

Generalized absorber theory and the Einstein-Podolsky-Rosen paradox

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A generalized form of Wheeler-Feynman absorber theory is used to explain the quantum-mechanical paradox proposed by Einstein, Podolsky, and Rosen (EPR). The advanced solutions of the electromagnetic wave equation and of relativistic quantum-mechanical wave equations are shown to play the role of "verifier" in quantum-mechanical "transactions," providing microscopic communication paths between detectors across spacelike intervals in violation of the EPR locality postulate. The principle of causality is discussed in the context of this approach, and possibilities for experimental tests of the theory are examined.

I. THE EINSTEIN-PODOLSKY-ROSEN PARADOX AND THE BELL INEQUALITY

The quantum-mechanical paradox proposed by Einstein, Podolsky, and Rosen¹ (EPR) in 1935 is essentially a demonstration that the results of quantum mechanics are logically inconsistent with the premise that a measurement made with one instrument cannot influence the measurement made by another instrument if the measurement events are separated by a spacelike interval.² This is sometimes called the locality premise.

In 1964 it was demonstrated by Bell³ in analyzing a *Gedankenexperiment* suggested by Bohm and Aharonov⁴ that locality implied inequalities in the measured probabilities of spin orientation experiments on certain physical systems. Recently, it has been shown that these Bell inequalities lead to experimental predictions which differ markedly from those of quantum mechanics.^{5,6} Thus it has become feasible to confront these two divergent views of reality, quantum mechanics and the EPR locality premise, with experimental tests.⁹ A number of such experimental tests have now been performed,^{7,8,10-13} and the most reasonable interpretation of the experimental results is that the quantum-mechanical predictions have been confirmed.^{9,10,14}

The implication of these experimental results is that, although the EPR locality premise seems eminently reasonable, it must be wrong. However, the locality premise is not easily relinquished, for if one measurement *can* alter the result of another measurement across a spacelike interval, then a suitable choice of inertial reference frames can make the "effect," i.e., the altered measurement, precede in time sequence the "cause," i.e., the altering measurement, in violation of the principle of causality. Clearly then, these experimental tests, while confirming the validity of quantum mechanics, have not clarified the EPR paradox, nor do they provide us with

any new insights as to how the premise of locality (or causality) could be violated in quantum-mechanical systems. It is the purpose of this paper to attempt to clarify this situation.

II. ADVANCED AND RETARDED ELECTROMAGNETIC WAVES

The analysis of the EPR paradox which will be presented here will involve the interaction of advanced and retarded wave functions. Therefore, we must start by examining these wave functions in the context of classical electrodynamics. The electromagnetic wave equation¹⁵ for source-free space can be written in the form

$$c^2 \nabla^2 \vec{F} = d^2 \vec{F} / dt^2, \quad (1)$$

where ∇^2 is the Laplacian operator providing the second space derivative in three dimensions and \vec{F} represents either the electric field vector \vec{E} or the magnetic field vector \vec{B} of the wave. Since this differential equation is second order in both time and space, it has two independent time solutions and two independent space solutions.

Let us restrict our consideration to one dimension by requiring that the wave motion described by Eq. (1) moves along the x axis and that the \vec{E} vector of the wave is along the y axis. Then two independent time solutions of Eq. (1) might have the form

$$\vec{E}_+(x, t) = \mathcal{Y} E_0 \sin[2\pi(x/\lambda \pm ft)] \quad (2)$$

and

$$\vec{E}_-(x, t) = \vec{B}_0 \sin[2\pi(x/\lambda \pm ft)], \quad (3)$$

where λ and f are the wavelength and frequency of the wave and the alternating signs in Eqs. (2) and (3) represent the two independent time solutions mentioned above. If the source of this radiation is considered to be at the origin and emitting in the $+x$ direction, then these waves will exist only for $x > 0$. We can investigate the path of these

waves by requiring that the argument of the sinusoidal function in Eqs. (2) and (3) be a constant phase angle and examining the (x, t) locus which this implies. The wave corresponding to E_+ and B_+ will exist only when $t < 0$ while the wave corresponding to E_- and B_- will exist only for $t > 0$. Thus the E_- wave arrives at a point x in a time t after emission, while the E_+ wave arrives at x in a time t before emission.

We can also examine the energy and momentum flow produced by these waves. From Maxwell's equations,

$$\nabla \times \vec{E}_\pm = -d\vec{B}_\pm/dt \quad (4a)$$

and

$$\nabla \times \vec{B}_\pm = \hat{z} dE_\pm/dx$$

$$= \hat{z} E_0 (2\pi/\lambda) \cos[2\pi(x/\lambda \pm ft)], \quad (4b)$$

$$d\vec{B}_\pm/dt = \pm (2\pi f) \vec{B}_0 \cos[2\pi(x/\lambda \pm ft)], \quad (4c)$$

so

$$\vec{B}_0 = \mp \hat{z} E_0/\lambda f = \mp \hat{z} E_0/c. \quad (4d)$$

Therefore, the Poynting vector, which indicates the direction of energy and momentum flow of the wave, is

$$\vec{S} = (\vec{E}_\pm \times \vec{B}_\pm)/\mu_0 = \mp (\hat{y} \times \hat{z})(1/\mu_0) E_0^2/c$$

$$= \mp \hat{x} E_0^2/\mu_0 c, \quad (5)$$

where \hat{x} , \hat{y} , and \hat{z} are unit vectors along the Cartesian axes.

Therefore, the upper sign in Eqs. (2) and (3) corresponds to a wave which is emitted from the origin in the $+x$ direction but which corresponds to energy and momentum flow in the $-x$ direction. Thus, wave $E_+(x, t)$ is a *negative-energy* (and *negative-frequency*) solution of Eq. (1). As mentioned above, it will arrive at a point a distance x from the source at a time $t = x/c$ before the instant of emission. For this reason, it is called an *advanced* wave. Solution $E_-(x, t)$, on the other hand, is the more familiar positive-energy solution of Eq. (1). It arrives at x a time $t = x/c$ after the instant of emission and is called the *retarded* solution.

This advanced/retarded dichotomy emerges even more clearly when one examines the Lienard-Wiechert solutions of Eq. (1) when the latter is interpreted as a differential equation involving the electromagnetic four-potential.¹⁵ The advanced and retarded potential solutions then explicitly involve the evaluation of the potential at an advanced or retarded time depending of the distance from the source and the corresponding negative or positive transit time. These potentials correspond to the negative-energy advanced solution and the positive-

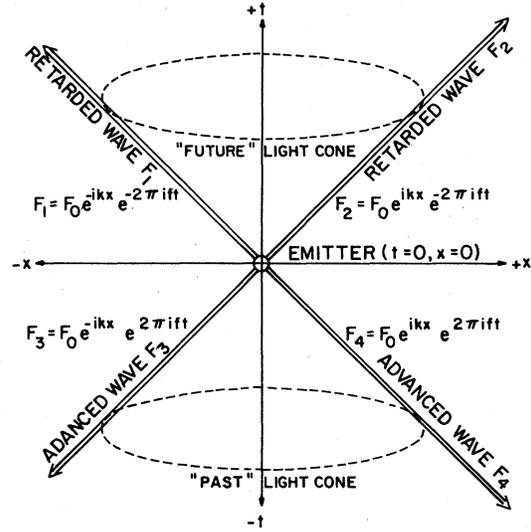


FIG. 1. Minkowski diagram of the four solutions of the electromagnetic wave equation which are represented by Eq. (1). Here the wave number \vec{k} is taken to be along the x axis and the emitting source is located at the origin.

energy retarded solution of the wave equation which are discussed above.

