (strict conditional), $\wedge$ means "and" (conjunction), and $-$ means "it is false that" (negation)]

$$(A_1 \wedge B_2 \wedge y_A) \rightarrow (A_1 \wedge B_2 \wedge y_B) , \tag{17a}$$

$$(A_2 \wedge B_2 \wedge y_B) \rightarrow (A_2 \wedge B_2 \wedge n_A) , \tag{17b}$$

$$(A_2 \wedge B_1 \wedge n_A) \rightarrow (A_2 \wedge B_1 \wedge n_B) , \tag{17c}$$

$$-[(A_1 \wedge B_1 \wedge y_A) \rightarrow (A_1 \wedge B_1 \wedge n_B)] . \tag{17d}$$

The first condition says that if measurement 1_A were to be performed in region A and measurement 2_B were to be performed in region B and the result "yes" were to appear in region A, then the result "yes" must (with probability unity) appear in region B. The fourth condition is a consequence of the fact that, if measurement 1_A were to be performed in A and measurement 1_B were to be performed in B then the quantum probability for the result [yes, yes] would be nonzero.

The no-faster-than-light-influence condition asserts that the following four conditions all hold:

$$[A_1 \wedge B_1 \wedge y_A] \rightarrow [(A_1 \wedge B_2) \rightarrow (A_1 \wedge B_2 \wedge y_A)] ,$$

$$[A_1 \wedge B_2 \wedge y_B] \rightarrow [(A_2 \wedge B_2) \rightarrow (A_2 \wedge B_2 \wedge y_B)] ,$$

$$[A_2 \wedge B_2 \wedge n_A] \rightarrow [(A_2 \wedge B_1) \rightarrow (A_2 \wedge B_1 \wedge n_a)] ,$$

$$[A_2 \wedge B_1 \wedge n_B] \rightarrow [(A_1 \wedge B_1) \rightarrow (A_1 \wedge B_1 \wedge n_B)] .$$

The first condition asserts that if the measurement 1_A were to be performed in region A and the measurement 1_B were to be performed in region B and the result "yes" were to appear in region A, then this same result "yes" must appear in region A also in case the "future" (in some frame of reference) measurement in region B were to be 2_B: The choice of which measurement will eventually be performed (at some "later" time) in region B is asserted to have no effect at all on what appears (at the earlier time) in region A. The other three instances of the no-faster-than-light-influence condition have similar meanings.

In a general theoretical context in which the choices that fix which of the alternative possible measurements will eventually be performed is still undecided, there must be, for each of the alternative possible measurement that might be chosen, a no-faster-than-light condition—a condition that will become applicable if that particular possibility becomes the chosen one. The present theory is formulated in the general context in which the choices between the various alternative possible measurements are controlled by random variables. These choices are therefore considered to be still undecided. Hence a condition for each of the eventual possible cases must be included.

Theorem. In the context provided by our assumptions, the predictions of quantum theory cannot be reconciled with the assumption that there is no faster-than-light influence of any kind.

Proof:

$$\begin{aligned}(A_1 \wedge B_1 \wedge y_A) &\rightarrow [(A_1 \wedge B_2) \rightarrow (A_1 \wedge B_2 \wedge y_A)]\\
&\rightarrow [(A_1 \wedge B_2) \rightarrow (A_1 \wedge B_2 \wedge y_B)]\\
&\rightarrow [(A_1 \wedge B_2) \rightarrow [(A_2 \wedge B_2) \rightarrow (A_2 \wedge B_2 \wedge y_B)]]\\
&\rightarrow [(A_1 \wedge B_2) \rightarrow [(A_2 \wedge B_2) \rightarrow (A_2 \wedge B_2 \wedge n_A)]]\\
&\rightarrow [(A_1 \wedge B_2) \rightarrow [(A_2 \wedge B_2) \rightarrow [(A_2 \wedge B_1) \rightarrow (A_2 \wedge B_1 \wedge n_A)]]]\\
&\rightarrow [(A_1 \wedge B_2) \rightarrow [(A_2 \wedge B_2) \rightarrow [(A_2 \wedge B_1) \rightarrow (A_2 \wedge B_1 \wedge n_B)]]]\\
&\rightarrow [(A_1 \wedge B_2) \rightarrow [(A_2 \wedge B_2) \rightarrow [(A_2 \wedge B_1) \rightarrow [(A_1 \wedge B_1) \rightarrow (A_1 \wedge B_1 \wedge n_B)]]]] .\end{aligned}$$

The long chain of implications in the final line collapses to give

$$(A_1 \wedge B_1 \wedge y_B) \rightarrow (A_1 \wedge B_1 \wedge n_B) ,$$

which contradicts condition (17d).

The reason the change of conditions

$$[(A_1 \wedge B_2) \rightarrow [(A_2 \wedge B_2) \rightarrow [(A_2 \wedge B_1) \rightarrow [(A_1 \wedge B_1)$$

can be omitted is that they completely countermand each other: there are only four alternative possible choices under consideration, and the chain of countermanding conditions returns the choice back to the original one. Each choice is determined by an independent random variable, and no condition is placed upon the result that emerges under any of the countermanded conditions. Thus the conditions are simply returned to the initial ones.

Note that the various results ascribed during the course of the argument to various unperformed experiments were not *assumed* to exist: Such an assumption would constitute a hidden assumption of "counterfactual definiteness," which, together with the assumption of determinism, is not invoked. All of the occurring values except the single initial value y_A were *deduced* directly from the explicitly stated assumptions of the theorem; they were not *assumed* to exist. The single initial value y_A represents a conceivable possibility under condition $A_1 \wedge B_1$, and one that, by virtue of the prediction that led to (17d), can occur.

This result constitutes an apparent liability for theories having objective Heisenberg reductions, as contrasted to Everett-type theories having only von Neumann reductions. However, this liability is not necessarily a fatal flaw. For, on the one hand, it has not yet been shown how, as required by the Everett approach, an unambiguous separation of the single quantum universe into distinctly perceived classical branches can be rationally deduced from the Schrödinger equation alone. On the other hand, the apparent existence of an empirically determinable preferred rest frame of the universe, defined by the primordial black-body radiation, renders the concept of a subtle instantaneous interaction less objectionable than it was in the past.

ACKNOWLEDGMENTS

I thank Philip Pearle for useful correspondence. This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

APPENDIX

Consider a conducting sphere of diameter a in an electric field of strength E. This field induces a surface charge density $\rho = E$ per cm^2 normal to **E**. This charge density produces a current density of magnitude

$$|J| = |\dot{E}| = |\ddot{A}| = |\omega^2 A| \ .$$

This charge density produces power dissipation J^2/σ per cm^3. The total power dissipation is then $(4\pi/3)(\omega^4 a^3/\sigma)A^2$. The two directions of polarization give a factor of 2 (in place of $-g_{\mu\nu}$). One must divide the power dissipation by $\hbar$, and also by 2, to get the contribution to the phase of the wave function coming from the second-order term in the evolution operator $U(t'-t'')$. Then one must multiply by 2 to get the contributions of these two equal terms to Eq. (14). They give the contribution corresponding to $\Phi(0)=1$.

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