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The Wheeler–Feynman absorber theory, the Einstein–Podolski–Rosen paradox, and stochastic electrodynamics

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Abstract. The classical Wheeler–Feynman absorber theory with a postulate of Lorentz-invariant zero-point electromagnetic radiation is proposed to explain quantum phenomena in a similar manner to that of stochastic electrodynamics. For this purpose, Cramer's model of a 'minimum emitter–absorber transaction' is extended to the case where zero-point radiation exists, in the context of the classical Wheeler–Feynman theory. The Einstein–Podolski–Rosen paradox and the quantum levels of a charged simple harmonic oscillator are derived from the theory. It is shown that the condition for a transaction plays an essential role, such as in the radiative balance of a simple harmonic oscillator.

1. Introduction

In a recent paper, Cramer (1980) presented an explanation of the Einstein, Podolski and Rosen (1935) (EPR) paradox on the basis of a quantum mechanical formulation of the Wheeler–Feynman absorber theory (see e.g. Hoyle and Narliker 1969, 1971, Davies 1970). His explanation is naturally concerned with the 'non-locality' aspect of the EPR paradox: he developed a model based on the half-retarded and half-advanced field electrodynamics of Wheeler and Feynman (1945, 1949) and called it a 'minimum emitter–absorber transaction'. Extending his idea to a simultaneous double transaction, Cramer applied it to discuss the result of the polarisation experiment of a double-photon decay of Freedman and Clauser (1972) and explained the non-locality aspect of the EPR paradox. The EPR paradox has two distinct aspects: the incompleteness and the non-locality (or the non-separability of two quantum substates once they have interacted in quantum theory) (cf Einstein *et al* 1935). Cramer's argument, a quantum mechanical one, naturally accepted the quantum mechanical description of reality as being complete and explained the non-locality aspect of quantum phenomena, pointed out in the paper by EPR, as being non-contradictory.

As for the incompleteness aspect of quantum theory, an extensive controversy has arisen since the establishment of quantum mechanics. The interpretation of Bohr and others, who are associated with the 'Copenhagen school', found favour with a majority

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of physicists. Furthermore, a theorem by von Neumann (1955) concerning the non-possibility of any hidden-variables theory influenced certain physicists to believe that the incompleteness aspect of quantum theory is not a defect but is the ultimate nature of physical theory and no further inquiry into the problem is fruitful. However, by the efforts of physicists who were not satisfied by the quantum mechanical interpretation of physical reality, hidden-variables theories, the Brownian motion interpretation of quantum phenomena, stochastic electrodynamics (which we are going to discuss), plus other theories grew out of the attempts to replace the quantum axiom by other axioms which retain the character of classical physics as their foundation. Many of these theories aim at a complete description, or a better understanding of physical reality than that afforded by quantum mechanics. These theories have succeeded in explaining certain quantum phenomena without the use of the quantum axiom, and, furthermore, some of the theories make more predictions or different predictions than those of quantum mechanics (for example, the hidden-variables theory of Bohm and Bub (1966)). Bell (1964) brought the academic problem—the different predictions of local hidden-variables theories and quantum mechanics—into the domain of experimental test by formulating Bell's inequality, which has been tested experimentally by various groups using methods based on various phenomena. The experimental results in general favour the predictions of quantum mechanics rather than those of local hidden-variables theories. However, Aspect (1976) has proposed a more sophisticated experiment to test the validity of quantum mechanics. For a typical case, we deal with the experiment of Freedman and Clauser (1972).

With the help of the idea of Cramer's transaction, we study the same problem but along the lines of stochastic electrodynamics, i.e. without the use of the quantum axiom. In this paper we present a theory to deal with the non-locality aspect of the Freedman–Clauser experiment in connection with the EPR paradox in the context of classical theory, i.e. the Wheeler–Feynman absorber theory with a postulate of the existence of a zero-point electromagnetic radiation in the universe. In our theory, the non-locality aspect of the EPR paradox and the polarisation experiment of Freedman and Clauser can be explained in a similar manner to Cramer's quantum formulation of the Wheeler–Feynman absorber theory. Thus, whether one uses a quantum mechanical formulation or a classical formulation of the Wheeler–Feynman absorber theory depends on how one wishes to respond to the incompleteness aspect brought about by the EPR paradox; that the two aspects, i.e. non-locality and incompleteness, are closely connected is shown by Einstein as follows. The completeness of the quantum mechanical description by means of the wavefunction, and the locality premise, are not compatible as shown by Einstein *et al* (1935) and also quoted by Bohr (1949). Those who use the quantum mechanical formulation of the Wheeler–Feynman theory need to explain only the non-locality aspect, while those who use the classical version of the Wheeler–Feynman theory need to explain both aspects within their theories.

Stochastic electrodynamics, which aims at explaining both aspects of quantum phenomena, has been developed over more than a decade by several authors (e.g. Marshall 1963, Santos 1974, de la Peña-Auerbach 1978, de la Peña-Auerbach and Cetto 1976). It had several successes in explaining certain quantum phenomena on the basis of classical electrodynamics of the Maxwell–Lorentz theory with the addition of an *ad hoc* postulate of stochastic zero-point electromagnetic radiation (or a zero-point fluctuation field) existing as a background radiation in the universe. The zero-point radiation was first used by Marshall (1963) to explain the quantum mechanical behaviour of a charged classical harmonic oscillator in its ground state. Boyer (1969), following the idea, demonstrated an important character of the radiation, i.e. the zero-point radiation is Lorentz invariant, and derived Planck's law of radiation only by incorporating the zero-point radiation into classical statistical mechanics without the use of the quantum axiom. Furthermore, several authors have extended stochastic electrodynamics (by incorporating zero-point radiation) to explain a wider variety of quantum phenomena. Such are: the simple harmonic oscillator discussed above; the Casimir effect; the excited states of a simple harmonic oscillator; the Lamb shift; the decay of the excited states of atoms; and other phenomena.

According to the belief of some of those working in stochastic electrodynamics, the only difficulty they encounter is a mathematical one, and if the difficulty were overcome, the theory could explain all the quantum phenomena without recourse to the quantum axiom. However, stochastic electrodynamics currently has its intrinsic weakness. For example, although the energy levels of a harmonic oscillator in stochastic electrodynamics agree with those of quantum mechanics, a simple harmonic oscillator undergoes stochastic motion, losing or acquiring the energy and momentum through its interaction with the zero-point radiation. Therefore, the energy of a particle undergoing a simple harmonic oscillation (in its lowest energy state, say) takes any value at a certain instant of time with a certain probability due to a random walk process, and only the average over a sufficiently long period of time agrees with the prediction of quantum mechanics (see Santos 1974). The condition of radiative balance, discussed by Marshall and Claverie (1980), is not inherent in stochastic electrodynamics. In this respect, the theory does not explicitly show the non-locality aspect of quantum phenomena such as is described by Cramer's emitter–absorber transaction model. But the theory may give a different prediction from quantum mechanics for a properly conducted double-photon correlation experiment such as that proposed by Aspect (1976) and discussed by Marshall (1980), for example.