Negative-energy solutions also appear in quantum-mechanical treatments of electromagnetism. We can, for example, consider Eq. (1) to be a quantum-mechanical wave equation, and can investigate the properties of its solutions by examining their eigenvalues. We can, for example, choose plane-wave solutions to Eq. (1) which have the form

$$\vec{F} = \vec{F}_0 \exp[\pm i(\vec{k} \cdot \vec{r})] \exp(\pm i 2\pi f t) \exp(i\phi), \quad (6)$$

where \vec{k} is the wave number ($k = 2\pi/\lambda$) of the wave and points in the direction of propagation, and ϕ is an arbitrary phase. The alternating signs in Eq. (6) indicate the pairs of space and time solutions mentioned above. The Minkowski diagram in Fig. 1 shows the world lines corresponding to the various sign combinations of Eq. (6), for the case where the propagation vector \vec{k} is along the $\pm x$ axis [the alternating sign corresponding to the sign of the exponent in the first exponential of Eq. (6)] and the phase ϕ is zero. In this diagram the wave labeled F_1 and F_2 move forward in time along the positive t axis, i.e., they lie on the "future" light cone. As in the classical case discussed above, these are called *retarded* waves. The waves F_3 and F_4 , on the other hand, move backward in time along the negative t axis. They lie on the "past" light cone, and as before are called *advanced* waves. We see in Fig. 1 that waves F_2 and F_3 are continuous, in the sense

that they lie along the same lightlike world line, and so are waves F_1 and F_4 . For the purposes of the present discussion we will consider only F_2 and F_3 , since F_1 and F_4 just represent the other pairs of independent spatial solutions of the wave equation.

The waves F_2 and F_3 still have an undefined phase factor ϕ . Assume that there is an electron at the origin of Fig. 1 which is oscillating with a position $y(t) = y_0 \cos(2\pi f)$ such as to produce these waves. It is well known¹⁵ that the retarded wave will lag the oscillation in phase by 90° , so $\text{Re}(F_2)$ is proportional to $+\sin(2\pi f)$ and $\exp(i\phi_2) = -i$. The advanced wave F_3 , which is the time reverse and therefore the complex conjugate of F_2 , will have a corresponding phase factor $\exp(i\phi_3) = +i$. Therefore, we may define the retarded- and advanced-wave solution in terms of these waves:

$$F_{\text{ret}} = F_2 = -iF_0 \exp[i(\vec{k} \cdot \vec{r} - 2\pi ft)] \quad (7)$$

and

$$F_{\text{adv}} = F_3 = +iF_0 \exp[i(-\vec{k} \cdot \vec{r} + 2\pi ft)]. \quad (8)$$

If we follow the space-time trajectory of these waves from negative x and t to positive x and t , we will see a continuous wave, expect that it has a 180° phase change at the origin in Fig. 1, i.e., the location of the source which produces the advanced and retarded waves. Thus, a superimposed wave which cancels F_{adv} will tend to reinforce F_{ret} and vice versa.

We can investigate the energies and momenta of these two waves by operating on them with the total energy operator $\underline{H} \equiv (i\hbar)d/dt$ and the momentum operator $\underline{P} \equiv i\hbar\nabla$. Doing this, we find that

$$\underline{H}(F_{\text{ret}}) = +hfF_{\text{ret}}, \quad \underline{P}(F_{\text{ret}}) = +\hbar\vec{k}F_{\text{ret}}, \quad (9)$$

and

$$\underline{H}(F_{\text{adv}}) = -hfF_{\text{adv}}, \quad \underline{P}(F_{\text{adv}}) = -\hbar\vec{k}F_{\text{adv}}. \quad (10)$$

We note that the energy of a photon is $E = hf$ and its momentum is $\vec{p} = \hbar\vec{k}$. Thus, the retarded solution is characteristic of a light photon having a momentum vector \vec{p} and positive energy, while the advanced solution is characteristic of a light photon having negative energy and has a momentum vector $-\vec{p}$, i.e., in the opposite direction from that of the retarded wave. Although the energy and momentum were obtained for a specific example, the result is quite general.

In Fig. 1 waves F_1 and F_2 both have positive energy, while waves F_3 and F_4 both have negative energy. This bears on the "zig-zag" problem posed by Gold^{16,27}; there is *no* solution of the electromagnetic wave equation which has the characteristic of negative energy and also moves in the

"future" light cone. This is because the time direction and the characteristic energy are intimately connected and share the same sign. In the example given in Eq. (6) the sign of the second exponential determines both the time direction and the sign of the characteristic energy of the wave.

The conventional interpretation of the above solutions is that the retarded solution corresponds to the process of emission of electromagnetic radiation, e.g., from an accelerated charge, and the advanced solution describes the absorption of electromagnetic radiation, so that the characteristic negative energy of that solution has the effect of increasing the energy of the absorber. Thus, we would have

$$F_{\text{rad}}(\vec{r}, t) = F_{\text{ret}}(\vec{r}, t) \quad (11)$$

and

$$F_{\text{abs}}(\vec{r}, t) = F_{\text{adv}}(\vec{r}, t). \quad (12)$$

In one sense the conventional approach does apparently have time symmetry, because an observer viewing a movie made of a microscopic emission of radiation followed by its absorption would not be able to say whether the movie was running forward or backward in time sequence. This apparent symmetry and the association of advanced radiation with absorption has led to some confusion in the literature,¹⁷ as to the time symmetry of the conventional approach to electrodynamics. However, in a deeper sense it should be clear that the conventional boundary conditions on electromagnetic radiation are *not* time symmetric, since they predict that if we pass an alternating current through an antenna we will observe retarded waves diverging from the antenna to infinity and toward the infinite future, not advanced waves converging on the antenna from infinity and from the infinite past. The choice of the conventional boundary condition imposes an *ad hoc* electromagnetic direction of time.

III. WHEELER-FEYNMAN ABSORBER THEORY

In 1945 a paper was published by Wheeler and Feynman¹⁸ describing what has come to be known as Wheeler-Feynman absorber theory, or simply absorber theory.¹⁹ This approach to electromagnetism, which was anticipated to some extent by the work of Dirac,²⁰ Fokker,²¹ and of Tetode,²² proposes a time-symmetric boundary condition which asserts that a proper electromagnetic wave is composed of a half-amplitude retarded wave and a half-amplitude advanced wave, and that such waves are characteristic of both emission and absorption processes.

The 1945 Wheeler-Feynman paper¹⁸ was pre-

occupied with radiative reaction and damping and demonstrated in four separate ways that the damping arose not from the interaction of the radiating particle with its own field but from its interaction with the advanced wave(s) produced by the distant absorber(s). It asserted as a postulate that the radiating particle did *not* interact with its own field, and placed a great deal of importance on this postulate because of its implications for the self-energy problem of the electron. However, Feynman later pointed out²³ that this noninteraction postulate is probably invalid, as demonstrated in certain situations arising in quantum electrodynamics (e.g., the Lamb shift) in which the interaction of an electron with its own field is required.

For the purpose of the present work the validity of the self-interaction postulate is considered irrelevant. As will be shown below, the time symmetry of the emitted radiation requires that there be no *net* reaction and damping when a time-symmetric pair of waves, advanced and retarded, are emitted simultaneously and so the noninteraction postulate is not needed. Further, the electron's self-energy is *needed* to explain the Lamb shift, and so the "out" of eliminating the self-energy problem by invoking the noninteraction postulate looks considerably less attractive.

