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The Arrow of Electromagnetic Time and the Generalized Absorber Theory

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The problem of the direction of electromagnetic time, i.e., the complete dominance of retarded electromagnetic radiation over advanced radiaton in the universe, is considered in the context of a generalized form of the Wheeler–Feynman absorber theory in an open expanding universe with a singularity at T = 0. *It is shown that the application of a four-vector reflection boundary condition at the singularity leads to the observed dominance of retarded radiation; it also clarifies the role of advanced and retarded waves in the emission of very weakly absorbed radiation such as neutrinos.*

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1. INTRODUCTION

The problem of the direction of the electromagnetic arrow of time is perhaps the most perplexing of the major unsolved problems of contemporary physics, because the usual tools of theoretical physics cannot be used to investigate it. Even the clues provided by the CP violation of the K_2^0 meson, which have led to a profound insight into the dominance of matter over antimatter in the universe, have not shed any light on the problem of the origins of the electromagnetic arrow of time.

The fundamental reason why the arrow of time has been found to be such an intractable problem lies in the conventional treatment of the solutions of the relativistically invariant wave equations describing massive and massless particles. These equations have both retarded (or positive mass-energy) solutions and advanced (or negative mass-energy) solutions which are characteristic of the two possible directions of the arrow. However, the usual procedure is to invoke a "Causality" boundary condition which justifies the elimination of the advanced solutions as unphysical. Once

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causality is invoked, an arrow of time has been built into the formalism, and it is no longer possible to use the formalism as a tool for the investigation of the origins of the arrow.

However, there is an alternative approach which, while not in the mainstream of contemporary theory, represents an effective way of preserving the intrinsic time symmetry of the relativistically invariant wave equations and thereby avoiding the *ad hoc* insertion of an arrow of time into the formalism. This is the Wheeler–Feynman (WF) approach,(1) which was anticipated to some extent by the work of Tetrode,(2) Fokker,(3) and Dirac,(4) and which has been given quantum mechanical treatments and generalized by Hoyle and Narlikar,(5) Davies,(6) and Cramer.(7) The WF approach is to choose a time-symmetric linear combination of advanced and retarded solutions to the wave equation of interest, and to produce whatever time asymmetries are required to agree with experimental observation through the application of external boundary conditions which do not explicitly involve causality. The WF approach will be discussed further below.

While the time-symmetric WF formalism can, in principle, provide a tool for the investigation of the arrow of time problem, the previous uses of this tool for that purpose have not been notably successful. In fact, as will be discussed later, the best work employing the WF theory with various cosmological models would seem to predict an arrow of time which points in the wrong direction!

In a previous paper(7) (hereafter referred to as AT1) we employed a generalized form of the WF approach(1) to provide a solution to a number of "interpretational" quantum mechanical paradoxes (The EPR paradox,(8) The Schrödinger's cat paradox, Wheeler's delayed choice experiments, etc.). The basis for this work is the WF description of an emission-absorption event as an interchange of retarded and advanced waves between the emitter and absorber, respectively. This interchange can be thought of as the emitter sending out a probe wave in various allowed directions, seeking a "transaction" which is verified by the absorber. This transaction concept was shown to provide a mechanistic way of explaining the nonlocality of quantum mechanical processes, and thus to provide a partial solution to the twin problems of locality and completeness which have troubled the interpretation of quantum mechanics since its inception.

However, in AT1 the WF protocol for describing the emission processes was found to be inadequate for describing the emission of weakly absorbed radiation. In particular, when the WF description was applied to the emission of very weakly absorbed particles and waves such as neutrinos and certain frequencies of radio waves, the observed emission of such entities could not be readily reconciled with the less-than-unity probability of their future absorption. This problem is most dramatically illustrated by the case of low-energy neutrino emission, where there is a very high probability that there will be no future absorber (or scatterer) to provide the needed verification for the emitted neutrinos.