We develop a new theory of classical stochastic electrodynamics which replaces classical Maxwell–Lorentz electrodynamics (in which only a fully retarded field is utilised) by using a 'half-retarded and half-advanced fields' formulation of the Wheeler–Feynman theory†.

As is well known, the Wheeler–Feynman absorber theory has some distinct features, but shares many features in common with Maxwell–Lorentz electrodynamics. Therefore, stochastic electrodynamics with the Wheeler–Feynman absorber theory has many features in common with, but has a distinct feature from, the current theory of stochastic electrodynamics. For example, the dispersion in the value of the energy of a stationary state, under the influence of zero-point electromagnetic radiation, can be removed in our theory when the Wheeler–Feynman theory and thus the transaction of an 'emitter–absorber' are incorporated. In this theory, the condition for an 'emitter–absorber transaction' is derived. To apply the transaction condition in our theory, we have extended the 'minimum emitter–absorber transaction' of Cramer to the case where zero-point electromagnetic radiation is present. We will show, in an example of a charged simple harmonic oscillator, that the condition of transaction for an emitter–absorber system plays the role of the radiative balance condition, and retains the system adiabatically invariant. Thus, possible solution of the EPR paradox within the framework of classical electrodynamics, with an additional postulate of the existence of a

† Some consideration has been given to the Wheeler–Feynman approach in stochastic electrodynamics by Braffort and Tzara (1954) and Marshall (1968). The authors are grateful to one of the referees for this information.

zero-point electromagnetic radiation, becomes much more feasible. We explore this possibility and discuss it in this paper.

2. Wheeler–Feynman absorber theory with zero-point radiation

A consequence of the existence of zero-point electromagnetic radiation is that any system of particles in the universe, such as the emitter–absorber system considered by Cramer, can no longer be considered as an isolated system. Thus, we do not choose to take the usual assumption for the boundary conditions in the Wheeler–Feynman absorber theory, but, instead, both the incoming and the outgoing fields are non-zero and are given by the zero-point electromagnetic radiation considered in stochastic electrodynamics.

The total field acting on particle C as a result of the rest of the particles (labelled j) in the universe is (see Davies 1974)

$$F^{(C)}_{\text{total}}=\tfrac{1}{2}\sum_{j\neq C}[F^{(j)}_{\text{ret}}+F^{(j)}_{\text{adv}}]+\tfrac{1}{2}[F_{\text{in}}+F_{\text{out}}]. \tag{1}$$

(Here, the italic superscript in brackets labels the particle.) Since the background radiation $\frac{1}{2}[F_{\text{in}}+F_{\text{out}}]$ has its source outside the system (i.e. on the past light-cone and the future light-cone), this field is a solution of the homogeneous Maxwell equations valid inside the boundary—and thus it contains certain ambiguity unless the boundary surface is clearly defined. The fields, $\frac{1}{2}F_{\text{in}}$ and $\frac{1}{2}F_{\text{out}}$, at the past and the future boundary surfaces are, respectively, identified to be the zero-point electromagnetic radiation at the boundary surfaces on both light-cones. From the Lorentz-invariant nature of the zero-point electromagnetic radiation, the frequency spectrum is uniquely determined up to a multiplicative constant, as given by Boyer (1969),

$$I(\omega)=\tfrac{1}{2}\hbar\omega^3 \tag{2}$$

where $\frac{1}{2}\hbar$ is chosen as the multiplicative constant. (An upper limit of ω must exist, otherwise the energy of the field would diverge†.) The meaning of the invariance of the zero-point electromagnetic radiation under a Lorentz transformation is, as Boyer demonstrated, that the inertial observer who measures the energy of the radiation with the same band filter, which selects a frequency band between ω and $\omega+\mathrm{d}\omega$, obtains the same energy density regardless of the value of ω and of his velocity.

The derivation of the frequency spectrum of the zero-point radiation is as follows (Boyer 1969). Let the zero-point electromagnetic radiation be expressed by

$$\boldsymbol{E}(\boldsymbol{x},t)=\mathrm{Re}\sum_{\lambda=1}^{2}\int \mathrm{d}^3k\,\boldsymbol{\varepsilon}(k,\lambda)h(\omega_k)\exp(\mathrm{i}\omega_k t-\mathrm{i}\boldsymbol{kx}-\mathrm{i}\theta(\boldsymbol{k},\lambda))$$

$$\boldsymbol{B}(\boldsymbol{x},t)=\mathrm{Re}\sum_{\lambda=1}^{2}\int \mathrm{d}^3k\,\frac{\boldsymbol{k}\times\boldsymbol{\varepsilon}(k,\lambda)}{k}h(\omega_k)\exp(\mathrm{i}\omega_k t-\mathrm{i}\boldsymbol{kx}-\mathrm{i}\theta(\boldsymbol{k},\lambda)). \tag{3}$$

Here $\boldsymbol{E}$ and $\boldsymbol{B}$ are the electric and magnetic field components of the radiation. The

† In order that the total energy of the zero-point electromagnetic radiation be finite, a departure from the spectrum of equation (2) is to be expected at some high frequencies beyond which the present laws of physics may break down. A suggested upper limit of the frequency is $(c^5/G\hbar)^{1/2}\approx 10^{54}\,\mathrm{s}^{-1}$, where G is the gravitational constant; or alternatively at energy $E\approx\hbar\omega\approx 10^{40}$ eV.

function $h(\omega_k)$ depends only on $\omega_k = ck = c|\boldsymbol{k}|$ because of the assumed isotropy of the radiation. $\theta(\boldsymbol{k}, \lambda)$ is the random phase to indicate the character of the radiation. Then the spectral density $\rho(\omega)$ is calculated from (3) to be

$$\int \rho(\omega)\,\mathrm{d}\omega \equiv \frac{1}{8\pi}\langle \boldsymbol{E}^2+\boldsymbol{B}^2\rangle = \int_{-\infty}^{\infty} \mathrm{d}\omega\,\frac{\omega^2}{c^3}\,h^2(\omega). \tag{4}$$

In deriving the last part of equation (4), use is made of the random correlation between the random phases $\theta(\boldsymbol{k}, \lambda)$. Using the Lorentz transformation formula for $\boldsymbol{E}, \boldsymbol{B}, \boldsymbol{k}, \boldsymbol{x}$ and t, thus obtaining the corresponding primed variables, we have, by the same calculation by which equation (4) was derived,

$$\frac{1}{8\pi}\langle \boldsymbol{E}^2+\boldsymbol{B}^2\rangle = \int_{\omega'=0}^{\infty} \mathrm{d}^3k'\,h^2(\omega_k)\gamma\left(1-\frac{vk_x}{\omega_k}\right) \tag{5}$$

where $\boldsymbol{k}'$ and γ are the Lorentz-transformed wavevector and the Lorentz factor, respectively.

