Why the Quantum Absorber Condition is Not a Light-Tight Box

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ABSTRACT. This paper discusses the nature of the boundary condition applying to the direct-action theory of fields, also known as the 'absorber' theory, first developed in a classical version by Wheeler and Feynman. The traditional understanding of these authors and others who followed is that the direct-action theory requires that 'all emitted radiation be absorbed,' or that 'the universe is a perfect (or complete) of absorber of radiation,' implying the need for a specific sort of cosmological boundary condition that may or may not obtain in our universe. It is pointed out that this interpretation requires critical scrutiny even at the classical level, and in any case does not apply to the fully quantum form of the direct-action theory (QDAT), which involves discrete energy transfers by way of photons. In the latter case, the absorption boundary condition describes a specific interactive relationship between emitters and absorbers that is independent of cosmological boundary conditions. Thus, the quantum direct-action theory does not require any special cosmological boundary condition in order for it describe the physical world.

1. Introduction and Background

This paper seeks to clarify the nature of the 'light tight box' condition applying to the direct-action theory (DAT) of fields, also known as the 'absorber' theory. The DAT was first developed in a classical version by Wheeler and Feynman (1945, 1949). The traditional understanding of these authors, and others who followed, is that the DAT requires that 'all emitted radiation be absorbed,' or that 'the universe is a perfect (or complete) of absorber of radiation,' implying the need for a specific sort of cosmological boundary condition that may or may not obtain in our universe. In what follows, we will critically examine this interpretation and find that, at best, it applies only to the classical absorber theory--not to the fully quantum form of the direct-action theory (QDAT). Thus, contrary to what has traditionally been assumed, the quantum direct-action theory does not require any special cosmological boundary condition in order for it describe the physical world.

Before reviewing the details of the theory, let us first address an interpretive matter: what is the physical meaning of a 'field' in a 'direct-action' theory? Does it exist as a physical entity, or not? In this work, the concept of 'field' is taken as still physically applicable in the form of a potential, describing the strength of an interaction between sources. However, it does not constitute an independently existing medium. Thus, the usual parlance of 'eliminating the field' in the direct-action theory means the elimination of an independently existing, local medium of oscillators, not the denial of a physical referent for the potential A when charges are present. The field A still exists as a physically real, direct connection between charges. It differs from the standard notion of a 'field' in that its existence is contingent on the existence of the charges that are its source. Without sources, it vanishes.

Let us now recall a crucial difference between classical and quantum electromagnetic theory. In the classical case, radiated energy is continuous and unrelated to frequency, while in the quantum case, the opposite holds: radiated energy is discrete, by way of indivisible photons, whose energies are related to frequency by the famous Planck relation:

$$E = h\nu \tag{1}$$

In the classical theory, there is no fundamental difference between the 'near field' (Coulomb field) and the 'far field' (radiation field), and both are considered as continuous wavelike entities that can mutually interfere. But in the quantum form of the direct-action theory, the Coulomb field is strictly a field of *force*, not energy; it is not radiation. Put differently, the Coulomb field is mediated by virtual (off the mass shell) photons only. In contrast, the 'far field' corresponds to one or more radiated (real, on-shell) photons. This distinction is crucial in what follows, where we show that in the fully quantum version of the direct-action theory (QDAT), the 'near' field does not involve any 'absorber response' but is instead simply the time-symmetric direct connection between charges (virtual photons). Meanwhile, the far field corresponds to real photons, and only exists contingent on appropriate absorber response. Thus, *the existence or non-existence of absorber response* is what defines the distinction between a real and virtual photon, and is an essential aspect of what was formerly presented as a 'light tight box' condition.

However, at the relativistic level, the term 'absorber response' also needs modification, since the relevant process is actually a mutual one in that emitter and absorber *together* initiate a non-unitary interaction that gives rise to a real (on-shell), as opposed to virtual (off-shell), photon. That is, both the emitter and absorber must participate in creating any real photon; neither the emitter nor absorber alone can create the requisite on-shell field. In particular, contrary to the usual parlance in the DAT, it is not the case that the emitter 'first' creates a field to which an absorber 'responds'. So rather than 'absorber response,' this quantum relativistic process is really a *mutual* agreement to generate an on-shell field that satisfies conservation requirements (in contrast to the time-symmetric field, which does not). This mutual non-unitary process needs a new name, so let us call it 'Real Photon Generation' or RPG. We make this more quantitative in the next section.