This problem and the related arrow of time problem were identified in AT1 as unsolved problems which represented serious *de facto* criticisms of the generalized WF approach. Before embarking on further applications of the WF approach, we will give a brief review of its formulation.

2. WHEELER–FEYNMAN ABSORBER THEORY

The Wheeler–Feynman absorber theory(1) was originally conceived as a time-symmetric alternative to conventional electromagnetism which, unlike the latter, imposes no *ad hoc* time direction on the electromagnetic processes. It is essentially a set of boundary-condition rules arising from the requirement of time-symmetry which are restated in AT1 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 axis 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; and (3) an advanced wave may be *reinterpreted* by an observer as a retarded wave by reversing the signs of the energy and momentum (and therefore the time direction) of the wave, and likewise an observer may reinterpret a retarded wave as an advanced wave.

Figure 1 illustrates this emitter-absorber protocol schematically using a Minkowski diagram. Here the relative phases of the waves are schematically represented as sinusoids inscribed on the light-like world-lines of the waves. The emitter-wave is shown as a solid line and the absorber-wave as a dashed line. In regions where they have opposite phases they will cancel each other and in regions where they have the same phase they will reinforce each other.

This combination of advanced and retarded waves specified by rule (1) describes both emission and absorption with the *same* time-symmetric combination of advanced and retarded radiation. While interacting with this time-symmetric field which it has produced, the emitter (or absorber) *cannot* change its energy or momentum, because such changes are intrinsically unsymmetric in time and therefore cannot result from the 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 therefore

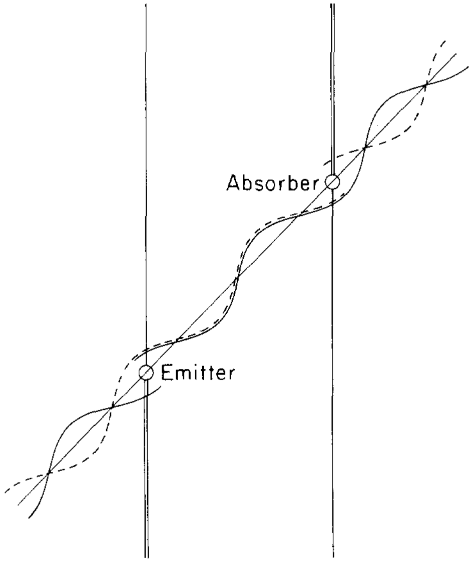

Fig. 1. Minkowski diagram showing an emitter-absorber transaction. The single vertical line indicates that the emitter or absorber is in a state of low-energy, while the double vertical line indicates a higher-energy state. Waves produced by the emitter and absorber will lie along the diagonal light-like world-line, but here the emitter waves are indicated schematically by the solid sinusoidal curves. Similarly, waves produced by the absorber are indicated schematically by the dashed sinusoidal curves. As can be seen, the advanced waves before the emission event and the retarded waves after the absorption event are 180° out of phase and will cancel each other, while the advanced and retarded wave in the interval between the emission and absorption events will reinforce each other.

raises some immediate problems in its correspondence with observation, because the emitter experiences neither recoil (i.e., momentum transfer) nor energy loss in the act of emission. However, if the *absorption* of the emitted retarded wave occurs sometime later, then, the correspondence with observation is restored. The observed recoiling during emission and absorption occur because the respective electrons move in the electromagnetic fields of the waves, advanced and retarded, respectively, sent to them by the *other* electron, as demonstrated by Wheeler and Feynman.(1)

As mentioned previously, the process described above can be though of as the emitter sending out a probe wave in various allowed directions, seeking a transaction. An absorber, responding to one of these probe waves, sends a verifying wave back to the emitter verifying the transaction and arranging for the transfer of energy and momentum. This and the previous point are discussed fully in AT1.

Of course, these transactions must be time-symmetric and therefore need not take place in the "emitter-absorber" the sequence described above. If there were only time-symmetric constraints on the system, the absorption could just as well have involved the *advanced* wave and it could have occurred *before* the emission, giving an "absorber-emitter" time sequence. It is the purpose of the present paper to explain why emitter-absorber events are observed in nature, but not the absorber-emitter events by explaining the origin of the time-asymmetric constraints on the system. We will return to this point later.

