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Communication

Electron as a Tiny Mirror: Radiation from a Worldline with Asymptotic Inertia

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Abstract: We present a moving mirror analog of the electron, whose worldline possesses asymptotic constant velocity with corresponding Bogoliubov β coefficients that are consistent with finite total emitted energy. Furthermore, the quantum analog model is in agreement with the total energy obtained by integrating the classical Larmor power.

Keywords: acceleration radiation; moving mirrors; radiation by moving charges; quantum aspects of black holes; Davies-Fulling-Unruh effect

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1. Introduction: Fixed Radiation

Uniform acceleration, while attractive and simple enough is not globally physical. Consider the problem of infinite radiation energy from an eternal uniformly accelerated charge. The physics of eternal unlimited motions is not only the cause of misunderstandings, but also the starting point of incorrect physical interpretations, especially when considering global calculable quantities, such as the total radiation emitted of a moving charge. Infinite radiation energy afflicts the accurate scrutiny of physical connections between acceleration, temperature, and particle creation.

More collective consideration should be prescribed to straighten out the issue. One path forward is the use of limited non-uniform accelerated trajectories that are capable of rendering finite global total radiation energy. The trade-off with these trajectories is usually the lack of simplicity or tractability in determining the radiation spectrum in the first place.

In this short paper, we present a solution for finite radiation energy and its corresponding spectrum. Limited solutions of this type are rare and can be employed to investigate the physics associated with contexts where a globally continuous equation of motion is desired. For instance, the solution is suited for applications such as the harvesting of entropy from a globally defined trajectory of an Unruh-DeWitt detector, the non-equilibrium thermodynamics of the non-uniform Davies-Fulling-Unruh effect, or the dynamical Casimir effect [1], and the particle production of the moving mirror model [2–4].

Providing a straightforward conceptual and quantitative analog application to understanding the radiation emitted by an electron, we demonstrate the existence of a correspondence (see similar correspondences in Refs. [5–11]) between the electron and the moving mirror. At the very least, this functional coincidence is general enough to be applied to any tractably integrable rectilinear classical trajectory that emits finite radiation energy. Here, we analytically compute the relevant integrable quantities for the specific solution and demonstrate full consistency. The analog approach treats the electron as a tiny moving mirror, somewhat similar to the Schwarzschild [12], Reissner–Nordström [13], and Kerr [14] black mirror analogies, but with the asymptotic inertia of a limited acceleration trajectory. Interestingly, the analog reveals previously unknown electron acceleration radiation spectra, thus helping to develop general but precise links between acceleration, gravity, and thermodynamics.

2. Elements of Electrodynamics: Energy From Moving Electrons

In electrodynamics [15–17], the relativistically covariant Larmor formula (the speed of light, c, the electron charge, q_e, and vacuum permittivity, ϵ_0, are set to unity),

$$P = \frac{\alpha^2}{6\pi}, \tag{1}$$

is used to calculate the total power radiated by an accelerating point charge [15]. The Larmor formula's usefulness is due in part to Lorentz invariance and proper acceleration, α, is intuitive, being what an accelerometer measures in the accelerometer's own instantaneous rest frame [18].

When any charged particle accelerates, energy is radiated in the form of electromagnetic waves, and the total energy of these waves is found by integrating over coordinate time. That is, the time-integral,

$$E = \int_{-\infty}^{\infty} P \,\mathrm{d}t, \tag{2}$$

demonstrates that the Larmor power Equation (1) immediately tells an observer the total energy emitted by a point charge along the point's entire time-like worldline. This includes trajectories that lack horizons; see, e.g., [19]. This result is finite only when the proper acceleration is asymptotically zero, i.e., the worldline must be asymptotically inertial.

The force of radiation resistance, whose magnitude is given relativistically as the proper time, τ, derivative (notified by the prime) of the proper acceleration,

$$F = \frac{\alpha'(\tau)}{6\pi}, \tag{3}$$

is known as the magnitude of the Lorentz–Abraham–Dirac (LAD) force, see, e.g., [20]. The power, $F \cdot v$, associated with this force can be called the Feynman power [21]; here v denotes the speed of the point. The total energy emitted is also consistent with the Feynman power, where one checks:

$$E = -\int_{-\infty}^{\infty} F \cdot v \,\mathrm{d}t. \tag{4}$$

The negative sign demonstrates that the total work against the LAD force represents the total energy loss. That is, the total energy loss from radiation resistance due to Feynman power must equal the total energy radiated by the Larmor power Equation (1). Larmor and Feynman powers are not the same, but the magnitude of the total energy from both are identical, at least for rectilinear trajectories that are asymptotically inertial.