2. The direct-action theory

In this section, we will first review the basic classical absorber theory and a semi-classical quantum version due to Davies (1971, 1972). It should be noted that Davies' treatment, while an advance in the quantum direction from the original classical Wheeler-Feynman theory, remained semi-classical insofar as it tacitly identified radiation with continuous fields, and assumed that a real photon could be unilaterally emitted, which is not the case at the quantum level. Thus, ambiguity remained in that account regarding the distinction between real and virtual photons and the nature of the relevant absorber boundary condition, which has led to some confusion. However, it is a useful starting point for the present work, which revises certain features pertaining to the quantization of the radiated field. The revised account makes clear the fully quantum nature of the appropriate boundary condition, which is really a particular sort of emitter/absorber interaction rather than any specific configuration of absorbers.

2a. The classical direct-action theory: basics

We first revisit standard classical electromagnetic theory. The standard way of representing the field *A* acting on an accelerating charge *i* due to other charges *j* is as the sum of the retarded fields due to *j* and a 'free field':

$$A = \sum_{j \neq i} A_{(j)}^{ret} + \frac{1}{2}\left(A_{(i)}^{ret} - A_{(i)}^{adv}\right) \qquad (2)$$

In the classical expression (2), self-action is omitted to avoid infinities (which are dealt with in quantum field theory by renormalization). $A_{(j)}^{ret}$ is the retarded solution to the inhomogeneous equation, i.e., the field equation with a source, while the second term pertaining only to *i* is a solution to the homogeneous field equation (source-free). The latter quantity, the 'radiation term,' is originally due to Dirac and is necessary in order to account for the loss of energy by a radiating charge if it is assumed that all sourced fields are retarded only. Wheeler and Feynman (1945) critically remark in this regard:

> "The physical origin of Dirac's radiation field is nevertheless not clear. (a) This field is defined for times before as well as after the moment of acceleration of the particle. (b) The field has no singularity at the position of the particle and by Maxwell's equations must, therefore, be attributed either to sources other than the charge itself or to radiation coming in from an infinite distance." (p. 159)

These authors' concern about the source of Dirac's radiation field is resolved in the DAT. The classical direct-action or 'absorber' theory proposed that the total field $A^{(DA)}$ acting on *i* is given by:

$$A^{(DA)} = \sum_{j \neq i} \frac{1}{2}\left(A_{(j)}^{ret} + A_{(j)}^{adv}\right) \qquad (3)$$

i.e., it is given by the sum of the time-symmetric fields generated by all charges *except i*. Absorbing charges respond to the emitted field with their own time-symmetric field, contributing to the sum in (3). Wheeler and Feynman noted that (2) and (3) are equivalent provided that their difference is zero, i.e.:

$$\sum_{\forall j}\frac{1}{2}\left(A^{ret}_{(j)} - A^{adv}_{(j)}\right) = 0 \qquad (4)$$

Under the condition (4), the responses of absorbing charges to the time-symmetric field of the emitting charge yields an effective 'free field' applying only to the emitting charge; i.e. the second term of (2). It's important to note that this term attributes a solution to the homogeneous equation to a particular charge that is (of course) not its source, as observed by WF above. In the DAT, the 'free field' is actually sourced by other charges (responding absorbers) and only *appears* to have the form of a free field from the standpoint of the accelerating charge whose index it bears.

The condition (4) is historically termed the 'light tight box' condition (LTB) in the classical theory. It is commonly interpreted as the constraint that 'all radiation is absorbed,' but this characterization is misleading even at the classical level, and requires explicit reformulation at the quantum level. For one thing, it conflates the static, time-symmetric Coulomb field with a dynamic radiation field.[1] In addition, the mathematical content of (4) says only that the net radiation field is zero. This can just as easily be interpreted to mean that *there is no true free (unsourced) radiation field*. While selective cancellation of fields does occur among charges to produce the effective radiation field, the absence of an unsourced radiation field is the primary physical content of the "LTB" condition for the quantum form of the DAT, as we will see in §2b.

Other weaknesses in the original classical DAT have been discussed by Gründler (2015), who notes that field cancellation via explicit evaluation of the interactions between the emitter and the other charges depends on imposing an arguably unjustified asymmetrical condition: an effective index of refraction applying only to absorber responses. He argues that the equivalence between the classical DAT and standard classical electrodynamics for individual charges amounts only to a formal one based on (3) and (4).

In any case, the ambiguity inherent in the classical treatment, and the practice of interpreting (4) as being about some specific distribution of charges, has led to some confusion regarding the nature of the relevant condition -- the analog of (4) -- pertaining to the quantum case. The goal of the present work is to clarify the situation and to define the appropriate absorber condition for the quantum version of the theory. We now turn to the fully quantum version of the direct-action theory, or 'QDAT' for short.

