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Vacuum lightcone fluctuations in a dielectric

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HIGHLIGHTS

- Lightcone fluctuations, quantum fluctuations of the effective speed of light, are a feature of quantum gravity.
- Nonlinear dielectrics have a variable speed of light, analogous to the effects of gravity.
- Fluctuating electric fields create the effect of lightcone fluctuations in a nonlinear material.
- In our model, switched vacuum fluctuations sampled in a finite time are the source of the fluctuating field.
- The geometry of the dielectric material defines the switching of the vacuum fluctuations.

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ABSTRACT

A model for observable effects of time modulated electromagnetic vacuum fluctuations is presented. The model involves a probe pulse which traverses a slab of nonlinear optical material with a nonzero second order polarizability. We argue that the pulse interacts with the ambient vacuum fluctuations of other modes of the quantized electric field, and these vacuum fluctuations cause variations in the flight time of the pulse through the material. The geometry of the slab of material defines a sampling function for the quantized electric field, which in turn determines that vacuum modes whose wavelengths are of the order of the thickness of the slab give the dominant contribution. Some numerical estimates are made, which indicate that fractional fluctuations in flight time of the order of 10^{-8} are possible in realistic situations. The model presented here is both an illustration of a physical effect of vacuum fluctuations occurring in a finite interval of time, and an analog model for the lightcone fluctuations predicted by quantum gravity.

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1. Introduction

Vacuum fluctuations of the electromagnetic field are responsible for several observed phenomena, including the Lamb shift and the Casimir effect. However, these effects are typically energy level shifts in stationary systems, not events which can be localized in time. The dynamical Casimir effect, which has been observed in superconducting circuits [1], does involve time dependence. However, it is not really a vacuum fluctuation effect in the sense of the static Casimir effect. Rather, the dynamical Casimir effect is quantum creation of particles by a time dependent background, and is essentially the same effect as particle creation in an expanding universe [2], or quantum radiation by moving mirrors [3–5].

There is still debate about the reality of vacuum fluctuations as temporal events [6,7]. Here we explore the viewpoint that vacuum fluctuations can be just as real as thermal fluctuations, but are often not noticed because of strong anticorrelations. The anticorrelations prevent an electric charge from undergoing observable Brownian motion in the vacuum state. The charge can temporarily acquire energy from a vacuum electric field fluctuation, but this energy will be taken away by an anticorrelated fluctuation on a time scale consistent with the energy–time uncertainty principle. This viewpoint is supported by calculations in models where the cancellation is upset by a time dependent background [8–11]. We will here construct a model without an explicit external time dependent background, but where vacuum electric field fluctuations on a finite time scale have a clear, and potentially observable, physical effect.

Let E be a Cartesian component of the quantized electric field operator. Vacuum expectation values of even powers of E are divergent due to the contribution of high frequency modes. This divergence may be removed by replacing E by its time average with a suitable sampling function, or test function, $f_\tau(t)$, where τ is the characteristic width of the function. Let

$$\bar{E} = \int_{-\infty}^{\infty} E(t)\, f_\tau(t)\, dt. \tag{1}$$

Here $E(t)$ is the field operator at any fixed space point, and

$$\int_{-\infty}^{\infty} f_\tau(t)\, dt = 1. \tag{2}$$

The moments of $\bar{E}$ are finite and those of a Gaussian distribution, determined by the second moment

$$\langle 0|\bar{E}^2|0\rangle = \frac{a}{\tau^4}, \tag{3}$$

where the numerical constant a depends upon the choice of sampling function. (Lorentz–Heaviside units with $c = \hbar = 1$ will be used here, except as otherwise noted. In these units, electric field has dimensions of inverse time squared or inverse length squared.) For the case of a Lorentzian function,

$$f_\tau(t) = \frac{\tau}{\pi(t^2 + \tau^2)}, \tag{4}$$

we have $a = 1/(16\pi^2)$. Modes whose period is of order τ give the dominant contribution here, with the contribution of shorter wavelength suppressed by the time averaging. This may be seen by noting that the time averaging replaces the sinusoidal time dependence, $\exp(-i\omega t)$, of a mode function with the Fourier transform of the sampling function, which is $\exp(-\omega\tau)$ in the case of the Lorentzian function. In rigorous treatments of quantum field theory, test functions, usually with compact support, are used to define well-behaved operators. See, for example, Ref. [12]. However, this use of test functions is purely formal, and no physical interpretation is made. One of the purposes of this paper will be to provide an example where the function $f_\tau(t)$ has a clear meaning defined by the physical system of interest. A different physical example was recently given in Ref. [13], which discussed the role of switched electric field fluctuations upon barrier penetration by an electron.

Our model will involve light propagation in a nonlinear material. Related models were presented in Ref. [14], as an analog model for semiclassical gravity, and in Ref. [15], as a model for the lightcone