3. PREVIOUS APPLICATIONS OF ABSORBER THEORY TO COSMOLOGY

There have been a number of attempts in the literature to apply the WF approach to cosmology and to deduce from this the observed predominance of retarded radiation over advanced radiation. In their original paper,(1) Wheeler and Feynman attempted to derive this predominance from the thermodynamic properties of the absorbing medium in a static euclidian universe, attributing the electromagnetic arrow of time to the thermodynamic arrow of time implicit in the second law. Later authors have tended to reject this approach because of its incompatibility with reasonable models of the universe.

Hogarth demonstrated(9) that the application of the WF approach to a system with many interconnected electromagnetic interactions involving radiation and absorption and a high absorption probability in one or both time directions leads to only two stable equilibrium conditions: the system is either completely dominated by advanced radiation or by retarded radiation, depending on the difference in the probability of absorption in the past and in the future. Hogarth then attempted to connect the electromagnetic arrow of time to the cosmological expansion of the universe. Hoyle and Narlikar(5) later adopted a similar approach in relation to their "*C*-field" cosmological model based on an expanding universe with the continuous creation of particles. They argued that the *C*-field model alone is consistent with the dominance of retarded radiation and took this as evidence in support of their model. Roe(10) and Burman(11,12) have also employed the absorber theory and the observed dominance of retarded radiation as tools for investigating cosmological models.

Unfortunately, none of the treatments which "explain" the dominance of retarded radiation has been able to withstand close scrutiny. Davies(13) has shown quite convincingly that *any* ever-expanding cosmology (in the absence of a special postulate such as continuous creation of matter) will be transparent (i.e., deficient in future absorption) if $R(T)$ grows faster than $T^{1/3}$, where $R(T)$ is the time-dependent scale factor of the model, e.g., the radius of the universe. This means that there will always be more absorption in the past, where the absorber density is large because R is small, than in the "transparent" future.

Given the observed dominance of retarded radiation, this argument excludes *all* open-universe models except the Dirac model ($\sqrt{N}_p = m_p T$) and some of the C-field models of Hoyle and Narlikar. Moreover, Davies has also been able to show that the C-field models are not able to explain the dominance of retarded radiation for other reasons. In the context of absorber theory, this leads to the conclusion that the electromagnetic arrow of time should point in the *opposite* direction from that of the cosmological expansion of the universe, in clear contradiction to observation.

Closed universe models such as the oscillating Friedmann models are not subject to this criticism because they become opaque during their collapsing phase if R collapses faster than $T^{1/3}$, which is normally the case. However, because they collapse in *both* time directions, such models are intrinsically time-symmetric and cannot explain the dominance of retarded over advanced radiation (in the absence of additional special postulates). Treatments which assume that thermodynamic processes also have time-symmetry in such a model(10) therefore imply the necessity for a *mixture* of advanced and retarded radiation, in contradiction to observation.

If we generalize the ideas of the absorber theory beyond their application to classical electromagnetic radiation, as was done in AT1 and elsewhere, by assuming that the emitter-absorber transaction also applies to the emission and absorption of neutrinos, then models of the universe can also be examined as they apply to the neutrino processes. This has been done by Narlikar,(14) Csonka,(15) and Burman.(16,17,18) We note that the evidence for the complete dominance of retarded neutrino radiation is less compelling then is the case for the dominance of retarded electromagnetic radiation, but it is still fairly strong. In particular, experimental searches for post-endpoint electrons in beta decay processes (which would imply negative-energy, i.e., advanced neutrinos) have in effect set very low upper limits on the emission of advanced neutrinos with negative energies of less than −60 eV.(19)