2b. The quantum direct-action theory: basics

[1] Actually, the classical DAT appears to assume that even the time-symmetric fields are present only in the case of an accelerating charge, which neglects the static Coulomb interaction.

In what follows, we will discuss the DAT in terms of Green's functions or 'propagators' (solutions to the field equation for a point source, and related source-free forms), since that is the natural way to formulate the QDAT. It should be noted that, in contrast to the fields *A(x)* with a single argument, propagators are functions of two arguments, and always relate two specific coordinate points. In standard quantum field theory, they are correlation functions for pairs of field coordinates.[2]

The corresponding quantities are:

$D_{ret}(x-y)$: retarded solution to the inhomogeneous equation

$D_{adv}(x-y)$: advanced solution to the inhomogeneous equation

$\bar{D}(x-y) = \frac{1}{2}\left(D_{ret} + D_{adv}\right)$: time-symmetric solution to the inhomogeneous equation

$D(x-y) = \left(D_{ret} - D_{adv}\right)$: odd solution to the homogeneous equation

In terms of these, we can see that the following identity holds:

$$D_{ret} = \bar{D} + \frac{1}{2}D \qquad (5)$$

This describes the elementary field of a single charge in the DAT, taking into account the 'response of the absorber' corresponding to the second term. It differs from (2) in that it does not exclude the charge from the effects of the field. As noted by Wheeler and Feynman (1945), the first term is singular, and this effect must be dealt with at the quantum level through renormalization. However, this expression shows how a net retarded field arises due to the combination of 'absorber response' (an effective 'free field' acting on the emitting charge) with the basic time-symmetric field of the emitting charge. We now investigate the analogous situation in the QDAT.

First, it is important to note that the propagators defined above make no distinction between positive and negative frequencies, since the classical theory makes no connection between frequency and energy (or other conserved quantities). However, the quantum theory of fields must explicitly deal with the existence of positive and negative frequencies. Thus, in the QDAT, each of the quantities above must be understood as comprising positive- and negative-frequency components. Since there are many different conventions for defining these quantities, we write the components here explicitly in terms of vacuum expectation values or 'cut propagators' $\Delta^{\pm}$. In these terms,

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[2] As suggest by Auyang (1995), these coordinates are best understood as parameters of the field, rather than 'locations in spacetime.' The same understanding can be applied to the non-quantized field of the QDAT, in which field sources are the referent for the parameters.

$$iD(x-y) \equiv i\Delta(x-y) = \langle 0 | [A(x), A(y)] | 0 \rangle$$
$$= \left(\langle 0 | A(x)A(y) | 0 \rangle - \langle 0 | A(y)A(x) | 0 \rangle \right) \equiv \left(\Delta^{+} - \Delta^{-} \right) \qquad (6)$$

Where, under Davies' convention for the components, we define

$$D(x-y) = D^{+} + D^{-} = \left(-i\Delta^{+} \right) + \left(i\Delta^{-} \right) \qquad (7)$$

Note in particular, for later purposes, that D– is defined with the opposite sign of the negative-frequency cut propagator Δ^{-}:

$$iD^{-}(x-y) \equiv -\Delta^{-}(x-y) = -\langle 0 | A(y)A(x) | 0 \rangle \qquad (8)$$

We also need the even solution to the homogeneous equation, D_1 (cf. Bjorken and Drell, 1965, Appendix C):

$$D_1(x-y) = i\left(D^{+}(x-y) - D^{-}(x-y) \right) = \Delta^{+}(x-y) + \Delta^{-}(x-y) \qquad (9)$$

Note that each of the positive- and negative-frequency components of these fields independently reflects the same relationship of retarded and advanced solutions as the total field; e.g., $D^{+}(x-y) = \left(D^{+}_{ret} - D^{+}_{adv} \right)$.

Feynman's innovation was to interpret negative frequencies as antiparticles; specifically, as 'particles with negative energies propagating into the past.' This is equivalent to antiparticles with positive energy propagating into the future, where antiparticles have the opposite charge (cf. Kastner 2016). To that end, he defined a propagator that does just that, i.e. assigns the retarded propagator only to positive frequencies and the advanced propagator only to negative frequencies. The result is the 'Feynman propagator,' D_F:

$$D_F = D^{+}_{ret} + D^{-}_{adv} \qquad (10)$$

This satisfies an identity analogous to (5):

$$D_F = \bar{D} - \frac{i}{2} D_1 \qquad (11)$$

To see (10) explicitly, we write the quantities in terms of their positive- and negative frequency components, i.e. :

$$\bar{D} - \frac{i}{2} D_1 = \frac{1}{2}\left[\left(D^+_{ret} + D^+_{adv}\right) + \left(D^-_{ret} + D^-_{adv}\right)\right] + \frac{1}{2}\left[\left(D^+_{ret} - D^+_{adv}\right) - \left(D^-_{ret} - D^-_{adv}\right)\right]$$
$$= \left(D^+_{ret} + D^-_{adv}\right) = D_F \qquad (12)$$