However, there is a related problem for which absorber theory offers an advantage. Dirac, in his analysis of the radiation of an accelerated electron,²⁰ pointed out that the conventional approach to electrodynamics is troubled not only by the self-energy divergence but also by analogous singularities in the radiation field near the radiating electron. He showed this by including the advanced-wave contributions to the radiation field (which is equivalent to using the Wheeler-Feynman time-symmetric boundary condition), these radiation-field singularities (but not the self-energy singularity) were eliminated. For this reason, Konopinski²⁴ in his Lorentz-covariant treatment of electron radiation has adopted this "Lorentz-Dirac" approach, and points out that this elimination of the radiation-field singularities amounts to a *de facto* renormalization of the theory.

Another difference in approach between the present work and previous treatments of absorber theory^{18,19,25-27} is that the latter papers employ very general (but rather nontransparent) formalism and are concerned with the interaction between the emitter and a large number of absorbing sites. Here, on the other hand, we will use the simplest and most transparent formalism which is consistent with the points to be made and will concentrate on a "minimum" emitter-absorber "transaction." More elaborate emitter-absorber events such as those discussed in previous works

on absorber theory^{18,19,25,27} (cf. the two examples given in Ref. 18) are linear superpositions of these minimum transactions.

The time-symmetric boundary conditions postulated by Wheeler and Feynman do not impose an *ad hoc* time direction. They may be restated as follows: (1) The process of emission produces an electromagnetic wave consisting of a half-amplitude retarded wave and a half-amplitude advanced wave which lie along the same four-vector but with opposite time directions. (2) The process of absorption is identical to that of emission and occurs in such a way that the wave produced by the absorber is 180° out of phase with the wave incident on it from the emitter. (3) An advanced wave may be *reinterpreted* as a retarded wave by reversing the signs of the energy and momentum (and therefore the time direction) of the wave, and likewise a retarded wave may be reinterpreted as an advanced wave. Thus in the Wheeler-Feynman scheme, emission and absorption will correspond to the time-symmetric combinations

$$\vec{F}_{\text{rad}}(\vec{r}, t) = \left[\frac{1}{2} \vec{F}_{\text{ret}}(\vec{r}, t) + \frac{1}{2} \vec{F}_{\text{adv}}(\vec{r}, t) \right] \quad (13)$$

and

$$\vec{F}_{\text{abs}}(\vec{r}, t) = -\left[\frac{1}{2} \vec{F}_{\text{ret}}(\vec{r}, t) + \frac{1}{2} \vec{F}_{\text{adv}}(\vec{r}, t) \right]. \quad (14)$$

These describe both emission and absorption with the same time-symmetric combination of advanced and retarded radiation. In interacting with this time-symmetric field which it has produced, the emitter (or absorber) *cannot* change its energy or momentum, for such changes are intrinsically unsymmetric in time and therefore cannot result from interactions with a time-symmetric field. Thus, this simultaneous emission of a pair of waves, advanced and retarded, can produce no energy or momentum change in the emitter.

The emission of these time-symmetric electromagnetic waves produces some immediate problems in its correspondence with observation, for the emitter experiences neither recoil (i.e., momentum transfer) nor energy loss in the act of emission. Thus an emitter, e.g., an oscillating electron, could emit such radiation indefinitely without "noticing," since neither its energy nor its momentum would be affected by such emissions. Clearly this does not fit with observations.

However, if *absorption* of the emitted retarded wave occurs sometime later, the correspondence with observation is restored. Let us refer to Fig. 2, in which an emitter + absorber event is illustrated. The absorber, according to rule (2) above, can be considered to perform the absorption by producing a canceling retarded wave which is exactly 180° out of phase with an incident radiation, so that the incident wave "stops" at

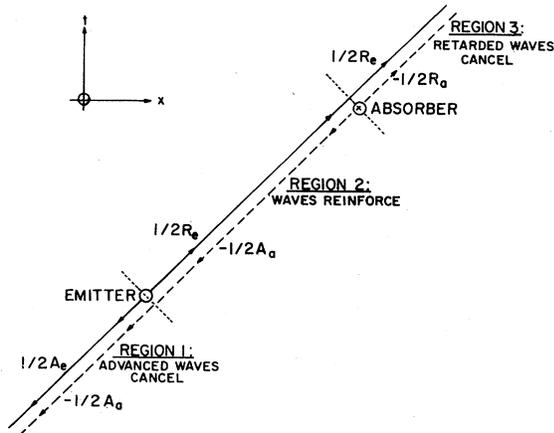


FIG. 2. Minkowski diagram of type I emitter-absorber transaction. The emitter produces a retarded half-amplitude wave R_e and an advanced half-amplitude wave A_e . The absorber produces a half-amplitude retarded wave R_a which cancels R_e in region 3. It also produces a half-amplitude advanced wave A_a which reinforces R_e in region 2 and cancels A_e in region 1. An observer sees only a full-amplitude retarded wave ($R_e + A_a$) in region 2 passing from emitter to absorber. (Dashed lines indicate 180° phase shift.)

the absorber. But the Wheeler-Feynman time-symmetric boundary condition tells us that the production of this canceling wave will be accompanied by the production of an *advanced* wave, which will carry negative energy in the reverse time direction and travel back, both in space and in time, to the point and the *instant* of emission. This advanced wave, according to rule (3) above, may be reinterpreted as a retarded wave traveling in the opposite direction and will *reinforce* the initial retarded wave, raising it from half to full amplitude. When the new advanced wave “passes” the point (and instant) of emission it will be superimposed on the initial half-amplitude advanced wave and, because of the 180° phase difference imposed by the absorber, it will cancel this wave completely.

Thus, an observer viewing this process will perceive no advanced radiation, but will describe the event as the emission of a *full-amplitude* retarded wave by the emitter, with appropriate energy loss and recoil, followed by the absorption of this retarded wave by the absorber at some later time, with accompanying energy *gain* and recoil. The recoils during emission and absorption occur because the respective emitter and absorber, presumably charged particles such as electrons, move in the electromagnetic fields of the waves, advanced and retarded, respectively, sent to them by the *other* charged particle, as demonstrated by Wheeler and Feynman.¹⁸ The

energy loss during emission and gain during absorption occur because the uncanceled full-amplitude wave carries energy from the emitter to the absorber. From one point of view, the emission-absorption process can be thought of as a standing wave in space-time, with the boundaries of the wave being the “terminating” emitter and absorber which bounce the wave back (as advanced radiation) and forward (as retarded radiation) between them.

The process described above can also be thought of as the emitter sending out a “probe wave” in various allowed directions, seeking a transaction. An absorber, sensing one of these probe waves, sends a “verifying wave” back to the emitter conforming the transaction and arranging for the transfer of energy and momentum. This is very analogous to the “handshake” procedures which have been devised by the computer industry as a protocol for the communication between subsystems such as computers and their peripheral devices. It is also analogous to the way in which banks transfer money, requiring that a transaction is not considered complete until it is confirmed and verified.