If several inertial observers measure the original density of the radiation with the same instrument with the same filter, which selects a frequency band between $\omega_1 = a$ to $\omega_2 = b$ for arbitrary but fixed constants a and b, they all obtain the same energy density. Therefore, equations (4) and (5) require that

$$\int_{\omega_k=a}^{\omega_k=b} \mathrm{d}^3k\,h^2(\omega_k) = \int_{\omega'_{k'}=a}^{\omega'_{k'}=b} \mathrm{d}^3k'\,h^2(\omega_k)\gamma\left(1-\frac{vk_x}{\omega_k}\right) \tag{6}$$

for any fixed a and b. Since the variable of integration is a dummy variable, and a and b are taken arbitrarily, this requires that

$$h^2(\omega'_{k'}) = h^2(\omega_k)\gamma(1-vk_x/\omega_k). \tag{7}$$

From (7) it follows that

$$h^2(\omega'_{k'})/\omega'_{k'} = h^2(\omega_k)/\omega_k = \text{constant} \tag{8}$$

or $h^2(\omega)$ must be a linear function of ω. By a suitable adjustment of the normalisation constants in the original radiation fields, we have exactly an electromagnetic zero-point energy $\frac{1}{2}\hbar\omega$ per normal mode:

$$\pi^2 h^2(\omega) = \tfrac{1}{2}\hbar\omega.$$

The zero-point spectral density function $\rho(\omega)$ is

$$\rho(\omega) = \hbar\omega^3/2\pi^2c^3. \tag{9}$$

A fundamental difference between this radiation and the 2.7 K cosmic big-bang background radiation is that an inertial observer can find a relative velocity with respect to the latter radiation and can permanently absorb it, while with the former, due to the Lorentz-invariant nature of the radiation, this is not possible, as will be shown later.

From the Lorentz-invariant nature of the zero-point radiation together with the postulate that the incoming and outgoing fields, F_{in} and F_{out}, are to be regarded as the zero-point radiation, one can conclude that an emitter–absorber system can never permanently absorb the zero-point radiation, nor permanently emit an extra radiation going to ∞ or to $-\infty$ (for retarded or advanced radiation, respectively). This is because, if such radiation reaches the boundary surface at ∞ or $-\infty$, the F_{in} or F_{out} would no longer be zero-point radiation at some frequencies, which contradicts our assumption about F_{in} or F_{out}. This is true for all inertial observers, because the zero-point radiation is Lorentz-invariant, so that the spectrum is independent of the velocity of the inertial observers.

When an emitter–absorber system emits or absorbs zero-point radiation, there should exist another system which emits or absorbs the deficient or excess component of the radiation other than the zero-point radiation, so that at both infinities F_{in} and F_{out} should be identified as an incoming or an outgoing zero-point radiation. The emitter–absorber system should include the other system, so that the whole system should be considered as an emitter–absorber system and the system cannot emit or absorb zero-point radiation of any frequency permanently. Thus, an emitter–absorber system absorbs the zero-point radiation temporarily, so that we cannot detect the existence of the zero-point radiation directly by measuring the permanent increase or decrease of the energy and momentum of the system due to the absorption or emission of the zero-point radiation, i.e. using the conservation laws of energy and momentum of the system. However, we can detect its existence by its effect exerted on a system through a 'quantum effect' which is caused by the zero-point radiation when it goes through an emitter–absorber system by a multiple transaction such as double-photon emission from an excited state of an atom. In this case the process does not violate the conservation laws of energy and momentum of the system, but the energy of the individual photon fluctuates due to the fluctuation of the zero-point radiation; this will be described later.

In the following section we describe the relation between the Lorentz invariance of the zero-point radiation and the emission and absorption of the radiation by an 'emitter–absorber' system through a 'transaction'.

3. An extension of Cramer's model of a minimum emitter–absorber transaction

In the Wheeler–Feynman (1945) theory, an absorber is not a single atom nor a single system, but includes all absorbers in the universe, coherently connected in the absorption process of the electromagnetic radiation emitted by an emitter at the centre. In the transaction model of Cramer (1980) a 'minimum emitter–absorber transaction' is defined as an emitter emitting a half-advanced field, $\frac{1}{2}F_{adv(emit)}$, and a half-retarded field, $\frac{1}{2}F_{ret(emit)}$, and an absorber, by the influence of the retarded field of the emitter, sending a half-advanced field, $\frac{1}{2}F_{adv(abs)}$, and a half-retarded field, $\frac{1}{2}F_{ret(abs)}$, in such a way that the emitter and the absorber exchange their fields. However, the emitter–absorber system, as a whole, does not emit any advanced or retarded field to the outside of the system (figure 1). Thus the following conditions hold for an emitter–absorber system as a whole:

$$\begin{aligned} F_{in} &= 0, \qquad [\tfrac{1}{2}F_{adv(emit)} + \tfrac{1}{2}F_{adv(abs)}]_{\substack{\text{at the past}\\ \text{boundary}}} = 0 \\ F_{out} &= 0, \qquad [\tfrac{1}{2}F_{ret(emit)} + \tfrac{1}{2}F_{ret(abs)}]_{\substack{\text{at the future}\\ \text{boundary}}} = 0. \end{aligned} \tag{10}$$

This is called the minimum emitter–absorber transaction of type I, where the boundary means a boundary surface of the minimum emitter–absorber system. Since there is no emission or absorption of the field by the emitter–absorber system when a transaction of