As observed by Davies (1971), a basic quantum version of the direct-action theory (QDAT) has actually been around since Feynman (1948). Feynman showed that the for the case when the number *n* of external (commonly termed 'real') photon states is zero, the standard quantum action *J* for the interaction of the quantized field $\hat{A}$ with a current *j* can be replaced by a direct current-to-current interaction, as follows:

$$J(n=0) = \sum_i \int j^\mu_{(i)}(x) \hat{A}_\mu(x)\ d^4x =$$
$$\sum_i \sum_j \frac{1}{2} \int j^\mu_{(i)}(x) D_F(x-y) j_{\mu(j)}(y)\ d^4x\ d^4y \qquad (13)$$

where D_F is the Feynman propagator as defined in (9) and (10). Davies notes that the same result is proved by way of the S-matrix in Akhiezer and Berestetskii (1965), p. 302 (henceforth 'AB'). So it is important to note that (13) *is a theorem,* and holds even if one has started from the usual assumption that there exists an independent quantum electromagnetic field $\hat{A}_\mu$.

Now, the entire content of the so-called 'light tight box condition' (LTB) for the quantum version of the direct action theory (QDAT) is contained in the condition for the equivalence of the two expressions in (13). But the LTB condition has traditionally been deeply mired in ambiguity about what sort of entity counts as a 'real photon,' and about what physical situations give rise to 'real photons.' It has additionally been hampered by a semi-classical notion of 'absorption of radiation.' However, it is straightforward from the mathematics that what is actually required for the equivalence of the two expressions in (13) is simply the non-existence of an independent quantized electromagnetic operator field $\hat{A}_\mu$ -- i.e., vanishing of the usual postulated system of oscillators of standard quantum field theory! We can see that explicitly by way of the proof of AB, who obtain an expression for the scattering matrix *S* in the general case, with no restriction. That expression is:

$$S = \exp\left(-\frac{i}{2}\int j^\mu(x) D_F(x-y) j_\mu(y)\ d^4x\ d^4y\right) \times \exp\left(i \int j_\mu(x) \hat{A}^\mu(x)\ d^4x\right) \qquad (14)$$

where the usual chronological ordering of quantum field operators is understood, and $\hat{A}_\mu$ is the usual quantized electromagnetic field. AB then say: "In processes in which no photons participate, the last factor is equal to unity, and the scattering matrix assumes the form [*S* with final Lagrangian as in eqn. (13)]." But again, this brings in the ill-defined notion of 'participation of photons,' when what is really done to obtain the final result is to simply *set the quantized electromagnetic field* $\hat{A}_\mu$ *to zero*. This, then, is essentially all there is to the so-called 'light tight box' condition for the QDAT expressed in terms of the

Feynman propagator D_F: Wheeler and Feynman's original proposal to eliminate the electromagnetic field as an independent mechanical system. Note that this corresponds to the condition (4) as interpreted in the previous section; i.e., that there simply are no genuinely unsourced 'free fields.' Rather, any effective field of the form D (or D_1 for the QDAT) is obtained through an interaction between sources, i.e., between emitters and absorbers.

In the next section we examine the QDAT in more detail, resolving some ambiguities about the distinction between real and virtual photons and discussing the relevance of the distinction for the quantum form of the LTB. We'll see that the only additional condition for equivalence of the QDAT with the standard theory amounts to the quantum completeness condition (and an appropriate phasing of the fields of the emitter and absorbers), which assures recovery of the Feynman propagator.

3. The Feynman propagator and 'Real Photon Generation'

The Feynman propagator D_F is the quantum analog of (2); it reflects a "causal" field directed from smaller to greater temporal values for the case of positive frequencies and from greater to smaller temporal values for negative frequencies, with an effective 'free field' for radiative processes. D_F arises due to the quantum analog of 'absorber response,' which differs from the classical theory in several important respects. One is the need to take into account negative frequencies not present in the classical case, which requires separate phasing of the positive- and negative-frequency field components and leads to D_1 rather than D for the free field, as discussed above. Another is the mutuality of the emitter/absorber interaction giving rise to the 'free field'. As noted above, this mutual interaction giving rise to the effective free field is termed 'Real Photon Generation' (RPG). The basic probability of RPG is given by the fine structure constant α, equivalent to the square of the unit charge e. (This point is discussed in detail in Kastner and Cramer, 2018).