Interestingly, the above results also hold in a quantum analog model of a moving mirror. A central novelty of this paper is to explicitly connect the quantum moving mirror radiation spectra with classical moving point charge radiation spectra. Traditionally (e.g., [2–4,22–24]) and recently (e.g., [25–27]), moving mirror models in $(1+1)$ dimensions are employed to study the properties of Hawking radiation for black holes. Here, we show that it is also useful to model the spectral finite energy of electron radiation. In particular, a suitably constructed mirror trajectory (which is quite natural) can produce the same total energy consistent with Equation (4) via the Bogoliubov energy, see e.g., [22]

$$E = \int_0^{\infty}\int_0^{\infty} \omega |\beta_{\omega\omega'}|^2 \,\mathrm{d}\omega\,\mathrm{d}\omega'. \tag{5}$$

Here, β are the Bogoliubov β coefficients and ω' and ω are the two sets of incoming and outgoing mode frequencies, respectively.

The final drifting speed, s, of the mirror or electron will be less than the speed of light: $0 < s < 1$. We also denote $a := \omega(1+s) + \omega'(1-s)$, $b := \omega(1-s) + \omega'(1+s)$, $c := a+b$, and $d := a-b$; note that then $c = 2(\omega + \omega')$.

3. GO Trajectory for Finite Energy Emission

We consider a globally defined, continuous worldline, which is rectilinear, time-like, and possesses asymptotic zero velocity in the far past, while travelling to an asymptotically constant velocity in the far future (but asymptotically inertial both to the past and the future). It radiates a finite amount of positive energy and has beta Bogoliubov coefficients that are analytically tractable. The Good-Ong (GO) trajectory, as defined by the authors [28], proceeds as follows:

$$z(t) = \frac{s}{2\kappa}\ln(e^{2\kappa t}+1), \tag{6}$$

where κ is an acceleration parameter. The GO trajectory's total power, applying the Larmor formula Equation (1), is

$$P = \frac{2\kappa^2}{3\pi}\frac{s^2 e^{-4\kappa t}\left(1+e^{-2\kappa t}\right)^2}{\left[\left(1+e^{-2\kappa t}\right)^2 - s^2\right]^3}. \tag{7}$$

Let us note that the power is always positive and it asymptotically drops to zero, as Figure 1 illustrates.