The treatment of Burman in investigating the transparency of cosmological models to neutrinos follows that of Davies(13) discussed above, and concludes that open-universe models are transparent to neutrinos if R grows faster than $T^{1/3}$. This, then, is the same result which Davies obtained for electromagnetic radiation. However, in deriving this result Burman employed the assumption, based on the current-current model without weak neutral currents (which was the standard weak interaction model at the time the calculations were performed), that the effective neutrino cross section is independent of energy even at low energies. The neutral current model of weak interactions would imply that the latter assumption is correct at higher energies, but that as their energy goes to zero the neutrinos should gain transparency. It predicts(20) that at low energies the neutrino absorption cross section vanishes and the neutrino scattering cross section becomes proportional to E^2. The effect will become important for the red-shifted neutrinos traveling cosmological distances in an open universe, and implies that such a universe is transparent to neutrinos if R grows faster that $T^{1/5}$. This revision of Burman's calculation by the author then excludes the Dirac model mentioned above.

The conclusion of this body of work is that no reasonable model of the universe, either open or closed, is consistent with the observed predominance of retarded radiation in the context of the Wheeler–Feynman absorber theory, at least in the way in which the latter has been used in these calculations. This, then, would appear to place the WF absorber theory in direct conflict with contemporary cosmology. If no way can be found around this difficulty, it is a very serious criticism of the whole absorber theory approach.

4. A BOUNDARY CONDITION MODEL OF THE $T=0$ BIG BANG

The body of work cited above has demonstrated that essentially all of the open-universe models are "future-transparent," i.e., that these models lack the absorption necessary to account for all of the present emission of neutrinos and electromagnetic radiation in the context of the generalized Wheeler–Feynman absorber theory. However, there is also another problem which arises in considering the backward extrapolation of advanced waves to the $T=0$ point or the "origin" of a Big Bang model.

Let us imagine an advanced wave function which has just been produced in the emission of a very low-energy neutrino, and which now propagates backward in time toward the Big Bang. Assume that the medium is transparent enough to permit the wave to penetrate the region of high density and energy just after the "origin." What happens when it reaches the $T=0$ singularity? Clearly, no matter how penetrating and noninteracting such a wave is, it seems unreasonable that it should extend to a time *before* the $T=0$ origin. If it does not, then it must terminate at (or after) the $T=0$ point.

Let us, then, adopt a boundary-condition model for the $T=0$ Big Bang by assuming that all waves extending backward in time to the $T=0$ point must terminate there without a transfer of energy, i.e., that $\Psi(T)=0$ and $\Delta E=0$ for $T\leqslant 0$. This is effectively a reflection boundary condition analogous to that employed in electrical circuit theory to describe the interaction of the electrical impulse traveling in a transmission line with a "shorted" termination of the transmission line. However, while the latter boundary condition requires cancellation of the impulse only at a boundary point in the "space" of the one-dimensional transmission line, the $T=0$ boundary condition stated above requires an analogous cancellation of a four-vector wave function at a locus in space-time which includes all four-vector world lines. Such a condition produces a cancellation not only at that locus, but also elsewhere along the four-vector.

It is implicit in the WF description of the emission process that there is an advanced-to-retarded "phase flip" at the event-point of emission on the light-like world-line which contains the pair of emitted waves. It should be emphasized that in the $T=0$ reflection as described above there is no such advanced-to-retarded "phase flip" across the $T=0$ boundary point. The reflected wave is not a retarded wave ($E>0$) but an advanced wave ($E<0$) which "mirrors" the incident advanced wave. Thus no energy is exchanged with the $T=0$ boundary point, as required by the $\Delta E=0$ condition stated above.

Let us consider this boundary condition in the context of the "open-ended" emission of a low-energy neutrino as described above, which sends a retarded neutrino wave function into the future and at the same time sends an advanced neutrino wave function in the negative time direction until it encounters the $T=0$ Big Bang. The result of the $T=0$ boundary condition described above is the production of a "reflected" advanced neutrino wave function which is identical to, lies on the same world-line with, and is 180° out of phase with the incident advanced neutrino wave function. This produces a cancellation of the incident wave not only at the $T=0$ event but at every point along the world-line back to the point of emission. At that point the reflected advanced wave becomes in phase with the emitted retarded wave and the two are reinforced. To an external observer, this process involves no advanced waves at all, but only the "open-ended" emission of a retarded wave. This process is illustrated in Fig. 2.