Another important distinction between the classical DAT and the QDAT is that the relevant quantity for describing the interaction is the scattering matrix $S = Pe^{-iJ}$ (where J is the action and P a time-ordering operator), which defines probability amplitudes for transitions between initial and final states. This probabilistic behavior does not exist at all in the classical DAT, but is a crucial aspect of the QDAT. The need for a probabilistic description arises because in the quantum case, one must take into account that the field is not equivalent to a 'photon' in that a photon is discrete while the field is continuous (at least with respect to the parameter x). As an illustration, suppose we are dealing with a field state corresponding to one photon. Such a field in general propagates between an emitter and many absorbers; many absorbers can respond, even though there is only one photon 'in the field.' While the responses contribute to the creation of the real photon field, the photon itself cannot go to all the responding absorbers; only one can actually receive it. This is where the probabilistic behavior, described by $S = Pe^{-iJ}$, enters. We make this issue more quantitative in what follows.

Looking at the Fourier components, one again sees that the Feynman propagator is complex, with both real and imaginary parts:

$$D_F(x) = \frac{1}{(2\pi)^4}\int\left(\frac{PV}{k^2} - i\pi\delta(k^2)\right)e^{ikx}\,dk = \bar{D}(x) - \frac{i}{2}D_1(x) \qquad (15)$$

The complexity of D_F implies intrinsic non-unitarity, a point whose implications we will consider in §4. In (15), 'PV' stands for the principal value. The real part $\bar{D}$ is the time-symmetric propagator, while the imaginary part D_1 is the even "free field" or solution to the homogeneous equation as defined above.[3]

As Davies notes, "The $\bar{D}$ part (bound field) leads to the real principal [value] term which describes virtual photons ($k^2 \neq 0$), whilst the imaginary part D_1 (free field) describes photons with $k^2 = 0$, that is, real photons, through the delta function term." (Davies 1972, p. 1027). The D_1 term is the quantum analog of the free field in eqns. (2) and (5). In the classical DAT, the 'free field' is assumed to be present for all accelerated particles due to the 'the response of the universe' or 'absorber response'. In order to understand the circumstances and physical meaning of the D_1 interaction for the QDAT, we must clearly define the quantum analog of acceleration and distinguish that from the static case, in which only the Coulomb (non-radiative) interaction $\bar{D}$ is present. The quantum analog of acceleration is a state transition, such as from a higher to a lower atomic energy state, accompanied by radiation. In contrast, for the static case, there is no radiation, so there is no effective free field-- no 'absorber response.' Thus, in the QDAT, the presence or absence of 'absorber response' -- really a mutual interaction, RPG, as discussed above-- is what dictates whether there will be a D_1 interaction and hence a quantum form of acceleration accompanied by radiation (i.e., the exchange of transversely polarized, real photons). Without the RPG, one still has the basic time-symmetric interaction corresponding to the Coulomb force; i.e. one has virtual photon exchange but not real photon exchange. As noted above, and as discussed in Kastner (2018) and Kastner and Cramer (2018), the basic probability of the occurrence of RPG and real photon transfer via the interaction D_1 is the fine structure constant.

In contrast, traditional quantum field theory (QFT) uses the entire D_F universally. In view of the distinct physical significance of the real and imaginary part of the Feynman propagator as noted above, which holds regardless of the specific model considered, a shortcoming of traditional QFT is that no physical distinction can be made in that theory between radiative and non-radiative processes at the level of the propagator. Indeed, in standard QFT the term 'virtual photon' is routinely taken as synonymous with 'internal line' in a Feynman diagram. This is inadequate, as it is only a contextual criterion (depending on 'how far out we look') and thus does not describe the photon itself. While Davies' definition quoted above (virtual photon is off the mass shell, while real photon is on the mass shell) is the correct account of the physical distinction between real and virtual

[3] Here, we are using the sign conventions in Bjorken & Drell (1965), Appendix C.

photons, his treatment of the real/virtual distinction in both Davies (1971) and (1972) falters into an ambiguous one alternating between (a) the standard QFT characterization of the 'real vs. virtual' distinction as a merely contextual one, i.e. as an 'internal' vs 'external' photon dependent on our zoom level and (b) the assumption that in order to obey the uncertainty principle, a real photon must have an infinite lifetime and therefore can only be truly 'external.' [4]

The error leading to (b) is the assumption that a real photon must have a precise energy (i.e. $\Delta E=0$). But in fact, for any actual emission and absorption process, there must be a finite ΔE. Davies even notes this in his (1972), commenting that the finite level width is what gives rise to real photon emission.[5] A finite ΔE does not preclude an on-shell photon, since one can still have $\Delta E= \Delta pc$. Thus a real, on-shell photon can indeed have a finite lifetime Δt; it can be emitted and absorbed. This point--that real photons are *both* emitted and absorbed and therefore can be considered a form of 'internal line'-- is key in understanding the relevant quantum analog of the LTB condition.