It is sometimes stated that Wheeler-Feynman absorber theory requires that there be an absorber for each emitted wave. This is not strictly true, as can be seen by considering another kind of transaction which can be deduced from absorber theory, and which is illustrated in Fig. 3. Here

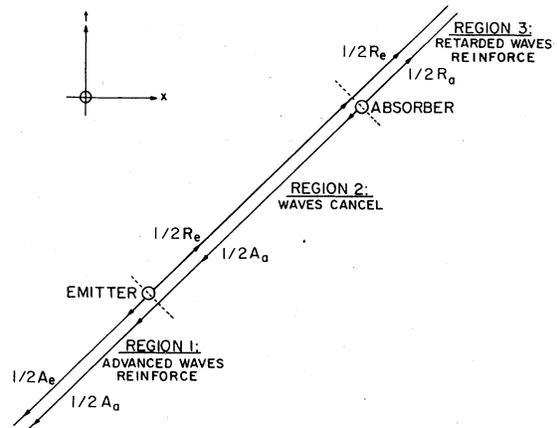


FIG. 3. Minkowski diagram of type II emitter-absorber transaction. As before the emitter produced half-amplitude waves A_e and R_e while the absorber produced half-amplitude waves A_a and R_a . Waves R_e and A_a cancel in region 2 while advanced waves A_e and A_a reinforce in region 1 and retarded waves R_e and R_a reinforce in region 3. An observer sees a full-amplitude advanced wave moving from emitter in negative t direction and a full-amplitude retarded wave moving from emitter in positive t direction. Both waves are “open ended,” in that they do not (and must not) have absorbers or emitters at their “other ends.”

we have the same emission and absorption events as those described in Fig. 2, except that the sign of the waves produced by the absorber is reversed. Because of this, it is the waves connecting the emitter and absorber which are canceled, while the advanced wave from the emitter toward negative time and retarded wave from the absorber in the positive time direction are brought up to full amplitude. This will be called a type II transaction, as contrasted with the previously described transaction which we will henceforth designate as type I. It has the problem that neither of the emitted waves may be terminated by later absorbers (or by earlier emitters) which is unlikely in most physically realistic cases. For the purposes of the present discussion, therefore, we will give no further consideration to type II transactions. We note that Wheeler and Feynman¹⁸ and a number of subsequent authors have discussed rather complicated emitter-absorber situations, but that these can always be reduced to a linear superposition of the type I and type II transactions described above.

Of course, these transactions must be time symmetric and therefore need not take place in the sequence described above and shown in Figs. 2 and 3. The absorption could have just as well have involved the *advanced* wave and have occurred *before* the emission. If we exchange the labels "emitter" and "absorber" in Fig. 2, then it also illustrates this process. However, Hogarth has shown²⁵ that in Wheeler-Feynman absorber theory for a system with many interconnected electromagnetic interactions involving radiation and absorption there are only two stable equilibrium conditions: The system is either completely dominated by advanced or by retarded radiation, depending on differences in the probability of absorption in the past and in the future. There have been attempts to deduce the observed predominance of retarded radiation over advanced radiation in two distinct ways. Wheeler and Feynman have attempted to derive this predominance from the thermodynamic properties of the absorbing medium. More recently cosmologists, particularly Hogarth²⁵ and Hoyle and Narlikar²⁶ have attempted to derive it from the cosmological expansion of the Universe. Neither approach, however, has been able to withstand close scrutiny²⁸ and the connection between the predominance of retarded electromagnetic radiation and the other time asymmetries of our Universe is still an unsolved problem.

It might be argued that the Wheeler-Feynman formulation of absorber theory is strictly a classical one, and is therefore inappropriate to discussions of quantum-mechanical paradoxes. However, the approach lends itself quite naturally to

a quantum-mechanical formulation since it is basically just an alteration of the choice of boundary conditions applied to the solutions of classical or quantum-mechanical wave equations. In particular, Hoyle and Narlikar^{29,30} and Davies³¹⁻³³ have presented quantum-mechanical formulations of absorber theory. Hoyle and Narlikar have demonstrated, using the Feynman path-integral technique, that absorber theory can be applied to the description of spontaneous transitions in atoms. They point out that second quantization of the field is absent in their formulation, but demonstrate that they are able to successfully describe a process usually thought to require a description involving second quantization. They have also demonstrated in their second paper³⁰ that all of the rules of quantum electrodynamics derived by Feynman can also be obtained from this quantum-mechanical formulation of absorber theory. Davies has presented a quantum-mechanical formulation using the S-matrix approach³¹ and has extended this formulation to the relativistic domain.³² He has also been able to derive from his formulation of absorber theory³³ the usual expression for the real photon processes of quantum electrodynamics. This body of work provides fairly convincing evidence that there are no barriers to treating absorber theory in a full quantum-mechanical framework.

In the discussion which follows, therefore, we will take as given that a complete quantum-mechanical formulation of absorber theory can be accomplished, and will concentrate on the insights into quantum-mechanical paradoxes that such a formulation provides.

IV. STRONG AND WEAK CAUSALITY

Absorber theory, because it involves advanced radiation, is not without its causality problems. At this point, however, we would like to make a distinction between two forms of the principle of causality which are often used interchangeably. We will call these the principles of strong and weak causality.

Strong-causality principle. A cause must always precede all of its effects in any reference frame. Information, microscopic or macroscopic, can never be transmitted over a spacelike interval or over a negative timelike or negative lightlike interval.

Weak-causality principle. A macroscopic cause must always precede its macroscopic effects in any reference frame. Macroscopic information can never be transmitted over a spacelike interval or over a negative timelike or negative lightlike interval.

Here by macroscopic cause we mean a cause initiated by an observer, by macroscopic effect we mean an effect which would allow an observer to receive information, and by macroscopic information we mean information which would allow one observer to communicate with another. Any other kinds of causes, effects, or information we consider to be microscopic, since they may affect the behavior of physical systems but are not useful for observer-observer communication. We note that an observer cannot use the EPR paradox to initiate the sending of a message from one detector to another, permitting another observer to receive it across a spacelike interval. Thus it is *microscopic* information transfer which is of concern in the EPR paradox, and therefore it is strong causality but *not* weak causality which is violated if the locality premise is shown to be invalid.

There is an analogy here to the situation with the group and phase velocities of electromagnetic waves in a wave guide¹⁵: The phase velocity can exceed c but cannot carry macroscopic information; the group velocity represents the speed of travel of macroscopic information but is never greater than c . If the phase of the wave can be considered to carry microscopic information (e.g., phase information which will affect interference phenomena) then its velocity represents a violation of strong causality. In any case, weak causality is not violated. We wish to emphasize that while there is abundant experimental evidence in support of the principle of weak causality, there is at present no experimental evidence for strong causality. Thus strong-causality violations are not a compelling reason for rejecting any particular approach.

In absorber theory there are always violations of strong causality since advanced radiation transfers microscopic information as well as energy in the negative time direction, but there can be no violations of weak causality as long as the absorption is complete in the "future" time direction, since absorber theory in this limit gives predictions identical with those of conventional electromagnetic theory.^{18,19} (Causality problems arising from incomplete future absorption are discussed more fully in Ref. 19.) Thus, assuming complete future absorption, absorber theory only implies violations of the strong-causality principle. Weak causality remains intact since there is no possibility of using the advanced waves to transmit macroscopic information. This is the reason that absorber theory is of interest in the context of the Einstein-Podolsky-Rosen paradox, for it is just such a violation of strong but not weak causality which is needed to explain the results of the tests of the Bell inequality.

V. ADVANCED RADIATION AND THE BELL INEQUALITY EXPERIMENTS

While the type I transaction described in Sec. III above is a simple one, the same "handshake" procedure can apply to a much more complicated process such as the simultaneous emission of two or more photons. This is relevant because in all but one case the experimental tests of the Bell inequality mentioned in Sec. I above involved the emission of pairs of polarization-correlated photons. Such a transaction would require a double "confirmation" from the two absorbers, or it would not take place. Note specifically that the two absorptions need *not* occur simultaneously in order to produce simultaneous confirmations at the point of emission because advanced radiation is the carrier of the confirmation and travels backward in time to the instant of emission, no matter how long after emission the absorption event occurred.