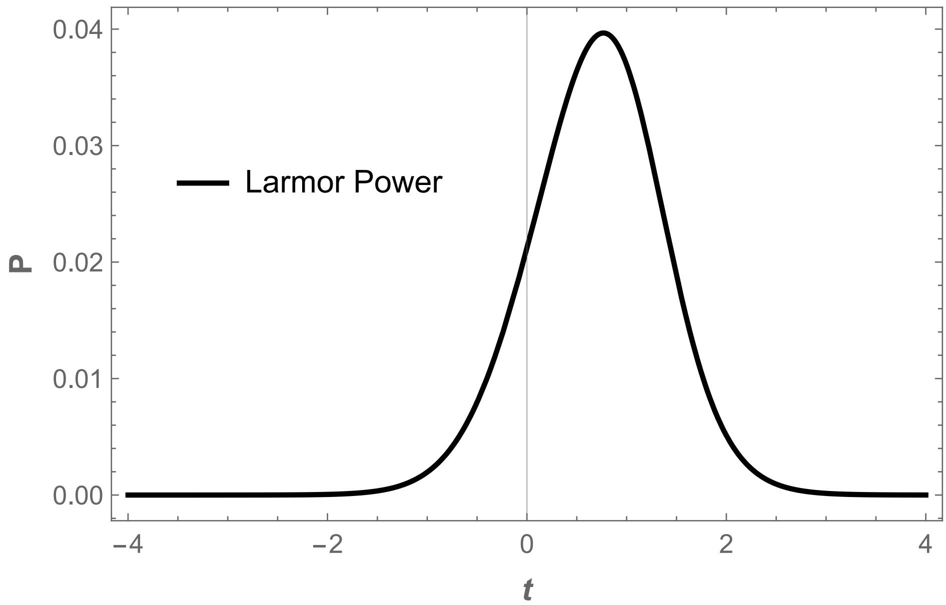

Figure 1. The Larmor power Equation (1) of the Good-Ong (GO) trajectory Equation (6) as a function of time, t, and at final constant speed, $s = 0.9$, i.e., Equation (7), with acceleration parameter, $\kappa = 1$. This plot illustrates that the Larmor power never emits negative energy flux (NEF) and asymptotically dies off, consistent with a physically finite amount of total radiation energy, Equation (2).

The Feynman power, $F \cdot v$, associated with the self-force Equation (3), is

$$F \cdot v = \frac{2\kappa^2 s^2 e^{4\kappa t}\left(j_1 e^{6\kappa t} + j_2 e^{4\kappa t} + e^{2\kappa t} + 1\right)}{3\pi\left(-j_1 e^{4\kappa t} + 2e^{2\kappa t} + 1\right)^3} \tag{8}$$

where $j_1 = s^2 - 1$ and $j_2 = 2s^2 - 1$. Similar to the Larmor power Equation (7), the Feynman power Equation (8) asymptotically dies off, but unlike the Larmor power, the Feynman power has a period of negative radiation reaction; as illustrated in Figure 2.

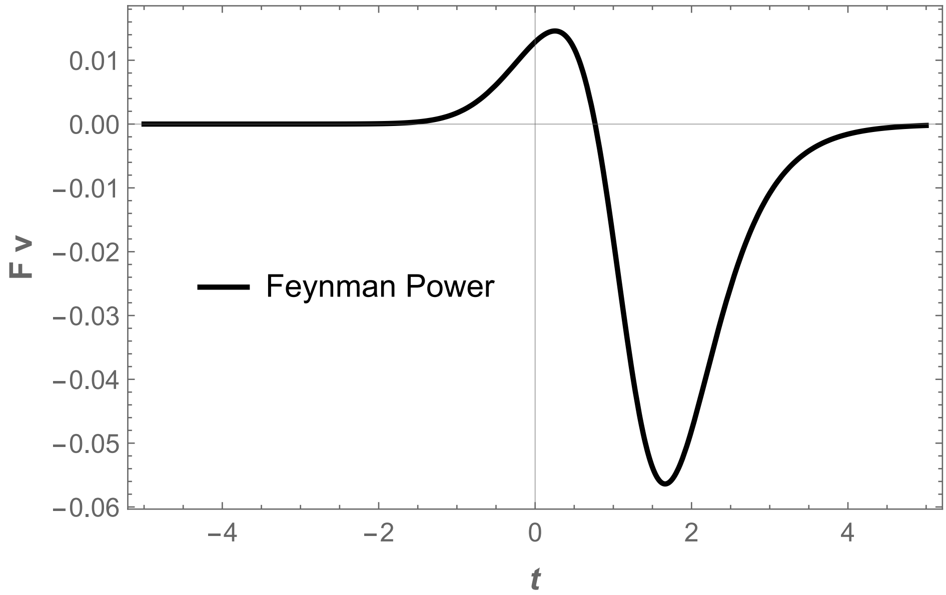

Figure 2. The Feynman power, $F \cdot v$, associated with the self-force, F, Equation (3), of the GO trajectory Equation (6), as a function of time and at final constant speed, $s = 0.9$, i.e., Equation (8), with $\kappa = 1$. This plot illustrates the Feynman power dies off asymptotically, has a period of negative radiation reaction, and is also consistent with a physically finite amount of total radiation energy, Equation (4).