Keeping in mind that it is indeed possible to have a 'real but internal' photon, let us review another useful account given in Davies (1971) of the relevant LTB condition for the QDAT. Davies correctly notes that the fully quantum form of the LTB is simply the requirement that there are no transitions between *external* fermion/photon states $|\beta\rangle = |\psi, n\rangle$ where photon number $n \neq 0$. He writes this as:

$$\sum_{\beta'} \left|\langle \beta' | S | \alpha \rangle\right|^2 = 0 \qquad (16)$$

where $|\alpha\rangle$ are states with n=0 and $|\beta'\rangle$ are states with $n \neq 0$. This is in keeping with the theorem (13) and the discussion of (14) above. But of course, the transition probability for each value of β' is a non-negative quantity, so each term must vanish separately:

$$\left|\langle \beta' | S | \alpha \rangle\right|^2 = 0, \ \forall \beta' \qquad (17)$$

Also, note that by symmetry the restriction on external photon states $n \neq 0$ holds for both initial states and final states. That is, one must exclude transitions *from* states $|\alpha'\rangle$ as well as transition t*o* states $|\beta'\rangle$. *Thus, the QDAT describes a world in which there simply are no truly external photons.* This, of course, corresponds to setting the independent quantized electromagnetic field $\hat{A}_\mu$ to zero.

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[4] However, Davies does correctly criticize Feynman's purely contextual account of the 'real vs virtual' distinction by noting that a true virtual photon has no well-defined direction of energy transfer and is described by the time-symmetric component of D_F (i.e. the real part $\overline{D}$) only (Davies 1972, p. 1028).

[5] Davies says of the Feynman propagator D_F in eqn (7): "The real part [$\overline{D}$] gives rise to the self-energy and level shift, whilst the imaginary part [D_1] gives the level width, or transition rate for real photon emission..." (Davies 1972, p. 1027)

Again, this does *not* mean that real photons are disallowed, an inference that leads to confusion in Davies' account. In fact, in the QDAT, the only way one obtains a real photon at all is through *both* emission and absorption, i.e., the participation of both the emitter and absorber(s) in the Real Photon Generation (RPG) interaction mentioned above. Specifically, the 'free field' propagator D_1, corresponding to a real (on-shell) photon, arises from the RPG interaction between emitters and absorbers that is the quantum analog of 'absorber response.' The creation of the real photon field can be quantified in terms of a complete set of field components propagating between the emitter and absorber(s); this has been presented in Kastner and Cramer (2018) and is reviewed below. In effect, the generation of a complete set of emitter/absorber fields (the analog of 'absorber responses' in the classical DAT) with an appropriate phase relationship is the entire content of the quantum LTB condition.

Davies views the existence of the D_1 term in the context of the restriction (16) as paradoxical, since he identifies the term 'real photon' solely with an external photon.[6] If we let go of that restriction (as was justified above in our observation that a real emitted or absorbed photon can indeed have a finite energy spread), we find that real photons are indeed transferred between currents via the D_1 term. In fact Davies (1972) gives a quantitative account of how this occurs (although he hesitates to acknowledge those 'internal' photons as real photons, calling the relevant construction 'formal'). We now review that account.

First, Davies notes the property

$$D^{+}(x-y) = i\langle 0|\hat{A}(x)\hat{A}(y)|0\rangle = -iD^{-}(y-x) \tag{18}$$

which is useful in what follows. Looking again at the expression from (13) for the first-order interaction,

$$\frac{1}{2}\sum_{i,j}\int j_i^{\mu}(x)D_F(x-y)j_{\mu,j}(y)\; d^4x\; d^4y \tag{19}$$

This is the first-order term in the *S* matrix, corresponding to the exchange of one photon (either virtual or real, since D_F does not make this distinction). Using the decomposition (11) for D_F, we can evaluate the real and imaginary parts:

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[6] Davies (1972, p. 1027) suggests that real photons can interfere with virtual photons, resulting in cancellation of the advanced effects of a real photon (which he assumes has an infinite lifetime). But this is only a semi-classical argument that does not carry over into the fully quantum form of the DAT, since different photons do not mutually interfere; and certainly not photons with different physical status regarding whether or not they are on the mass shell. This is also evident from the form of (17), in which different external photon states must vanish separately. Davies appeals to a semi-classical argument because he doesn't acknowledge that one can have a real, but 'internal,' photon.

$$\frac{1}{2}\sum_{i,j}\int j_i^{\mu}(x)\left(\bar{D}(x-y)-\frac{i}{2}D_1(x-y)\right)j_{\mu,j}(y)\ d^4x\ d^4y \tag{20}$$

As Davies notes, the first term (real part) gives us the basic time-symmetric interaction corresponding to off-shell (virtual) photons, while the second term (imaginary part) corresponds to on-shell, real photons. The second term can be written in terms of (9) as:

$$\frac{1}{4}\sum_{i,j}\int j_i^{\mu}(x)\left(D^+(x-y)-D^-(x-y)\right)j_{\mu,j}(y)\ d^4x\ d^4y\,, \tag{21}$$

which using property (18) becomes

$$\frac{1}{4}\sum_{i,j}\int j_i^{\mu}(x)\left(D^+(x-y)+D^+(y-x)\right)j_{\mu,j}(y)\ d^4x\ d^4y\,. \tag{22}$$

Because of the double summation over *i, j*, the two terms are the same, so we are left with:

$$\frac{1}{2}\sum_{i,j}\int j_i^{\mu}(x)D^+(x-y)j_{\mu,j}(y)\ d^4x\ d^4y \tag{23}$$

In other words, for real photons, the Feynman propagator leads to absorption of positive frequencies only. (The opposite phase relationship between the fields generated by emitters and absorbers would lead to the Dyson propagator, with negative frequencies being absorbed.)

Now, the final step is to note that D^+ in the integrand of (24) factorizes into a sum over momenta, i.e.:

$$D^+(x-y)=i\langle 0|\hat{A}(x)\hat{A}(y)|0\rangle = i\sum_k \langle 0|\hat{A}(x)|k\rangle\langle k|\hat{A}(y)|0\rangle \tag{25}$$

Again, this represents a real photon, since the action of the creation and annihilation operators in *A* is to create and to annihilate a real, on-shell photon described by the Fock state $|k\rangle$. This is how quantization arises: not from a pre-existing system of oscillators, but from a specific kind of field interaction--i.e., the RPG. Note that the right-hand side of (25) describes a sum over products of conjugate transition amplitudes for states of different momenta; this is the origin of the Born Rule. (See Kastner and Cramer, 2018 for an explicit calculation taking into account the interaction with currents). The photon can only end up going to one absorber, not to the many different absorbers implied by the sum, so this is why and how the probabilities enter.

In light of (25), the quantum version of the 'light tight box' condition is simply the completeness condition: i.e., the fact that the factorization over quantum states of a transferred photon can only be carried out if the set of states is complete. Physically, this means that absorbers corresponding to each possible value of *k* must respond; or, more accurately at the relativistic level, that the emitter and absorbers must engage in a mutual interaction, above and beyond the off-shell time-symmetric field $\overline{D}$, to generate an on-shell field that can be factorized, corresponding to the quantum completeness condition.

There is a bit of a subtlety here in understanding what counts as a 'complete set' of momenta. Typically, one assumes a continuum of momentum values, but this is a mathematical idealization that does not apply to physically realistic situations, and in particular not to the QDAT. All that is required is that all momentum projectors $|k_i\rangle\langle k_i|$ for the fields exchanged between the emitter and absorbers *i={1,N}* sum to the identity. A particular k_j refers to a particular absorber *j* that engages with the emitter to jointly create one component of the on-shell field whose quantum state can be written as $|\Psi\rangle = \sum_i \langle k_i|\Psi\rangle|k_i\rangle$. Thus, these states $|k_i\rangle$ have finite spread corresponding to the effective cross-section of each absorber and the uncertainty in the relevant energy levels.