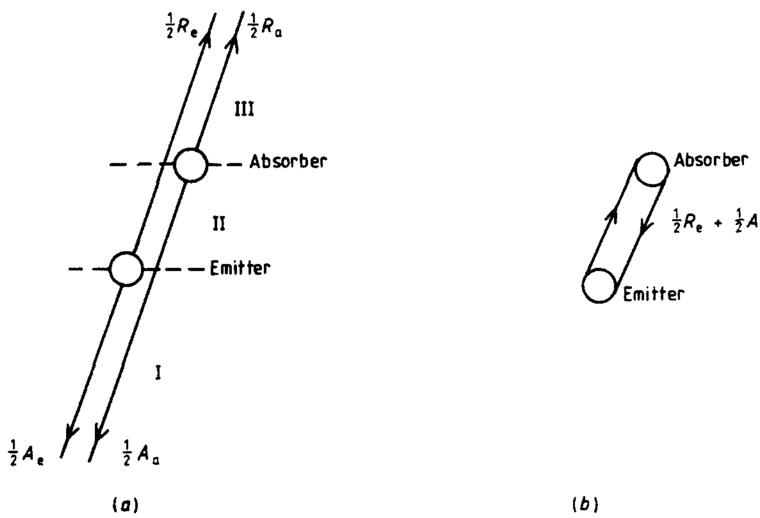

Figure 1. Transaction of type I. In (*a*) the emitter (absorber) produces retarded and advanced fields, R_e (R_a) and A_e (A_a), respectively. Here, $A_e + A_a = 0$ in region I, and $R_e + R_a = 0$ in region III. The transaction condition reduces the emitter–absorber system as if it were (*b*), an 'isolated' system with transaction taking place only within the system.

type I is concluded, the system is considered as isolated, and thus the energy and momentum of the system are strictly conserved under a transaction of type I.

The existence of a zero-point radiation, which influences any system in the universe, requires that the transaction of type I already described above must be extended. When an emitter–absorber transaction of type I is concluded, the incoming zero-point radiation is absorbed at the emitter end and the outgoing zero-point radiation is emitted at the absorber end of the emitter–absorber system.

Since the emitter–absorber system is self-contained, it behaves like an isolated system even under the influence of the zero-point radiation. The reason is the following. The emitter–absorber is stationary and inertial before and after the transaction (i.e. when the system has attained a stationary state). If an emitter–absorber system absorbs zero-point radiation permanently, a transaction has to be concluded between the system and the past infinity, which together form a new emitter–absorber system. The incoming field from the boundary at the past infinity will no longer be a zero-point radiation, as postulated for F_{in} or F_{out} in equation (1), and contradicts the Lorentz invariance (as seen from the observer sitting at the original inertial frame). This implies that the incoming zero-point radiation, which is temporarily absorbed by the system, should be re-emitted as an outgoing zero-point radiation when the emitter–absorber system has attained a stationary state. That is

$$(-F_{in}) + F_{out} = 0 \tag{11}$$

for a transaction. We may consider the process in a different way. The emitter–absorber system absorbs the incoming zero-point radiation tentatively, but re-emits the same radiation as the outgoing radiation by the time the transaction is over. The condition for the type I transaction (i.e. equation (10)) and that for the general transaction are expressed by a single equation (11). We may consider this condition as that of the zero-point radiation just passing through the emitter–absorber system during the transaction, as if no interaction had taken place. We call this transaction a general transaction of type I. Hereafter, a 'transaction' refers to a general transaction of type I unless otherwise stated (see figure 2). The application of the condition to a charged harmonic oscillator in a zero-point radiation will be given in §5.

As mentioned above, the zero-point radiation can never be permanently absorbed. An emitter–absorber system absorbs or emits zero-point radiation temporarily, so that we have no way of detecting it directly except by detecting the increase or decrease of the energy or momentum of the system due to a permanent emission or absorption of it.

One might, at first glance, think that the zero-point radiation cannot give rise to any physically observable effect on a physical system, as in the case of the energy levels of an atom. But this is not so in the case of a 'double transaction', which produces a different effect from the case discussed by Cramer, where zero-point radiation does not exist. We can detect the existence of the effect exerted on a system through a 'quantum effect', which is caused by zero-point radiation, but it does not violate conservation laws of energy and momentum. As will be described later, the effect manifests itself in the case when a system performs a multiple transaction. The incoming zero-point radiation is divided among the emitters and is emitted from different emitters of the emitter–absorber system. This will be shown in the Freedman–Clauser experiment, where two photons are emitted through a multiple 'transaction'.

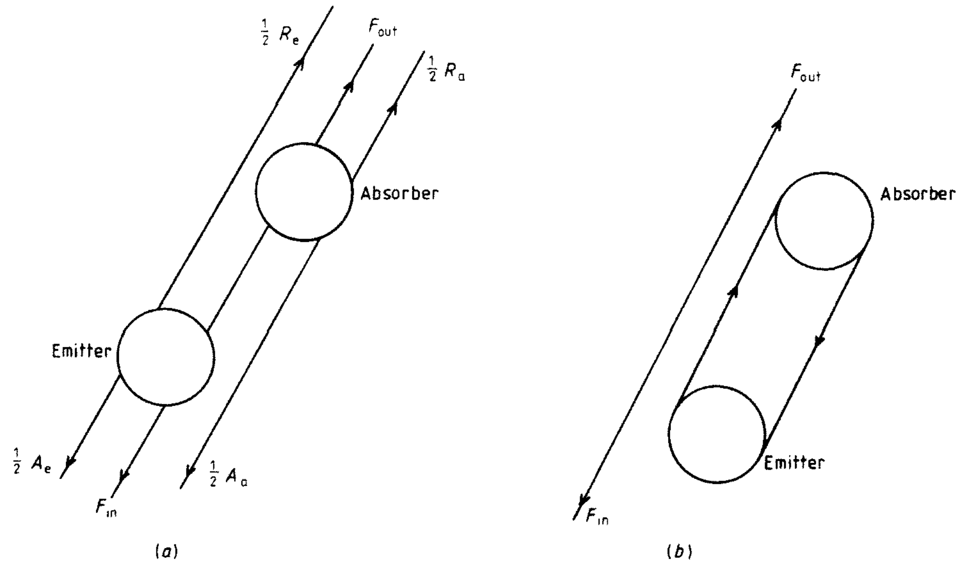

Figure 2. Transaction of type I in the presence of zero-point radiation. In (*a*) the emitter–absorber system of type I is under the influence of zero-point radiation. When a transaction of type I is concluded, the system behaves as if no interaction with the zero-point radiation had taken place, i.e. (*b*).

4. Non-locality aspect of the Freedman–Clauser experiment and the Wheeler–Feynman absorber theory

Cramer discussed the result of Freedman and Clauser's experimental test of Bell's inequality. A certain local hidden-variables theory of the second kind (see e.g.