Let us now compute the total energy using either the Larmor power or Feynman power, and integrating over time. In terms of the rapidity, $\eta = \tanh^{-1} v$, and Lorentz factor, γ, the total energy is given by

$$E = \frac{\kappa}{24\pi}\left[\left(\gamma^2 - 1\right) + \left(\frac{\eta}{s} - 1\right)\right]. \tag{9}$$

The second term, $(\frac{\eta}{s} - 1) = \frac{1}{2s}\ln\frac{1+s}{1-s} - 1$, is proportional to the lowest-order soft energy of inner bremsstrahlung in the case of beta decay (see Equation (3) in Ref. [11]), which is the deep infra-red contribution. One can see that Equation (9) is finite for all $0 < s < 1$ and consistent with both the Larmor power and Feynman power. Below, after we compute the Bogoliubov β-spectrum (and plot it in Figure 3), we compute the Bogoliubov total energy (and plot it in Figure 4). We call Equation (9) the Larmor energy to differentiate it from the Bogoliubov energy Equation (5), while substituting Equation (13) below. The energy is a function of the final constant speed, s.

Finally, the spectrum given by the Bogoliubov coefficients is best found by first considering the presence of a mirror in vacuum, e.g., [29,30]. The mode functions that correspond to the in-vacuum state,

$$\phi^{\text{in}}_{\omega'} = \frac{1}{\sqrt{4\pi\omega'}}\left[e^{-i\omega' v} - e^{-i\omega' p(u)}\right], \tag{10}$$

and mode functions that correspond to the out-vacuum state,

$$\phi^{\text{out}}_{\omega} = \frac{1}{\sqrt{4\pi\omega}}\left[e^{-i\omega f(v)} - e^{-i\omega u}\right], \tag{11}$$

comprise the two sets of incoming and outgoing modes needed for the Bogoliubov coefficients. The $f(v)$ and $p(u)$ functions express the trajectory Equation (6), of the mirror, but in null coordinates, $u = t - z$ and $v = t + z$. In spacetime coordinates congruent with Equation (6), one form of the β-integral [19] for one side of the mirror is

$$\beta_{\omega\omega'} = \int_{-\infty}^{\infty} \mathrm{d}z \frac{e^{i\omega_n z - i\omega_p t(z)}}{4\pi\sqrt{\omega\omega'}}\left[\omega_p - \omega_n t'(z)\right], \tag{12}$$

where $\omega_p = \omega + \omega'$ and $\omega_n = \omega - \omega'$. Combining the results for each side of the mirror [31] by adding the squares of the Bogoliubov β coefficients ensures that one accounts for all of the radiation emitted by the mirror [32]. The overall count per double-mode is

$$|\beta_{\omega\omega'}|^2 = \frac{s^2\omega\omega' Z}{2\pi abcd\kappa}\left(\frac{e^{\frac{\pi d}{4\kappa}}-1}{e^{\frac{\pi c}{4\kappa}}-1}\right)e^{\frac{\pi b}{4\kappa}}, \tag{13}$$

where $Z = b\,\mathrm{csch}\left(\frac{\pi a}{4\kappa}\right) + a\,\mathrm{csch}\left(\frac{\pi b}{4\kappa}\right)$. Equation (13) combines the squares, $|\beta_R|^2 + |\beta_L|^2$, of the coefficients for left (L) and right (R) sides of mirror [28]. Figure 3 shows a plot of the symmetry between the modes ω and ω'.