Unlike the other absorber theory transactions, this process has no time-reversed analog, because the $T=0$ Big Bang in an open universe model exists only on the "past" time direction, not in the "future" direction. This, then, accounts for the electromagnetic direction of time and for the analogous "weak" arrow of time associated with neutrino emission. It is also consistent with the general argument given by Gold,$^{(21)}$ showing that where

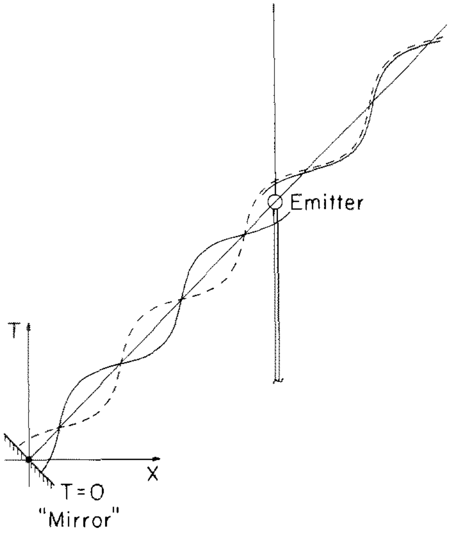

Fig. 2. Minkowski diagram showing an open-ended emission transaction. The conventions used here are the same as those used in Fig. 1. The advanced waves propagate backward in time to the $T=0$ origin, where they are subject to a reflection boundary condition. The reflected wave arising from the boundary condition cancels the advanced wave up to the emission event, and at times after emission it reinforces the retarded wave from the emitter.

all detailed physical theories are time-symmetric, the arrow of time must ultimately be associated with the large-scale properties of the universe.

The arguments given above must be modified to some extent because it is unlikely that waves traveling in the negative time direction could actually reach the $T=0$ point without being scattered or absorbed. The issue, however, is not the complete absence of interaction but whether the wave and its precursors retain serial identity, or whether they lose that identity and reach a condition of thermodynamic equilibrium before the $T=0$ point. Davies(22) has argued that such an equilibrium is more difficult to achieve than it might seem because the blue-shift in the negative time direction scales all energies together, so that the time-reversed wave is always orders of magnitude "hotter" than its environment and can retain its identity.

Nevertheless, there is a serious problem with this point of view at the extremely high densities, energies, and temperatures (10^{27} K) near the $T=0$ point. In such a domain there should be a complete breakdown of the spontaneous symmetry breakings which distinguish the strong interaction from the electromagnetic interaction and the electromagnetic interaction from the weak interaction. When such a breakdown occurs we lose the distinguishability of bosons vs. fermions, hadrons vs. leptons vs. photons, etc. The propagation of an advanced wave (or chain of advanced waves) through this "soup" to the $T=0$ boundary must be considered problematic at best. In fact, a detailed analysis of the likelihood of such an event is well beyond the scope of our present theoretical understanding because of the incredibly high densities and temperatures involved.

However, we may approach this problem from a slightly different perspective. Consider entities (we do not need to specify whether they are hadrons, leptons, or photons) which are produced a very short time after $T=0$. According to the generalized Wheeler–Feynman protocol, advanced and retarded wave functions for these entities will be produced in pairs. The advanced waves will then immediately propagate backward through the short time interval to $T=0$ where they will be "reflected" and cancelled. Thus, *from the start* the universe will have an established predominance of retarded waves, and according to the arguments given by Hogarth this will establish a time direction which is irreversible and will persist into our epoch.