Belinfante 1973) predicts Bell's inequality, which gives a different prediction on the non-locality aspect from that of the quantum theory. Following the argument of Cramer we will describe the result of the Freedman and Clauser (1972) experiment within the framework of Wheeler–Feynman classical electrodynamics with zero-point radiation.

A model of a more complex transaction process, e.g. Cramer's simultaneous multiple type I transaction, which contains an emitter and several absorbers in the case of successive emission of photons, would require a multiple simultaneous confirmation from all the absorbers by sending advanced waves to the emitter; otherwise the process does not proceed. Cramer explains a double emitter–absorber transaction as follows. The excited calcium atom, for example, emits a number of probe waves, corresponding to the possible emission of a pair of photons, in various directions with various allowed polarisation correlations. If 'verifying' advanced waves are sent back by the pair of absorbers, then the transaction is completed and a double detection event has occurred. If the verifying waves do not match an allowed polarisation correlation, then they will not conclude the same transaction. When a zero-point radiation is present, a multiple transaction diagram, similar to that of Cramer, is obtained, as schematically shown in figure 3. When the incoming zero-point radiation absorbed at the emitter end is re-emitted from two or more absorber ends, the transaction condition, which is an extension of equation (11), is

$$(-F_{\text{in}})+F_{\text{out}}^{(1)}+F_{\text{out}}^{(2)}+\ldots=0 \qquad (12)$$

where F_{in} and $F_{\text{out}}^{(i)}$ are defined as in equation (10). In this sense the two transactions between e–a_1 and e–a_2 are coherent (see figure 3), and the two photons emitted in the process are also coherent.

In the Freedman and Clauser experiment the directions of polarisation of the two photons are parallel and coherent. When each photon passes through each polariser it behaves as a single photon passing through two polarisers. Thus, the rate of coincidence

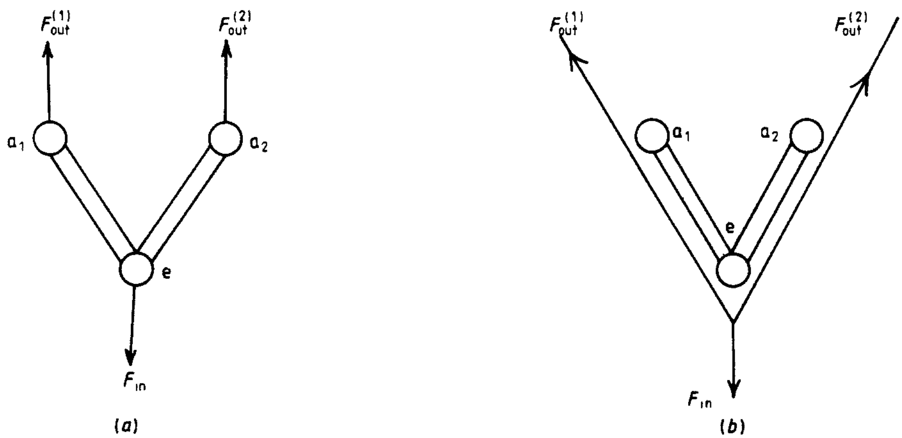

Figure 3. Multiple transaction in the presence of zero-point radiation: two simultaneous transactions taking place between an emitter e and two absorbers a_1 and a_2. The zero-point radiation absorbed at e is re-emitted from a_1 and a_2 as in (*a*). This can be considered as the zero-point radiation just passing through the system (*b*), divided into two parts which differ in proportion to the two outgoing zero-point radiations for the different cases.

of each of the two parallelly polarised photons passing through an individual polarisation filter is the same as that of a single photon passing through two polarisers, such that it is governed by Malus's law for linearly polarised light, as found in classical electromagnetic theory. The result also agrees with that of quantum theory. In this experiment the polarisation filters do not affect the zero-point radiation unless an emission–absorption system which includes the polariser is formed. Therefore the non-locality result of the Freedman and Clauser experiment is satisfactorily explained by Wheeler–Feynman classical electrodynamics, even in the presence of a zero-point radiation. A similar argument is valid for the experiment of Fry and Thompson (1976), which measures the linear polarisation correlation of photon pairs from the mercury atom, though the polarisation direction is parallel.

As to the incompleteness aspect, both Wheeler–Feynman electrodynamics with zero-point radiation, and stochastic electrodynamics, are expected to bring some similar results, but not always so (e.g. the 'radiative balance'), as will be shown later.

Using the Wheeler–Feynman absorber theory, we now derive the equation of motion of a charged particle in the electromagnetic fields of other charged particles and an external field, such as zero-point radiation, and compare it with that of Lorentz–Maxwell electrodynamics. From equation (1),

$$F^{(i)}_{\text{tot}} = \sum_{j\neq i} F^{(j)}_{\text{ret}} - \tfrac{1}{2}\sum_{\text{all } j} [F^{(j)}_{\text{ret}} - F^{(j)}_{\text{adv}}] + \tfrac{1}{2}[F^{(i)}_{\text{ret}} - F^{(i)}_{\text{adv}}] + \tfrac{1}{2}[F_{\text{in}} + F_{\text{out}}]. \tag{13}$$

Using

$$\tfrac{1}{2}[F_{\text{out}} - F_{\text{in}}] = \tfrac{1}{2}\sum_{\text{all } j} [F^{(j)}_{\text{ret}} - F^{(j)}_{\text{out}}]$$

and identifying that the term $\tfrac{1}{2}[F^{(i)}_{\text{ret}} - F^{(i)}_{\text{adv}}]$ is just the radiation damping term first obtained by Dirac (1938), we get from (1) the equation of motion of a charged particle of mass m,

$$m\ddot{x}^{(i)\mu} = e^{(i)}\dot{x}^{\nu}(F^{(i)}_{\text{tot}})^{\mu}_{\nu} = \gamma[\dddot{x}^{(i)\mu} + \ddot{x}^{(i)\nu}\ddot{x}^{(i)}_{\nu}\dot{x}^{(i)\mu}] + e\dot{x}^{(i)\nu}\left[\sum_{j\neq i} (F^{(j)}_{\text{ret}})^{\mu}_{\nu} + (F_{\text{in}})^{\mu}_{\nu}\right] \tag{14}$$

where $\gamma = 2e^2/3c^3$. The dot indicates differentiation with respect to proper time, and Greek indices label the temporal and the spatial components. In the non-relativistic case, equation (14) reduces to