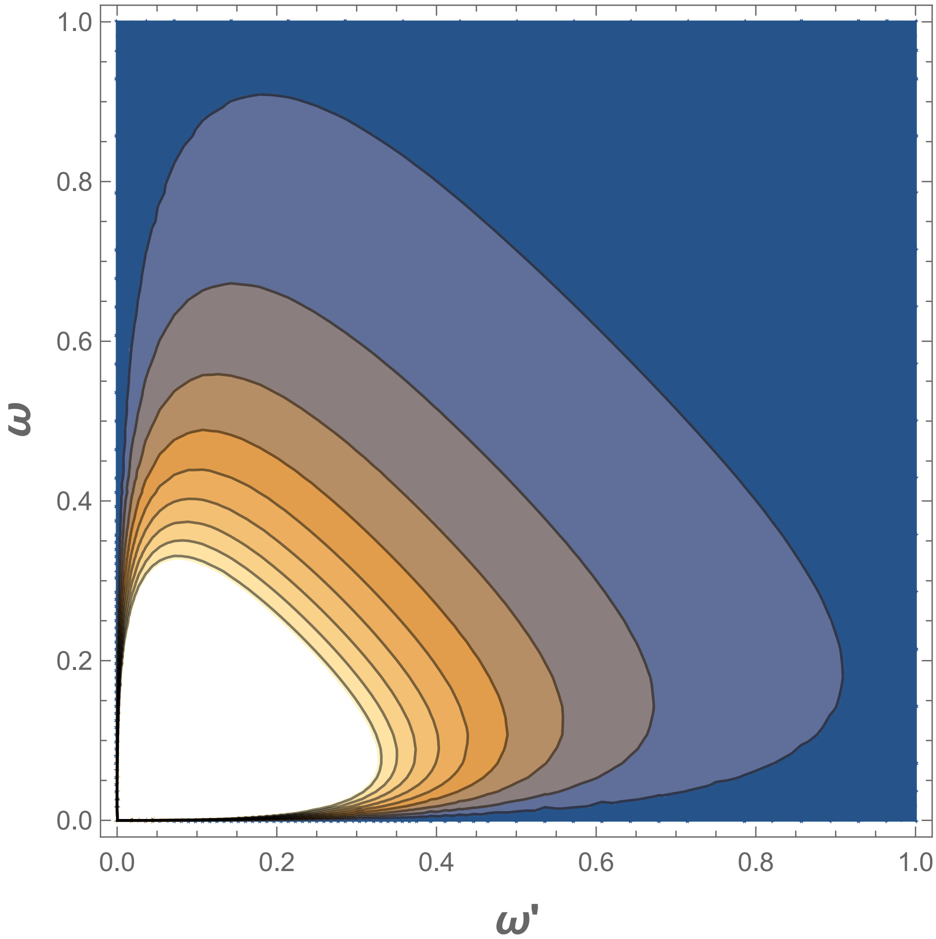

Figure 3. A contour plot of the coefficients, Equation (13) as a function of in and out modes, ω' and ω, where final constant speed, $s = 0.444$ and $\kappa = 1$. The color gradient darkens for lower values of the count. This plot underscores the symmetry of the modes in the particle per mode squared distribution spectrum of the Bogoliubov β coefficients, Equation (13).

It is then straightforward to verify that the total energy obtained by integrating the power is the same as by using the Bogoliubov β integral Equation (5). We cannot prove this analytically, but a numerical integral is quite convincing; see Figure 4 for a plot of the Larmor and Bogoliubov energies as a function of final constant speed.

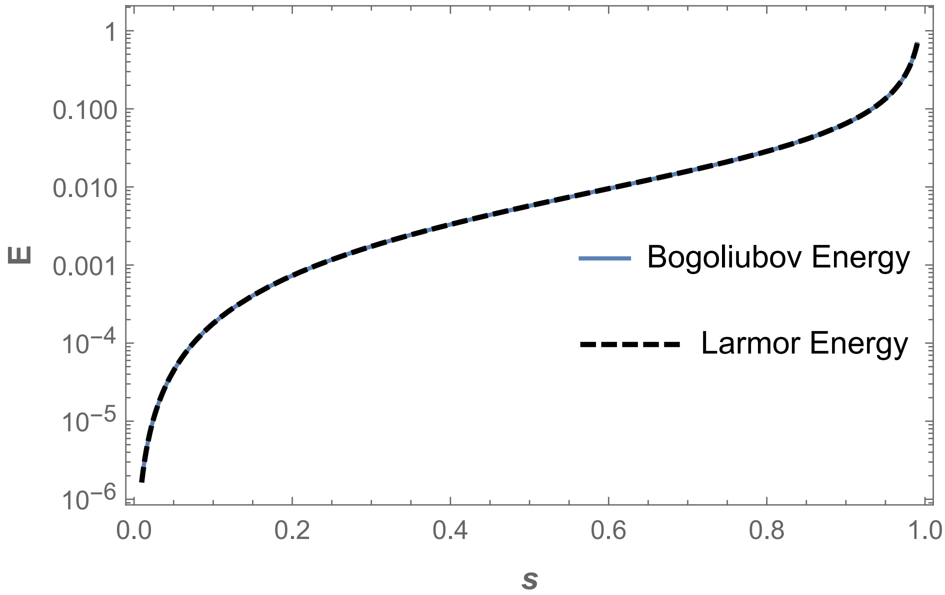

Figure 4. The Larmor energy Equation (9) and Bogoliubov energy Equation (5) as a function of final constant speed, s. Here, $0 < s < 0.99$ and $\kappa = 1$. This plot confirms that Larmor and Bogoliubov energies are equivalent, substantiating the double-sided moving mirror as an analog model of the electron.