It should be emphasized that, in the generalized version of the Wheeler–Feynman absorber theory presented here, the $T=0$ reflections are only a "transaction of last resort" for radiation which is too weakly absorbed to interact with a future absorber according to the emitter-absorber protocol described above and in AT1. In the more usual emitter-absorber transactions the advanced waves from the emitter are cancelled by those of the absorber so that the $T=0$ boundary condition plays no role in the transaction. Only when there is no future absorber does the effect of the $T=0$ boundary condition appear.

It can be argued that the $T=0$ boundary-condition model presented here, while plausible, is no better and no less *ad hoc* than any other boundary-condition model, and in particular, is no improvement over the "causality" boundary-condition model (CBC) usually applied to electrodynamics. The latter asserts as a boundary condition to the solution of the wave equation that the advanced fields and potentials do not exist because they would violate the principle of causality (i.e., the cause always precedes the effect in time sequence). There are several arguments which can be made against this point of view, which we will enumerate here:

(1) The $T=0$ boundary condition describes a plausible property of a physical boundary (the $T=0$ point) in the interaction of that boundary with advanced waves. The CBC, on the other hand, is not a boundary condition in the strict sense of the term, in that it seeks to directly establish a correspondence with observation rather that stating a property of a physical

boundary. The CBC is reminiscent of the Aristotelian boundary condition that "Nature abhors a Vacuum."

(2) The $T=0$ boundary condition, unlike the CBC, establishes a definite connection between the direction of electromagnetic time (the "retarded" direction) and the direction of cosmological time (the time direction in which the universe expands). Further, the $T=0$ boundary condition is specific, in that, unlike the CBC, it "works" only in an open universe, and is incompatible (without special assumptions) with closed and cyclic universe models.

(3) The goal of the present work is to find a way of reconciling the generalized absorber theory with the experimental fact of the dominance of retarded radiation in the universe. The motivation for attempting this synthesis is that the generalized absorber theory has been found to provide a solution to quantum mechanical paradoxes (see Ref. 7). The CBC precludes absorber-emitter transactions and therefore cannot achieve the desired synthesis. As was discussed in the preceding section, previous attempts to connect the electromagnetic and cosmological arrows of time using an absorption boundary condition have ultimately led to the conclusion that the electromagnetic arrow should be directed in the opposite direction.

(4) The CBC, given the dominance of retarded radiation, has no discernible consequences which lead to experimental tests. The $T=0$ model has at least one consequence which is, in principle, subject to experimental verification, i.e., the requirement of an open universe. As will be discussed in the next section, there may also be other consequences of the model which can be subjected to experimental tests.

5. POSSIBLE EXPERIMENTAL CONSEQUENCES

A possibly paradoxical corollary of the $T = 0$ boundary-condition model arises if the same arguments presented above are also applied in the *forward* time direction to radiation (or particles) encountering a black hole which eventually collapses to a singularity (rather than eventually evaporating through the Hawking process). While black holes are proper absorbers in the Wheeler–Feynman context since advanced waves can escape from them in the negative time direction (the time-reverse of radiation capture by a black hole), a "reflection" of incident retarded waves at the singularity of the black hole, in analogy to the $T=0$ boundary condition, would produce a cancellation of the incident wave functions. This leads to the curious conclusion that such black holes might create a condition such that *light could not be emitted in their direction*, i.e., that they might appear as *anti-emission loci.* In other words, such black holes might be truly black, in that light "would refuse to shine" in their directions.

However, in an open and continually universe, given enough time all black holes should eventually undergo Hawking evaporation. Further, there is no particular reason why a $\Psi = 0$ (at singularity and beyond) boundary condition need be applied to black holes. Moreover, the thermodynamics of a black hole should be rather different from the time-reversed Big Bang, in that the ambient temperature of the former would normally be very much higher than that of incident radiation, and thus the establishment of a thermodynamic equilibrium before reaching the singularity would be essentially certain. Thus, black holes would not be expected to be anti-emission loci. It would, nevertheless, be worth testing this point with a suitable experiment, if one could be designed.