Let us then consider in more detail an absorber theory description of a Bell inequality test. In particular, let us consider the experiment of Freedman and Clauser,⁷ which was the first published experimental test of the Bell inequality. A schematic diagram of their apparatus is shown in Fig. 4. Calcium atoms emitted from an oven are excited to the $4p^2(^1S_0)$ excited state by resonance fluorescence using $2275\text{-}\text{\AA}$ ultraviolet radiation, from which they decay by a $J=0$ to $J=1$ to $J=0$ cascade. If the pair of photons emitted in this cascade are "back-to-back" in direction then ac-

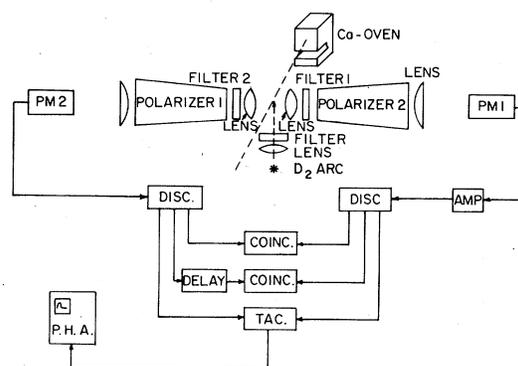


FIG. 4. Schematic diagram of the Freedman-Clauser experiment (Ref. 7). The oven (labeled Ca-OVEN) produces a beam of calcium atoms which are excited by ultraviolet light from arc discharge (D_2 ARC). Polarization-correlated light waves are detected by photomultipliers (PM 1, 2) after passing through the rotated polarization analyzers (POLARIZER 1, 2) [after Freedman and Clauser (Ref. 7)].

ording to angular momentum conservation they may be in any polarization state, but both must be in the *same* polarization state. The experiment measured the correlation of coincident photon detection rate as a function of the angle between the linear polarization analyzers in the two arms of the experiment. The results of the experiment were in good agreement with quantum-mechanical predictions and in conflict with the Bell inequality by several standard deviations. The EPR paradox, as it applies to this experiment, comes down to the question of how this quantum-mechanical result is enforced when the detection events are separated by a spacelike interval.

From the point of view of absorber theory it is not difficult to answer this question using the conceptual framework provided by the preceding discussion. The excited calcium atom will emit a number of probe waves corresponding to the possible emission of a pair of photons in various directions with various allowed polarization correlations. If "verifying" advanced waves are sent back by the pair of absorbers, then the transaction is complete and the double detection event has occurred. If the verifying waves do not match an allowed polarization correlation then they are not verifying the same transaction and will not, except accidentally, be correlated in time. This is illustrated in Fig. 5. In this situation the "two-bounce" standing wave described in Sec. II above becomes a "three-bounce" standing wave with one emission and two absorption boundaries.

Thus, in the context of absorber theory there is no paradox associated with the Freedman-Clauser result. It is just the consequence of a quantum-

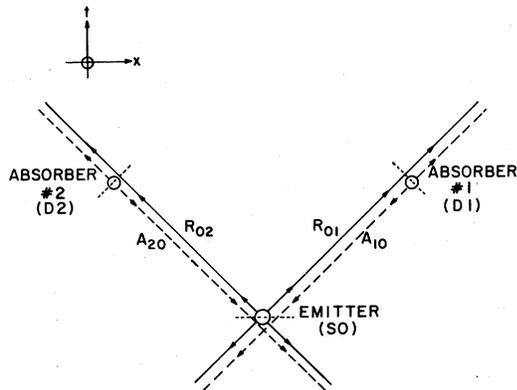


FIG. 5. Minkowski diagram of the absorber theory analysis of the Freedman-Clauser experiment (Ref. 7). The emitter (SO) sends half-amplitude retarded waves R_{01} and R_{02} to two detectors (D1 and D2). The detectors act as absorbers and produce advanced waves A_{10} and A_{20} which converge on source at instant of emission and "confirm" the "transaction."

mechanical transaction which takes place through the media of advanced and retarded electromagnetic waves. More specifically, let us consider the advanced and retarded waves to be four-vectors which provide lightlike space-time connections between detectors D1 and D2 and the source SO. The directions of these four-vectors represent the direction of transfer of microscopic information by the advanced and retarded waves. Let the source be separated from the two detectors by radius vectors \vec{r}_1 and \vec{r}_2 . The transit times for light to transverse these distances are t_1 and t_2 , respectively, and these are related to the distances by $ct_1 = r_1$ and $ct_2 = r_2$. The retarded waves traveling from the source to the detectors move along four-vectors which we will call R_{01} and R_{02} , and the advanced waves returning from the detectors to the source move along four-vectors which we will call A_{10} and A_{20} . Note that $R_{01} = -A_{10}$ and $R_{02} = -A_{20}$. Then the communication path from detector D1 to detector D2 is $A_{10} + R_{02}$. This is illustrated by a Minkowski diagram in Fig. 6(a).

The two lightlike four-vectors in this sum are

$$A_{10} = -R_{01} = -(\vec{r}_1, ict_1) = -(\vec{r}_1, ir_1) \quad (15)$$

and

$$R_{02} = (\vec{r}_2, ict_2) = (\vec{r}_2, ir_2), \quad (16)$$

and thus their sum is

$$A_{10} + R_{02} = ((\vec{r}_2 - \vec{r}_1), i(r_2 - r_1)). \quad (17)$$

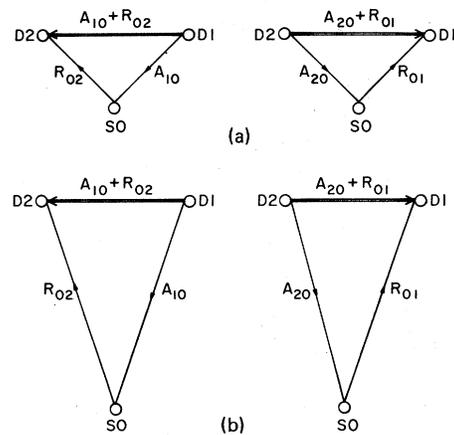


FIG. 6. (a) Minkowski diagram of the sums of lightlike four-vectors $A_{10} + R_{02}$ and $A_{20} + R_{01}$. Both combinations produce spacelike resultants (double lines). These are the communication paths between detectors in the Freedman-Clauser Experiment (Ref. 7). (b) Minkowski diagram of the sums of timelike four-vectors $A_{10} + R_{02}$ and $A_{20} + R_{01}$. Under the conditions stated in text, both combinations have spacelike resultants. These are the communication paths between detectors in the Laméhi-Rachti and Mittig experiment (Ref. 13).

The squares of the space and time parts of this sum are, respectively,

$$(\vec{r}_2 - \vec{r}_1)^2 = r_1^2 + r_2^2 - 2(\vec{r}_1 \cdot \vec{r}_2) \quad (18a)$$

and

$$(r_2 - r_1)^2 = r_1^2 + r_2^2 - 2r_1 r_2. \quad (18b)$$

But since $r_1 r_2 \geq (\vec{r}_1 \cdot \vec{r}_2)$, this four-vector will be *spacelike* unless \vec{r}_1 and \vec{r}_2 are exactly in the same direction, i.e., parallel, (which is not the case for any of the experimental tests of the Bell inequality). The communication path from detector $D2$ to $D1$, i.e., $A_{20} + R_{01}$, will also be spacelike.