Even though all *N* absorbers contribute to create the on-shell field, as noted above, the real photon can ultimately be received by only one absorber, and this corresponds to non-unitary state reduction to the value k_j for the received photon, with the probability $|\langle k_j|\Psi\rangle|^2$. Thus, besides the elimination of the independent system of field oscillators represented by the quantized field $\hat{A}$, the entire content of the quantum LTB is just the quantum completeness condition and the phase relationship that selects the Feynman rather than Dyson propagator. [7]

4. Non-unitarity

The S-matrix is unitary if all interacting currents are included in the sum (13) such that all state transitions involving those currents start from the photon vacuum state and return to the photon vacuum state. In this case, the total 'free field' vanishes because of the QDAT condition disallowing truly unsourced photon states (15). However, for a subset of interacting currents, the S-matrix contains a non-unitary component: that of the 'free field' D_1. While Davies (1972) found this feature 'puzzling,' the present author has noted that this

[7] The two choices of phasing of absorber response reflect the fact that the theory has two semi-groups. These are actually empirically indistinguishable. For the Feynman propagator, bound states are built on positive energies; for the Dyson propagator, bound states are built on negative energies. Thus, any observer would see an arrow of time/energy pointing to what they would consider 'the future,' and what constitutes 'positive' or 'negative' energy is only a convention based on the structure of the bound states. Here we differ with Davies (1972, pp. 1022-4), who suggests that the two choices are not the time-inverse of one another. That conclusion follows only if one retains the positive-energy structure of bound states while employing the Dyson propagator. But arguably, that is not appropriate.

element of non-unitarity provides a natural account of the measurement transition (Kastner 2015), Kastner and Cramer (2018).

The non-unitary property of the S-matrix in a vacuum-to-vacuum transition for a subset of all interacting currents is also discussed by Breuer and Petruccioni (2000), pp. 40-41. In a study of decoherence, these authors take note of the fact that the Feynman propagator is complex and contains an imaginary component of the action based on the effective 'free field' D_1. For a single current, the vacuum-to-vacuum scattering amplitude $S(D_1)$ corresponding to this component is:

$$S(D_1) = \exp\left(-\mathrm{Im}(D_F)\right) = \exp\left(-\frac{1}{4}\int j^{\mu}(x) D_1(x-y) j_{\mu}(y)\, d^4x\, d^4y\right) \qquad (26)$$

The integral in the exponential is real and positive, and can be interpreted as (half) the average number of photons $\bar{n}$ emitted by the current (and absorbed by another current). We can use this to find the probability that no photon is emitted by the current, since the vacuum-to-vacuum probability associated with that component is

$$\left|S(D_1)\right|^2 = \mathrm{e}^{-\bar{n}} < 1 \qquad (27)$$

Note that this is an explicit violation of unitarity at the level of the S-matrix for a single current (i.e., when final absorption of the emitted photon(s) by other current(s) is not taken into account). Based on this result, Breuer and Petruccioni note that it is the D_1 component that leads to decoherence. The present author discusses the crucial dependence of decoherence on non-unitarity in Kastner (2019).

Davies further notes that the complement of (27) is the probability of photon emission by the current:

$$1 - \left|S(D_1)\right|^2 = 1 - \mathrm{e}^{-\bar{n}} = \sum_{m=1}^{\infty} \mathrm{e}^{-\bar{n}} \frac{\bar{n}^m}{m!}, \qquad (28)$$

where each term in the sum is the probability of emission of m photon(s), the Poisson distribution applicable to the well-known infrared divergence.

5. Conclusion

The so-called 'light tight box' (LTB) condition applying to the direct-action or 'absorber' theory of fields has been critically revisited. The condition at the classical level, (4), can be interpreted to mean that there is no truly unsourced radiation field, rather than the usual interpretation that 'all emitted radiation is absorbed,' since the condition actually says nothing about absorption, but says only that the net free field is zero. At the quantum level (QDAT), the condition is represented by (17), which simply says that there exist no true 'external' photon states. A theorem showing the equivalence between the standard quantized field theory and the QDAT reveals that the condition is simply the vanishing of the quantized field $\hat{A}_\mu$. Instead, in the QDAT, interactions are mediated by a non-quantized electromagnetic potential that directly connects charged currents through the time-symmetric propagator.

In order to understand the conditions for real photon generation in the QDAT, it must be understood that a real photon does not need to have an infinite lifetime as traditionally assumed, but in fact has a finite energy uncertainty ΔE corresponding to the 'line width' or uncertainty of an energy level from which it is emitted. Under a form of the quantum completeness condition, and governed by the fine-structure constant and relevant transition probabilities, an effective 'free field' propagator corresponding to the even homogeneous solution, D_1, can arise. This is the quantum analog of 'absorber response,' which at the relativistic level is a mutual non-unitary interaction between emitter and absorber(s) that gives rise to one or more real, on-shell photons, even though such photons are technically 'internal' (i.e. both emitted and absorbed). The presence of D_1 converts the time-symmetric propagator into the usual Feynman propagator (eqn. 11). No 'light tight box,' i.e., no particular configuration of absorbers, is required for these processes to occur, so that no particular cosmological conditions need obtain in order for the QDAT to be fully applicable.

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