4. Discussions: Mirrors, Electrons, and Black Holes

Prior studies of accelerated electrons and their relationship to mirrors are few; however, several papers, e.g., [33,34], connect electrons to the general Davies-Fulling-Unruh effect (for example, perhaps the most known one is by Bell and Leinaas [35], which considered the possibility of using accelerated electrons as thermometers to demonstrate the relationship between acceleration and temperature). Nevertheless, perhaps an early clue a that functional identity existed was made in 1982 by Ford and Vilenkin [24], who found that the LAD self-force was the same form for both mirrors and electrons. In 1995, Nikishov and Ritus [5] asserted the spectral symmetry and found that the LAD radiation reaction has a term that corresponds to the negative energy flux (NEF) from moving mirrors. Ritus examined [6–8] the correspondence connecting the radiation from both the electron and mirror systems, claiming not only a deep symmetry between the two, but a fundamental identity related to bare charge quantization [10]. Recently, the duality was extended to Larmor power [32] and deep infrared radiation [11]. The approach has pedagogical application; for instance, it was used to demonstrate the physical difference between radiation power loss and kinetic power loss [9].

The GO moving mirror was initially constructed to model the evaporation of black holes that exhibit a "death gasp" [36–38]—an emission of NEF due to unitarity being preserved. Therefore, it is a sturdy result that the total finite energy emitted from the double-sided mirror matches the result from the Larmor formula for an electron. In this sense, the GO mirror trajectory represents a crude but functional analog of a drifting electron that starts at zero velocity and speeds away to some constant velocity. A single-sided moving mirror does not account for all of the radiation emitted by an electron, and as such, the single-sided mirror radiation spectrum differs from the electron spectrum. A notable difference: there is no known NEF radiated from an electron.

In the literature, one finds some properties that are shared by black holes and electrons. For example, the ratio of the magnetic moment of an electron (of mass m and charge e) to its spin angular momentum is $ge/2m$ with $g = 2$, which is twice the value of the gyromagnetic ratio for classical rotating charged bodies ($g = 1$). Curiously, as Carter has shown [39], a Kerr–Newmann black hole also has $g = 2$. This has led to some speculations as to whether the electron is a Kerr–Newman singularity (the angular momentum and charge of the electron are too large for a black hole of the electron's mass, so there is no horizon) [40] (see also [41,42]). The no-hair property of black holes is also similar to elementary particle indistinguishably: all electrons look the same. Certainly, the mirror model considered here looks too simple to seek certain further connections between particle physics and black holes; in particular, it does not involve any charge or angular momentum. Nevertheless, precisely because of this, it is surprising the total emitted energy in the model should be given by the integral of the Larmor formula.

Near-term possible theoretical applications of electron-mirror correspondence include extension to non-rectilinear trajectories; notably, the uniform accelerated worldlines of Letaw [43], which have Unruh-like temperatures [44] and power distributions [45]. Applying the general study of Kothawala and Padmanabhan [46] to electrons moving along time-dependent accelerations, and comparing the effect to an Unruh-DeWitt detector may prove to be fruitful for understanding the thermal response. Moreover, moving mirror models can be useful in cosmology [47], in particular, in modeling particle production due to the expansion of space [48]. This expansion is accelerated due to an unknown dark energy, which may not be a cosmological constant and thus can decay [49,50]. If dark energy is some kind of vacuum energy, it might be subject to further study from mirror analogs just like Casimir energy. (Actually, dark energy could be Casimir-like [51]).

Near-term possible experimental applications of electron-mirror holography include leveraging the correspondence to disentangle effects in experiments like in the Analog Black Hole Evaporation via Lasers (AnaBHEL) [52] and the RDK II [53,54] experiments (see also [55]). The former exploits the accelerating relativistic moving mirror as a probe of the spectrum of quantum vacuum radiation [56,57], and the latter measures the photon spectrum with high precision as the electron-mirror is subjected to extreme accelerations during the process of radiative neutron beta decay.

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