More generally, the sum of a lightlike four-vector with a negative time component and a lightlike four-vector with a positive time component will be a *spacelike* four-vector, unless the two four-vectors are exactly antiparallel in four-dimensional space. Thus, absorber theory provides a mechanism whereby detector $D1$ can communicate microscopically with detector $D2$, and vice versa, over a spacelike interval in just the way needed to explain the EPR paradox.

VI. OTHER QUANTUM-MECHANICAL PARADOXES

The conceptual framework provided by absorber theory, as outlined above, has provided a means of understanding the EPR paradox. Its application, however, is not limited to that particular conceptual problem of quantum mechanics but can also be applied to the understanding of other quantum-mechanical paradoxes.

Let us consider, for example, the famous "Schrödinger's cat" paradox³⁴ and Wigner's variant of this basic conceptual problem, which is sometimes called the "Wigner's friend" paradox.³⁵ The latter involves a variation of the former by introducing a second observer who observes what happens to the first observer (who replaces the cat) and by having both observers report their observations to a third observer. Both of these problems involve the role of the observer(s) in the experiment and particularly their role in the collapse of the state vector (or "wave packet") by the act of observation. From the point of view of absorber theory neither of these *Gedankenexperimente* is particularly troublesome because the collapse of the state vector is implemented in just the right way by the confirmation with advanced waves of the quantum-mechanical transaction. It is the absorber, not the observer, which collapses the state vector, but absorption is an essential part of observation.

The role of the absorber in the collapse of the state vector is perhaps even better illustrated by considering a new quantum-mechanical paradox

which has recently been proposed by Wheeler, which he calls a "delayed choice" experiment.³⁶ Since this paradox is not yet widely known, it would perhaps be appropriate to briefly describe it here: A standard Young two-slit interference experiment is modified (a) by arranging the light source to emit only one photon at a time, (b) by modifying the photographic emulsion which records the interference pattern so that it is mounted in a pivoting lattice of strips like a "Venetian blind," and (c) by placing behind this lattice two photomultiplier tubes with collimators and lenses arranged so that each may receive light from *only one* of the two slits. Thus, with the lattice closed to experiment records the interference pattern resulting from the wave function of the emitted photons passing through *both* slits, while when the lattice is opened the experiment determines the slit through which each photon passes (*either* slit 1 or slit 2).

So far there is no problem, since the experiments cannot be performed on the same photon, the lattice being either opened or closed. Further, while the experiments are complementary and mutually exclusive, both are feasible measurements. The paradox arises in the following way: The observer (who has a very fast reaction time) *waits until after the photon has passed through the slits to decide which of the two complementary experiments is to be performed*. This means that the photon must "commit itself" to passage through a single slit or both slits *before* it is decided which experiment is to be performed.

Wheeler's conclusion from considering this and several other delayed choice *Gedankenexperimente* is that the objective reality of the wave function during the passage of the photon through the slit system is brought into question; that the wave function is essentially *made* real by the "irreversible act of amplification" which tells us which slit was transited or by the "indelible record" made by the interference pattern on the photographic emulsion.

It is informative to analyze the delayed-choice experiment described above within the conceptual framework provided by absorber theory. The retarded "probe wave" from the light source spreads out in various directions, and in particular passes through both of the slits on its way to the detection apparatus. If the detector lattice is *closed*, then the wave impinges on the photographic emulsion and is absorbed. In the process of absorption the emulsion generates the advanced waves which confirm the transaction and these pass back through both slits to the light source, so that the event involves passage through both slits.

If the lattice is *open*, then the wave travels to the photomultiplier detectors, and one of these absorbs the wave, generating the confirming advanced wave. However, because of the collimator system associated with the photomultiplier, this advanced wave is able to travel back to the source through *only one of the slits* (the one at which the detector system is aimed). Thus the transaction in this case involves the passage of the photon through only one slit.

Notice that in this analysis the choice of which detector system is used can be made either before or after the retarded wave has passed through the slit system without affecting the analysis. This, of course, is because of the role of the advanced wave in traveling backward in time to the instant of emission to confirm the transaction across a negative lightlike interval.

The above example may be taken as illustrative of the power of the conceptual framework provided by absorber theory for dealing with quantum-mechanical paradoxes. We will limit our discussion to the above paradoxes. However, we have not as yet been able to discover any such paradox which cannot be satisfactorily dealt with in this conceptual framework. This gives us some assurance that quantum-mechanical wave functions *can* be viewed as having some objective reality beyond their role as a mathematical tool for calculating experimental results, at least within the context of absorber theory.

VII. GENERALIZED ABSORBER THEORY

In the discussion above, we have shown for the case of electromagnetic radiation that the problem posed by the EPR paradox can be solved by the application of Wheeler-Feynman absorber theory. We here assert that the Wheeler-Feynman protocol for an emission-absorption transaction is not a peculiarity of electromagnetism. Rather, *the Wheeler-Feynman emission-absorption protocol is a general feature of the emission and absorption of all particles and waves, whether fermions or bosons, whether charged or uncharged, whether massive or massless.* The justification for this assertion is that the Wheeler-Feynman description of emission and absorption accounts for the violations of locality in the Bell inequality experiments involving light waves (i.e., massless uncharged bosons), but the experimental results of Laméhi-Rachti and Mittig¹³ demonstrate that locality is violated also in a Bell inequality test involving protons (i.e., massive charged fermions). The Wheeler-Feynman description therefore must be generalized to make it applicable to the latter experimental result.

However, there are problems with such a generalization. The electromagnetic wave equation has advanced as well as retarded solutions because it is a second-order differential equation in the time variable. The corresponding wave equation for particles with nonzero rest mass is the Schrödinger equation. In its field-free time-dependent form, the Schrödinger equation can be written

$$-(\hbar^2/2M)\nabla^2\psi = i\hbar d\psi/dt, \quad (19)$$

where $-\hbar^2\nabla^2 \equiv \underline{P}^2$ is the momentum-squared operator, $i\hbar d/dt \equiv \underline{H}$ is the total energy operator, M is the particle mass, and ψ is the quantum-mechanical wave function of the particle of interest.

Clearly, this equation is only first order in time and would have only a single solution corresponding to the positive energy or retarded solution of the electromagnetic wave equation. Thus it would seem that the absorber theory arguments could not be applied to the case of massive particles.

However, we know that the Schrödinger equation is not correct, since it is not a proper relativistically invariant wave equation. For spin- $\frac{1}{2}$ particles the appropriate relativistically invariant equation is the Dirac equation,³⁷ which can be written in the form

$$-[c(\underline{\alpha} \cdot \underline{\vec{P}}) + \beta M c^2]\psi = i\hbar d\psi/dt, \quad (20)$$

where c is the velocity of light, $\underline{\vec{P}}$ is the momentum operator ($= -i\hbar \underline{\nabla}$), M is the rest mass of the particle of interest, and $\underline{\alpha}$ and β are dimensionless spin-dependent 4×4 matrices which are independent of momentum, energy, position, and time. This leads to a set of four coupled differential equations involving the initial and final spin states of the particle of interest, and these equations, like the electromagnetic wave equation, have both positive- and negative-energy solutions. The negative-energy solutions of the Dirac equation are conventionally interpreted as corresponding to antimatter waves (positrons, antiprotons, etc.).³⁹ We note that Pauli and Weisskopf⁴⁰ have shown that the quantized field energy is always positive, even when the eigenvalue of the energy operator \underline{H} has a negative sign. Thus when we call a particular solution of the wave equation a positive- or negative-energy solution, we refer to the eigenvalue of the \underline{H} operator.