There is also a second experimental effect which might arise from the $T = 0$ boundary condition model presented above. Let us make the plausible (but not completely necessary) *ansatz* that the probability of "open-ended" emission of a wave in a particular direction depends on the volume of momentum phase space occupied by four-vectors connecting the emission event with the $T = 0$ point in the reverse space-time direction. If this is the case then the emission probability for such waves will not necessarily be spatially isotropic. Indeed, the anisotropy of this phase space will be a function of the rest-frame of the emission event, and there will be a preferred inertial reference frame which has an isotropic phase space in all spatial directions.

This is analogous to the preferred reference frame defined by the isotropy of 2.7 K black-body radiation from the Big Bang, which is essentially the time-reverse of the phenomenon considered here. It has been demonstrated experimentally that the Earth has a velocity of about 0.1 % c with respect to the rest-frame defined by the 2.7 K radiation. Thus, it would be expected that "open-ended" emission processes might be slightly anisotropic if the emission occurs in any reference frame in which this phase space were skewed (such as that of the Earth). The anisotropy of the emitted radiation would not necessarily replicate the phase space anisotropy, if only because the rescattering of the advanced waves traveling back to the $T = 0$ point would tend to equilibrate these waves with the momenta of the scattering centers and would therefore tend to average out any such anisotropy. Furthermore, it is not clear that the dependence of the "open-ended" emission probability on the phase space volume is a necessary consequence of the $T = 0$ boundary condition.

Such a dependence would have consequences which could be observed experimentally. For the case of radio waves at frequencies around 10 GHz, two such tests have already been performed, and both experiments have given negative results.(23,24) However, it is not completely clear that radio waves represent a suitable case for "open-ended" emission, since the probability of absorption of such waves by the inverse bremsstrahlung process grows without limit as the waves are red-shifted while traveling cosmological distances in an open universe. Davies(13) has demonstrated that most open universe models are "transparent" to such radiation in the sense that the absorption cross section integrated over all future times is not infinite, but the latter, while finite, might still be very large. In that case, only an infinitesimal fraction of the transmitted flux might be truly "open-ended" emission events.

An alternative test of emission anisotropy involves the emission of *neutrinos*. Neutrinos cannot be absorbed in the equivalent of the inverse-bremsstrahlung process because they are fermions and have a neutral-weak-current scattering cross section which is inversely proportion to their wavelength at low energies. Such an experiment is now in progress at the University of Washington, and employs the angular correlation between the directions of neutrino and electron emission in a pure Gamow–Teller beta decay to deduce a possible anisotropy in neutrino emission by observing the spatial distribution of emitted electrons, as measured in back-to-back beta scintillation spectrometers. Any anisotropy in neutrino emission would be reflected in a nine times weaker anisotropy in electron (i.e., beta-particle) emission. The phase-space dependence assumption described above would imply that the maximum anisotropy which might be found in the electron emission would be about a part in 10^4, and it could be much weaker.

The size of the neutrino emission anisotropy, under the phase-space *ansatz* mentioned above, depends strongly on the velocity of the source. Thus, if the neutrinos are emitted from a source moving at a relativistic velocity, the anisotropy should be greatly magnified. In particular, the spatial anisotropies in neutrinos produced by the decay of a collimated beam of π mesons should be quite anisotropic, and this anisotropy should be reflected in the distribution of muons resulting from the pion decays. An experiment searching for such an anisotropy in the muon distribution in the pion center-of-mass reference frame has several advantages over the beta decay experiment: (1) It involves mu-neutrinos which are presumably more difficult to absorb than are electron-neutrinos; (2) it involves a two-body decay, with a back-to-back angular correlation between the decay products enforced by energy and momentum conservation (instead of the rather weak angular correlation of the beta decay experiment), and therefore there is a one-to-one correspondence between muon and neutrino anisotropies; and (3) since the center-of-mass velocity of the pion beam can be made very large compared to the laboratory rest-frame, an effect depending on phase space volume would be greatly magnified over a similar effect measured in the laboratory frame, leading to a greatly enhanced experimental sensitivity.