$$\begin{aligned} m\ddot{x}^{(i)\mu} &= \gamma\dddot{x}^{(i)\mu} - e^{(i)}\left[\sum_{j\neq i} (E^{(j)}_{\text{ret}})^{\mu} + (F_{\text{in}})^{\mu}\right] \\ E^{(j)}_{\text{ret}} &= -\text{grad}\, e^{(j)}/|R_{ij}|_{\text{ret}} \end{aligned} \tag{15}$$

where $R_{ij} = x_j - x_i$, x_i are 4-coordinates of the ith particle, and $|_{\text{ret}}$ means that the value is evaluated at the retarded time. Comparing equation (15) with the radiation damping equation of a charged particle in stochastic electrodynamics, where

$$m\ddot{x}^{(i)\mu} = \gamma\dddot{x}^{(i)\mu} + f^{\mu} + e^{(i)}E^{\mu}_{\text{in}} \qquad (F^{\mu}_{\text{in}} = -E^{\mu}_{\text{in}}), \tag{16}$$

we see that the difference is the second term on the right-hand side of equation (15). The retarded potential term due to the retarded Coulomb interaction is replaced, in the case of stochastic electrodynamics, by an external field which cannot always be derived solely from the retarded interaction of the charged particle.

Examining equations (13)–(16) we see that the advanced field of equation (13), which contributes to the non-locality aspect of the theory as discussed before, is absorbed partly into the radiation damping term and partly into F_{in} in equation (14), and does not appear explicitly in equations (14)–(16). The advanced field effects arising from the radiation damping term, $\gamma \dddot{x}^{(i)\mu}$ of equation (16), such as the pre-acceleration effect of an electron, in the Maxwell–Lorentz theory are quite natural in our Wheeler–Feynman theory, although such effects are considered unphysical and the solutions are discarded in Maxwell–Lorentz electrodynamics. However as Cramer showed, the non-local nature of some physical phenomena can be solved using advanced fields. Thus, the positive effect of advanced fields is demonstrated to be indispensable in explaining the non-locality aspect of quantum phenomena. Note that equations (14) and (15) are quite similar to the corresponding equations for a radiating charged particle in stochastic electrodynamics.

In the absence of the explicit form of advanced fields in Maxwell–Lorentz electrodynamics, and without the concept of a transaction of an emitter–absorber system, the non-locality nature of certain quantum phenomena, such as that of the result of Freedman and Clauser on the EPR paradox, remains difficult to explain within the framework of stochastic electrodynamics based on Maxwell–Lorentz electrodynamics. However, stochastic electrodynamics has had success in explaining certain quantum phenomena, as we have shown in § 2. In this respect, stochastic electrodynamics predicts a different result from that of quantum mechanics as described by Marshall (1980).

5. Example of a charged oscillator and the minimum emitter–absorber transaction

To illustrate a minimum emitter–absorber transaction and the application of the transaction condition, we deal with a charged simple harmonic oscillator of mass m and charge e placed in a zero-point radiation. The equation of motion of the oscillator is given by taking the particle C as the oscillating particle:

$$m\ddot{x}^{(C)} = -k^2 x^{(C)} + \frac{2e^2}{3c^3}\dddot{x}^{(C)} + eE(t) \tag{17}$$

for particle C, where $E(t)$ is the zero-point radiation contribution. The equation can be considered as a special case of the equation derived from the Wheeler–Feynman absorber theory with zero-point radiation.

The Hooke force $-k^2x$ acting on the particle C in (17) comes from the static approximation of the retarded potential of the other particles by replacing the velocity c in the retarded time by ∞. From equation (15)

$$e^{(C)} \sum_j E^{(j)}_{\text{ret}} = -e^{(C)} \operatorname{grad}\left(\sum_j \frac{e^{(j)}}{|R_{ij}|_{\text{ret}}}\right) = -e^{(C)} \operatorname{grad} \Phi^{(C)}_{\text{ret}}. \tag{18}$$

By putting $c = \infty$,

$$\Phi^{(C)}_{\text{ret}} \to \Phi^{(C)}_{t=0} = \sum_j \frac{e^{(j)}}{|R_{Cj}|_{t=0}}, \qquad R_{Cj} = x_C - x_j.$$

$\Phi^{(C)}_{t=0}$ is the static Coulomb potential due to the other particles $j = 1, 2, \ldots, N$. Assuming $\Phi^{(C)}_{t=0}$ has a minimum at $x = 0$, we obtain the Hooke potential. Equation (16) is valid for finite values of x around the minimum point of the potential $\Phi^{(C)}_{t=0}$.

For simplicity we deal with the one-dimensional oscillator. We may choose the configuration of a system of $N+1$ charged particles consisting of a particle C and N very heavy charged particles, $j=1,2,\ldots,N$, so that the motion of all the N heavy particles may be ignored, except the motion of particle C around the minimum point of the potential $\Phi^{(C)}$ constituting simple harmonic motion, and this is given by equation (17). Thus, the non-relativistic equation of motion of the system in the vicinity of a minimum point $x=0$ of the potential $\Phi^{(C)}$ in the Wheeler–Feynman theory with zero-point radiation is represented by equation (17). The particle C performs a motion, absorbs the zero-point radiation, represented by $E(t)$, and emits electromagnetic radiation which produces a radiation damping force of $(2e^2/3c^3)\dddot{x}$ on the charged particles.

The charged oscillating particle, together with N heavy charged potential-producing particles, considered as a minimum emitter–absorber system, was discussed in § 4: there, the same charged oscillating particle acts as an emitter and at the same time as an absorber; but in the process of emission and absorption, the oscillating particle and N heavy particles act coherently to the outside interactions. The system of $N+1$ particles together should be considered as a minimum emitter–absorber system concluding multiple transactions among themselves. The N heavy particles act as potential-producing particles, forming a background for the oscillating particle producing the Coulomb field in the static approximation. These N particles should be included in the emitter–absorber system. But these N particles do not emit or absorb sizable radiation through interaction with other systems, so that the charged particle appears to emit or absorb radiation by concluding transactions with other systems.