For particles having spins other than $\frac{1}{2}$, e.g., bosons, the situation is more confused because there are a number of alternative relativistically invariant wave equations found in the literature. A full catalog of such wave equations is beyond the scope of this paper, but several which are appropriate to massive spinless bosons are of particular interest. A wave equation widely used in

quantum mechanics at relativistic energies is the relativistic Schrödinger equation⁴¹ (sometimes also called the Thomas equation). In field-free space it has the time-dependent form

$$[-(\hbar c)^2 \nabla^2 + (Mc^2)^2]^{1/2} \psi = i\hbar d\psi/dt, \quad (21)$$

where ψ is the quantum-mechanical wave function of the particle of interest, $-\hbar^2 \nabla^2 \equiv \underline{P}^2$ is the momentum-squared operator, M is the rest mass of the particle, $i\hbar d/dt \equiv H$ is the total-energy operator, and the positive square root is assumed. This equation, like the nonrelativistic Schrödinger equation, is first order in time and therefore has only positive-energy solutions. It would therefore be inappropriate for a Wheeler-Feynman type of emitter-absorber transaction.

A more satisfactory alternative is the time-dependent Klein-Gordon equation,³⁷ which is essentially the square of the relativistic Schrödinger equation and in field-free space has the form

$$[-(\hbar c)^2 \nabla^2 + (Mc^2)^2] \psi = -\hbar^2 d^2 \psi / dt^2, \quad (22)$$

where the symbols are as defined above and $-\hbar^2 d^2/dt^2$ is the total-energy-squared operator. This equation, like the Dirac equation and the electromagnetic wave equation, has both positive- and negative-energy solutions and would therefore be appropriate for a generalization of the Wheeler-Feynman approach. Notice that when $M = 0$ the Klein-Gordon equation becomes effectively the same as the electromagnetic wave equation (1). We note that there are other more general wave equations, such as the Bethe-Salpeter equation,⁴² which also have the desired property of giving both positive- and negative-energy solutions.

To generalize absorber theory we assert that a proper wave equation for any particle, of whatever rest mass, charge, spin, and other quantum numbers, *must* have both positive- and negative-energy solutions, i.e., advanced and retarded solutions, so that the kind of transaction described above for electromagnetic waves can occur for the wave functions of all particles. We generalize the Wheeler-Feynman boundary conditions stated in Sec. III above to the following: (1) Emission of a particle (or wave) consists of the production of two half-amplitude wave functions with opposite time directions, energies, and charges. (2) Absorption consists of the same production of a pair of half-amplitude waves, such that the retarded wave produced by the absorber is 180° out of phase with the retarded wave received from the emitter. (3) The time directions of such waves can be reversed by reversing the signs of the energy and charge of the waves [as first pointed out by Stückelberg³⁸ and later by Feynman,³⁹ a positron (energy < 0) going backward in time is

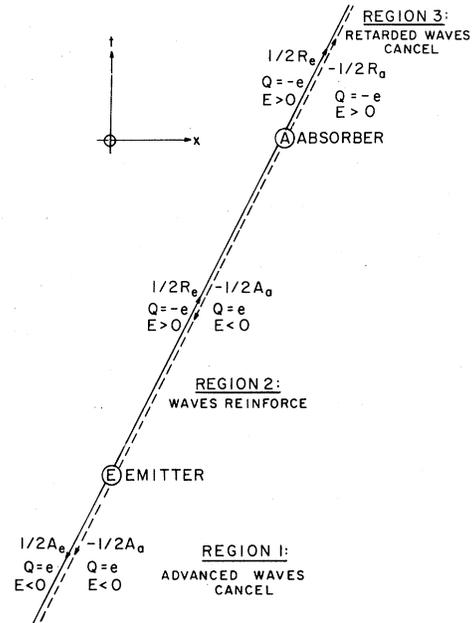


FIG. 7. Minkowski diagram of type I transaction involving the emission and absorption of an electron. The emitter produces half-amplitude wave functions A_e and R_e . The absorber, responding to R_e produces wave functions R_a and A_a such that R_a cancels R_e in region 3. Wave A_a reinforces R_e in region 2 and cancels A_e in region 1. An observer sees an electron traveling from emitter to absorber through region 2. (Dashed lines indicate 180° phase shift.)

indistinguishable from an electron (energy > 0) going forward in time]. (4) Only amplitudes with the same charge, time direction, and energy can interfere, subject to the reinterpretation given in (3) above. We note that while formally the advanced wave required by (1) above is a positron moving away from the point of emission, its negative energy in the context of rule (3) means that an observer would be likely to describe it as an electron with positive energy moving toward the point of emission.

Figure 7 illustrates the emission and absorption of an electron in this scheme. It is the electron analog of the photon emission and absorption which was shown in Fig. 2. The emitter (e.g., an atom emitting an electron by the Auger process) produces two half-amplitude waves R_e and A_e which are, respectively, a retarded wave having characteristics of negative charge, positive energy, positive time direction, and amplitude $\frac{1}{2}$, and an advanced wave having the characteristics of positive charge, negative energy, negative time direction, and amplitude $\frac{1}{2}$. The absorber is stimulated by the arriving wave R_e to produce the two half-amplitude waves R_a and A_a which are respectively, a retarded wave of amplitude $\frac{1}{2}$ identical to R_e ex-

cept that it is 180° out of phase, and an advanced wave which is identical to A_e except that it is 180° out of phase. We see that in the "future" of the absorption event R_e and R_a exactly cancel, while in the "past" of the emission event A_e and A_a exactly cancel. Further, using rule (3) above we may *reinterpret* wave function A_a in the interval between the emission and absorption events as a retarded wave with negative charge, positive energy, positive time direction, and amplitude $\frac{1}{2}$. Thus, R_e and A_a will constructively interfere to produce a full-amplitude wave function.

Here again we see that we can form a transaction between emitter and absorber by a superposition of advanced and retarded waves. We can apply this view to the Bell inequality experiment of Laméhi-Rachti and Mittag,¹³ in which a pair of spin-correlated protons in a relative S state are observed in detection events separated by a spacelike interval, paralleling our analysis of the Freedman-Clauser experiment discussed in Sec. V above. Here, however, the waves connecting the detectors with the source span *timelike* intervals, since the protons move with velocities less than c .

As was done for the Freedman-Clauser experiment, let us examine the communication path from detector $D1$ to detector $D2$ via advanced and retarded waves represented by the timelike four-vectors A_{10} and R_{02} . These four-vectors can be written as

$$A_{10} = (-\vec{r}_1, -ict_1) = -(\vec{r}_1, ir_1/\beta_1) \quad (23)$$

and

$$R_{02} = (\vec{r}_2, ict_2) = (\vec{r}_2, ir_2/\beta_2), \quad (24)$$

where β_1 and β_2 are the velocities ($\beta < 1$) of the protons traveling to detectors $D1$ and $D2$. The sum of these two timelike four-vectors is not necessarily spacelike, as was the case for light waves, but will be spacelike if the detectors are in opposite directions with equal path lengths and the two protons travel to the detectors with the same velocity. In that case, $\vec{r}_1 = -\vec{r}_2$ and $\beta_1 = \beta_2$, so the sum of the two four-vectors will be

$$(\vec{r}_1 - \vec{r}_2, i(r_1 - r_2)/\beta) = (2\vec{r}_1, 0), \quad (25)$$

which is clearly a spacelike interval. This is illustrated by the Minkowski diagram shown in Fig. 6(b).