It should be emphasized, however, that such experiments test the hypothesis that an "open-ended" emission process reflects the phase space of the Big Bang in the negative time direction. This is a far stronger assumption than the $T=0$ boundary-condition model itself. These proposed tests are, therefore, not definitive tests of the boundary-condition model presented here. In particular, a negative result from such experiments would not serve to eliminate the $T=0$ boundary-condition model but a positive result could be taken as evidence in favor of the model.

6. CONCLUSION

In the above discussion we have shown that a generalized form of the Wheeler–Feynman absorber theory can be made consistent with an open Big Bang model of the universe by imposing a plausible four-vector reflection boundary condition at the $T=0$ "origin" of the universe. This then provides the solutions for the weak absorption and time-arrow problems presented in the introduction and in AT1, because it provides for "open-ended" emission of weakly absorbed radiation (radio waves and neutrinos) and also gives an explanation for the observed dominance of retarded radiation. Effectively, in this model the $T=0$ boundary condition becomes "the absorber of last resort," confirming emitted waves which would otherwise have no corresponding absorption.

We note, however, that this boundary-condition model only provides solutions to these problems if the universe *is not closed*, i.e., the density of the universe is less than or equal to the critical density so that $k=0$ or -1 in the Friedmann model. If the density of the universe exceeds the critical density so that $k=+1$ and the universe is bounded in both time directions by $\Psi=0$ conditions at terminating singularities, then neither advanced nor retarded radiation would be allowed, so that *no* emission would be permitted.

Thus, the present work in essence connects the observed time asymmetry in radiation processes with the intrinsic time asymmetry in nonclosed Friedmann models of the universe and is inconsistent with closed and cyclic models. This connection has been established by replacing the absorption boundary condition which previous authors have used to describe the early universe with a four-vector reflection boundary condition. This boundary-condition model leads us to the insight that the arrow of electromagnetic time points in the "future" time direction for the same reason that the light from a spotlight points in a particular spatial direction: both have a reflector "behind" them which reflects all rays going the wrong way.

Thus the electromagnetic arrow of time, according to the arguments presented above, has a direct connection to the cosmological arrow of time, i.e., the time direction in which the universe is observed to expand. This leads to the question of how these two "arrows" are connected to the other arrows of time, particularly the thermodynamic arrow of time, i.e. the time direction of entropy increase as specified by the second law, and the CP arrow of time, which is related to the CP violation in the decay of K_2^0 meson. Recent progress on the grand unified theories has pointed to connection between the CP violation and the observed dominance of matter over antimatter in the universe, but as yet no connection has been made between the CP arrow and the other time arrows. It would seem that this problem should be carefully reconsidered in the framework of advanced and retarded waves as they pertain to the decay of the K_2^0 meson and other similar CP violating processes.

Several authors(5,9–12,15) have asserted that the thermodynamic arrow of time is a direct consequence of the electromagnetic arrow. On the other hand, Davies(22) has argued that a better connection can be made between the thermodynamic and cosmological arrows. We do not wish to enter deeply into this controversy in the present paper, but we feel that a case can be made for the former point of view. In particular, Boltzmann's famous H-theorem, which "demonstrates" the thermodynamic arrow's direction seemingly from first principles, is based on the apparently harmless assumption that the motions of particles in a system of particles are *uncorrelated before collision.* This leads to the conclusion that the entropy of the system is constant or increasing. If, on the other hand, one had made the assumption that the particles' motions were uncorrelated *after* the collision, one would have been led to an entropy which was constant or *decreasing.* It can be argued that the correlation or lack thereof arises from the propagation of information by the medium of retarded electromagnetic fields, and that the dominance of the retarded solution of Maxwell's equations insures that there will be no correlations of electromagnetically interacting particles *before* the interaction has occurred. This would lead to a direct connection between the electromagnetic and thermodynamic arrows of time.

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