This is the reason that the oscillating particle alone plays the role of an emitter–absorber system, and the N particles are receded in the background. Thus, the oscillating particle appears to conclude a transaction with itself by emitting or absorbing a radiation with other systems. The average energy per unit volume of the zero-point radiation is defined as

$$\langle u\rangle=\int_0^\infty \mathrm{d}\omega\,\rho(\omega), \qquad \rho(\omega)=\frac{I(\omega)}{\pi^2c^3} \tag{19}$$

where $\rho(\omega)$ is the spectral density of the zero-point radiation given in equation (2). Then, for the average rate of energy absorption by the oscillator, following the calculation of Boyer (1978), we obtain

$$E_\mathrm{a}=\langle e\dot{x}E(t)\rangle=(2\pi^2e^2/3m)\rho(\omega), \tag{20}$$

and the average rate of energy radiated by the oscillator is

$$E_\mathrm{e}=(2e^2/3c^3)\langle\ddot{x}^2\rangle=(2e^2/3c^3)\omega^4\langle x^2\rangle. \tag{21}$$

As described in detail above, strictly speaking, a charged particle alone cannot form an emitter–absorber system. A charged particle, even performing a periodic motion, cannot conclude a transaction with itself, because, in order to conclude a transaction, both ends of the system must be connected by a null-line if an emitter–absorber system is to form at all. But the light-cone emanating from a point on the world-line of a particle cannot intersect any other point on the world-line of the same particle. We need to include a set of heavy particles which produces Hooke's potential for a charged simple harmonic oscillator to form an emitter–absorber system, as described before.

We have started from equation (17) which has a similar form to that of a charged simple harmonic oscillator in a Hooke potential which was constructed from the static

Coulomb potential of Maxwell–Lorentz electrodynamics. However, we can apply the emitter–absorber transaction idea to a charged simple harmonic oscillator because our theory is based on the Wheeler–Feynman theory. In the static Coulomb approximation, the retarded and advanced fields of a charged particle are replaced by corresponding (instantaneous) fields propagating with infinite velocity. Denoting by $F^{(j)}_{adv}$ and $F^{(j)}_{ret}$ the fields (propagating with infinite velocity) of the jth particle (there are N such particles), which act on an oscillating particle C, the transaction condition is (as given by equation (11))

$$-F_{in}+F_{out}=0 \tag{22}$$

where

$$\tfrac{1}{2}F_{in}=\tfrac{1}{2}\left[\sum_{j=1}^{N} F^{(j)}_{ret}+F^{(C)}_{ret}\right], \qquad \tfrac{1}{2}F_{out}=\tfrac{1}{2}\left[\sum_{j=1}^{N} F^{(j)}_{adv}+F^{(C)}_{adv}\right]$$

(see figure 4).

The condition for a transaction of the minimum emitter–absorber system in a zero-point electromagnetic radiation for a simple harmonic oscillator gives the following condition:

$$E_a=E_e, \tag{23}$$

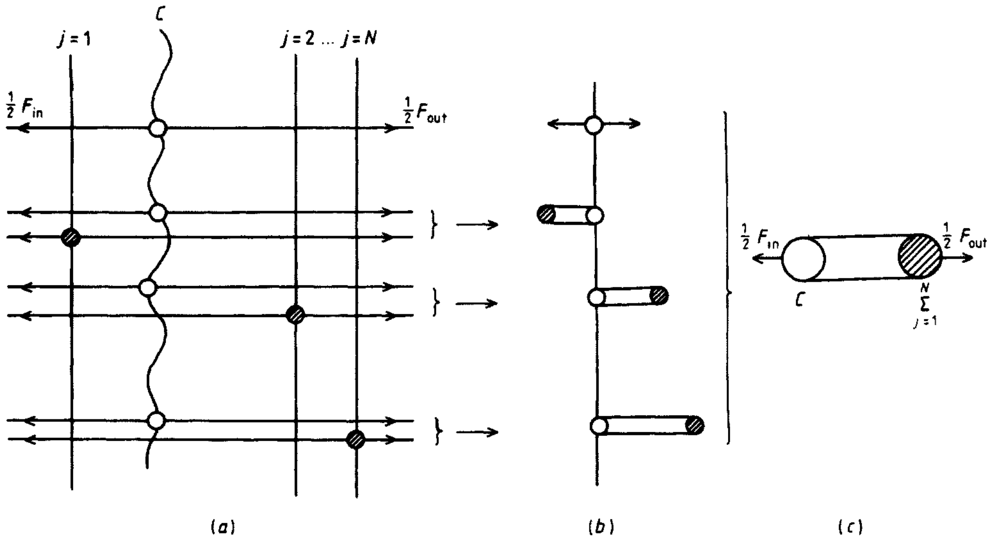

Figure 4. Charged simple harmonic oscillator: In (a) particles $j=1,2,\ldots,N$ are the source of the potential acting on a charged particle C. The advanced and retarded waves produced by the particles propagate with infinite velocities. The system is equivalent to a simple harmonic oscillator, where

$$\tfrac{1}{2}F_{in}=\left(\sum_{i=1}^{N}\tfrac{1}{2}F^{(i)}_{adv}\right)+\tfrac{1}{2}F^{(C)}_{adv}\approx\tfrac{1}{2}F^{(C)}_{adv},$$

$$\tfrac{1}{2}F_{out}=\left(\sum_{i=1}^{N}\tfrac{1}{2}F^{(i)}_{ret}\right)+\tfrac{1}{2}F^{(C)}_{ret}\approx\tfrac{1}{2}F^{(C)}_{ret}.$$

In (b) the system consists of N sub-emitter–absorber systems, which form a self-sustained emitter–absorber system, and a charged simple harmonic oscillating particle, which absorbs and emits zero-point radiation. In (c) all the radiation absorbed or emitted by N heavy particles can be neglected.

i.e. the energies absorbed and emitted by the oscillator during a transaction should be equal. Here, we may call the condition a 'radiative balance' condition, as in Boyer (1978). The condition of transaction for the oscillator implies that the energy and momentum are conserved for a transaction and that the oscillator (including the heavy particles) becomes, as a whole, a sort of isolated system. From equations (21) and (22) with transaction condition (23), we get the relation

$$\langle x^2\rangle = (\pi^2 c^3/m\omega^4)\rho(\omega). \tag{24}$$

The average energy $\langle E\rangle$ of the oscillator is obtained from equation (17):

$$\langle E\rangle = \langle \tfrac{1}{2}m\dot{x}^2 + \tfrac{1}{2}kx^2\rangle. \tag{25}$$

Using the energy balance equation (23), we find

$$\langle E\rangle = (\pi^2 c^3/\omega^2)\rho(\omega). \tag{26}$$

From equation (25) together with equation (19), we see that $\langle E\rangle/\omega$ becomes a constant (adiabatically invariant) only when $\rho(\omega)$ is a zero-point radiation given by

$$\rho(\omega) = (\omega/\pi^2 c^3)(\hbar\omega/2),$$

and we have

$$\langle E\rangle = \tfrac{1}{2}\hbar\omega. \tag{27}$$

The energy agrees with the lowest energy level of a harmonic oscillator in quantum mechanics.