We wish to acknowledge that the above description of detector-detector "communication" is very close to a more restricted and specific one given by Costa de Beauregard.^{43,44} He has pointed out that the timelike symmetry of electron and

positron wave functions in the Feynman picture can, in principle, account for violations of EPR locality and has certain implications about the CP invariance of such events. However, his conclusion is based on the consideration of the electron-positron waves in a creation-annihilation event. It therefore involves "true" positron wave functions having a time direction and energy which is opposite the advanced positron waves in the present description.

Thus we see that the generalized Wheeler-Feynman approach has provided an explanation of the results of all of the Bell inequality tests, whether involving light waves or protons. The conclusion then is that the concept of locality is invalid in quantum mechanics because there *is* communication of microscopic information between detectors over spacelike intervals arising from the verification of a quantum-mechanical "transaction" provided by advanced-wave functions.

VIII. EXPERIMENTAL CONSEQUENCES

The generalization of Wheeler-Feynman absorber theory presented here is not really a revision of the conventional theory, but only the application of slightly different boundary conditions to the solution of the wave equations and a reinterpretation of the results. Therefore, it would be very surprising if there were any substantive changes in the quantum-mechanical predictions of experimental results. Thus, a definitive experimental test of the approach may be difficult to arrange.

The requirement stated above that all wave equations must have negative-energy solutions is, at least in principle, experimentally testable. For instance, the relativistic Schrödinger equation predicts relativistic corrections to Rutherford scattering which are different and may be experimentally distinguishable from those predicted by the Klein-Gordon equation or the Bethe-Salpeter equation.⁴⁵ However, the existence of boson antiparticles, e.g., pions, kaons, η 's, etc., require this type of equation for adequate treatment in any case, so an experimental proof that the wave equations have negative-energy solutions could hardly be taken as verification of generalized absorber theory.

There is one other effect which is of possible experimental importance in this context. Absorber theory, unlike conventional quantum mechanics, predicts that in a situation where there is a deficiency of future absorption in a particular spatial direction, there will be a corresponding decrease in emission in that direction.

As a simple (classical) case of the above, an oscillating electron which was alone in an other-

wise "empty" (i.e., completely nonabsorbing) universe would not radiate at all.¹⁸ If a second electron were introduced, the first electron would be able to radiate only in the direction of this second "absorber" electron. In an "open" universe in which the absorbing matter is not distributed isotropically so that there was no absorption in a particular direction in space, we should find that an emitter will "refuse" to emit in that direction, because there must be (ignoring type II transactions for the moment) an absorber on the other end of every emission event to complete the transaction.

An attempt to observe this effect experimentally was made by Partridge using 9.7-GHz microwaves transmitted from a large conical horn antenna, so that the microwaves were beamed in various spatial directions and the power output of the transmitter accurately monitored.⁴⁶ Partridge found that there was no evidence for decreased emission in any direction, to any accuracy of a few parts in 10^9 . However, this experiment has been criticized by Davies⁴⁷ as necessarily yielding a null result because of absorption by the Earth of any advanced radiation approaching the back side of the experiment. In essence, Davies argues that the most general test of absorber theory would include the possibility of type II transactions, as discussed in Sec. III above. This would require an emitter system which was symmetric in opposite spatial directions, which, for microwaves, would probably require that the experiment was performed in deep space.

The author and collaborators⁴⁸ are currently performing an experiment similar to that of Partridge which satisfies the Davies criteria by employing neutrinos rather than microwaves as the "broadcast" medium. Since the Earth is quite transparent to low-energy neutrinos it is relatively straightforward to mount a bidirectionally symmetric experiment on the surface of the Earth. The "transmitter" is a radioactive source involving a pure Gamow-Teller β -decay transition which simultaneously emits neutrinos and direction-correlated β particles. Thus deficiencies in neutrinos emission will be reflected as asymmetries in the angular distribution of emitted β particles. An experiment of this type has several advantages over that of Partridge. (1) The Davies symmetry is easy to obtain in the experimental design. (2) The cosmological red-shift *decreases* the absorption probability; the low-energy cross section for the absorption of red-shifted photons goes up as $1/E$ because of the inverse bremsstrahlung process, while weak-neutral-current arguments imply that the low-energy neutrino scattering cross section at low energies should go down

as E^2 . (3) Since the neutrino is a fermion (and weakly interacting) it is intrinsically very difficult to absorb because the "left-over" half unit of spin is difficult for the absorber to dispose of without reemission. This experiment, of course, is not strictly speaking a test of the Wheeler-Feynman theory, which applied only to light waves, but rather a test of the generalized absorber theory as it applies to the emission and absorption of neutrinos.

It should also be pointed out that both this and the Partridge experiment are "long-shots," since most cosmological models of the Universe^{28,47,49,50} would predict negative results for both experiments. Thus the prospects for a definitive experimental test of generalized absorber theory appear at present to be rather unpromising, and the validity of this alternative approach to quantum mechanics may have to rest, at least for the moment, on its value in providing a framework for the resolution and understanding of quantum-mechanical paradoxes.

IX. CONCLUSION

In the preceding discussion we have demonstrated that generalizing Wheeler-Feynman absorber theory to make it a quantum-mechanical theory applying to all particles and waves has provided a conceptual framework within which a number of quantum-mechanical paradoxes can be resolved. In particular the Einstein-Podolsky-Rosen paradox,¹ the "Schrödinger's cat" paradox,³⁴ and indeed all other quantum-mechanical paradoxes examined including Wheeler's delayed-choice experiments,³⁶ can be understood by interpreting the lack of locality and the decomposition of the wave packet as arising from the action of advanced waves which verify the quantum-mechanical transactions. We have shown that the communication path between detectors in the Bell inequality experiments can span a spacelike interval and produce the quantum-mechanical result through the addition of two lightlike or timelike four-vectors having time components of opposite sign, thus accounting for the locality violations implied by the experimental results.

Accepting quantum-mechanical absorber theory as a favored alternative to the usual field-theory approach to quantum-mechanical phenomena has some implications of interpretation which should be seriously considered. As has been pointed out by other authors,^{18,19,27,29,31} absorber theory is basically an "action-at-a-distance" formulation. It demotes the concept of a field from the status of a real entity with its own degrees of freedom to that of a mathematical convenience, a conceptual

prop for thinking about transactions between emitters and absorbers. Whether this is acceptable must ultimately rest on the relative predictiveness of the two alternative approaches.

However, the absorber theory approach raises questions as well as settles them. In closing, therefore, we would like to enumerate three of the more troublesome questions raised by the generalized absorber theory presented here.

(1) If only a single particle is emitted by a system and future absorbers provide more than one "verification," how is the conflict of multiple verifications resolved so that only a single "transaction" is verified?

(2) If absorber theory is applied to very weakly absorbed particles such as neutrinos, how can the observed emission of such particles be reconciled with their low probability of future absorption, particularly in the open-universe models which are supported by some experimental evidence?

(3) How can the observed dominance of retarded radiation be accounted for in terms of absorber theory, when the big-bang model would imply at least as much as absorption in the past as in the future?

Problem (1) above is worth understanding, for it decides whether the Wheeler-Feynman approach is a deterministic or a probabilistic theory. If the "referee" which makes the decision in situations of multiple verifications acts strictly at random then the quantum theory described here, for all its verifications, transactions, and communication links is still a probabilistic theory, consistent with the Copenhagen interpretation of quantum mechanics.

Although problems (2) and (3) mentioned above do not currently have answers, we do not consider them to be without solution. In fact, their answers may be connected. In a subsequent publication⁵¹ we will seek to deal with them using the conceptual framework provided by the present work.

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