The simple harmonic oscillator which we considered to be an emitter–absorber system behaves as a self-sustained system: it emits and absorbs the same amount of zero-point radiation during a transaction. The system as a whole, attains the 'radiative balance' through the transaction condition.

In the case of an excited oscillator system, in order that the transaction condition should hold, and the adiabatic invariance of the energy spectrum should be equated to $(n+\tfrac{1}{2})\hbar$, the radiative balance between E_a and E_e should satisfy, instead of equation (23),

$$(2n+1)E_e = E_a. \tag{28}$$

For the simple harmonic oscillator in question, the oscillator has to be a multiple emitter–absorber system as considered before. The adiabatically invariant quantity $\langle E\rangle/\omega$ is then

$$\langle E\rangle/\omega = (n+\tfrac{1}{2})\hbar. \tag{29}$$

In an emitter–absorber system undergoing multiple transactions, the oscillating charged particle absorbs zero-point radiation over a number of periods of $(2n+1)$ cycles, coherently, and emits it as a radiation in a single transaction. The transaction condition for the simultaneous absorption of $(2n+1)$ absorbers a_i $(i = 1, 2, \ldots, 2n+1)$ and the emission by the emitter e (see figure 4) gives

$$(2e^2/3c^3)\langle \ddot{x}^2\rangle = (2n+1)\rho(\omega). \tag{30}$$

From equations (30) and (18), $\langle E\rangle/\omega$ is an adiabatic constant and we obtain equation (29).

In the above consideration, a charged simple harmonic oscillator behaves as an emitter–absorber system and, as a whole, is considered as an adiabatic system (even under the influence of the zero-point radiation). The energy–momentum conservation holds for each internal transaction, so that the absorbed zero-point radiation is re-emitted by the system, and the system maintains the same energy and momentum. The system, even though under the constant influence of the zero-point radiation, maintains the same energy and momentum over a long period of time, so that it remains in a stationary state.

The analogy may be extended to atoms which, even under the influence of a zero-point radiation, maintain a certain stability and a stationary state. The problem of atomic stability and the discreteness of the energy levels, in stochastic electrodynamics, may be solved quantitatively through the Kepler problem using the idea of a multiple transaction. In our model of an emitter–absorber transaction we can understand the stability of atoms, even in the presence of a zero-point radiation, as being a self-sustained system which strictly conserves the internal energy.

In our transaction model of an emitter–absorber system (an extension of that of Cramer), when an observation is made, an object and the measuring apparatus form an emitter–absorber system. The transaction is concluded between the object and the measuring apparatus. The transaction condition guarantees the re-emission of the absorbed zero-point radiation from the system, and therefore guarantees that the conservation laws are strictly implemented. The energy–momentum conservation strictly holds, and the deviation from their average values cannot be observed unless the transition process is a multiple one; for example, a process involving the emission of more than one photon. In the case of the emission of two photons from an excited calcium atom, the energy and momentum of one of the photons distribute around the average value, as is explained below.

Take, for example, the Freedman–Clauser experiment of successive decay of an excited calcium atom. From figure 3 we see that the energy–momentum variation of the photons due to the fluctuation of zero-point radiation, absorbed at the emitter and re-emitted at one of the absorber ends, is, from the transaction condition, given by equation (12):

$$-(F_{\text{in}}(t)+F^{(2)}_{\text{out}}(t))=F^{(1)}_{\text{out}}(t). \tag{31}$$

In this equation one of the terms can be taken to be independent and to be a zero-point radiation. We choose $F^{(1)}_{\text{out}}$ to be the independent term. Then, $F^{(1)}_{\text{out}}$ is given by equations (10) and (31), from which we can calculate the variance of the energy of the zero-point radiation. The quantity $(1/8\pi)(E^2+B^2)$ is averaged over a lifetime τ of the intermediate state of the atom, which is considered to be the time needed to conclude the transaction and during which the zero-point radiation is absorbed and re-emitted. A difference between this and the corresponding result of stochastic electrodynamics is that our theory predicts exactly the same energy for the sum of the energy of the two photons, although the energy of the individual photon fluctuates. On the other hand, stochastic electrodynamics gives a dispersion in the sum of the energies of the two photons.

6. Effect of cosmology

In our theory, the total field acting on a particle is completely time-symmetric, as can be seen from equation (1). But a zero-point electromagnetic radiation is not time-reversible. Therefore, for an emitter–absorber system, when a transaction is concluded, the time developments of the emitter and absorber are non-time-reversible, because the system absorbs and emits a non-time-reversible zero-point radiation. This non-time-reversibility of the emitter–absorber system will give an important insight into the measurement theory of quantum phenomena and will be discussed elsewhere. With regard to the zero-point electromagnetic radiation, the expansion of the universe has no effect on the spectrum, since the spectrum is Lorentz invariant and also invariant under adiabatic expansion of the radiation cavity (Boyer 1969).

In an open universe the future absorber is incomplete. Whether or not the expanding universe acts as a radiation cavity for the zero-point radiation remains to be answered. The Lorentz-invariant character of the radiation prevents red-shift of the radiation. However, the upper limit to the validity of the spectrum may be affected by the expansion of the universe. It has been suggested that the frequency of $(c^5/Gh)^{1/2} \sim 10^{54}\,s^{-1}$ or the energy $E = h\omega \sim 10^{40}$ eV may be the limit of the validity of the electrodynamics, or even of the laws of quantum physics. Therefore, the limit of the validity of the Lorentz-invariant spectrum of the zero-point electromagnetic radiation, in the expanding universe, may be the same as that of the laws of quantum mechanics. We note that the highest energy attainable at present is around 10^{20} eV, which is much less than 10^{40} eV. Thus, the validity of the spectrum cannot be tested experimentally.

A charged simple harmonic oscillator, or a system undergoing a periodic motion, which is performing a multiple emitter–absorber transaction within the system as described before, emitting and absorbing only the zero-point radiation for each transaction, can be considered to be in a stationary state. The lowest level of an atom may be such a system, and the adiabatic invariant quantity $\langle E \rangle/\omega$ is a constant irrespective of the influence of zero-point electromagnetic radiation. The effect of an open universe on the execution of an emitter–absorber transaction of type I is not considered in this paper. The detectability of the effect of the future absorber deficiency in the expanding universe may be tested by an experiment using a transaction of type II of Cramer, as discussed by Cramer. In this case an emitter–absorber transaction of type II involves two transactions between an emitter at the past infinity and an absorber at the future infinity, and emission and absorption including those do not originate in zero-point electromagnetic radiation (as suggested by Davies (1975)).

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