Can quantum vacuum fluctuations be considered real?

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Abstract

The main argument against the assumption that quantum fluctuations of the electromagnetic field are real is that they do not activate photon detectors. In order to met this objection I study several models of photon counter compatible with the reality of the fluctuations. The models predict a nonlinear dependence of the counting rate with the light intensity and the existence of a nonthermal dark rate, results which might explain the difficulty for performing loophole-free optical tests of Bell’s inequality.

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I. The vacuum fluctuations of the electromagnetic field

The existence of vacuum fluctuations is a straightforward consequence of field quantization. In addition, quantum vacuum fluctuations have consequences which have been tested empirically. For instance, the vacuum fluctuations of the electromagnetic field (or zeropoint field, ZPF) give rise to the main part of the Lamb shift and to the Casimir effect. The ZPF was proposed in 1912 by Planck, who wrote the radiation spectrum in the form

\[ \rho(\omega, T) = \frac{\omega^2}{\pi^2 c^3} \left[ \frac{\hbar \omega}{\exp(\hbar \omega/k_B T) - 1} + \frac{1}{2} \hbar \omega \right], \]  

(1)

where the second term represents the ZPF. That the thermal spectrum contains an \( \omega^3 \) term has been proved by experiments measuring current fluctuations in circuits with inductance at low temperature. Of course, the ZPF term is ultraviolet divergent so that some cutoff should be assumed, likely at about the Compton wavelength where the fluctuations of charged Fermi fields (the Dirac electron-positron sea) become important. We may conclude that the ZPF is well established by both, theoretical and empirical arguments.

A difficulty for understanding the nature of the ZPF is that we cannot interpret it naively as a real random electromagnetic field, a kind of universal noise. Indeed it seems to possess properties different from those to be expected for a classical noise. The two most obvious differences are that the ZPF apparently does not produce gravitational effects and that it does not activate photodetectors. With respect to the first problem, it has been speculated that the quantum vacuum fluctuations might be at the origin of the cosmological constant, whose nonzero value has been recently supported by astronomical observations. We shall not be concerned with gravitational effects in this paper but deal with the second problem, namely to explain why the ZPF does not activate photodetectors even in the absence of signals. A common solution to the problem is to say that the ZPF is not real, but virtual. But just replacing a word, real, by another one, virtual, with a less clear meaning is not a good solution. In the present article I shall attempt to show that the behaviour of photodetectors can be explained without renouncing to the reality of the ZPF.

If we compute the intensity of the ZPF, by integrating over frequencies the second term of eq. (1), we get an extremely large value. In fact the intensity is of the order of kilowatts per square centimeter, considering only
the visible part of the spectrum. The existence of such a high intensity is not the problem, because we might assume that photodetectors subtract that intensity so that they are sensitive only to the part which is above “the sea” of ZPF. Indeed, the standard quantum treatment of detection involves the use of normal ordering (of creation and annihilation photon operators), which may be seen as a formal procedure to subtract the ZPF. However that formal method cannot be interpreted as physical, because noise cannot be eliminated by just subtracting the mean. In order to get a physical interpretation of the subtraction, if we assume that the ZPF is real, there are two possible ways which might converge. The first method would be to refine the standard quantum treatment of detection, the second one is to propose specific detection models resting upon some plausible assumptions. The second method will be the main subject of the present paper, but I sketch the first method in the following paragraph.

The standard quantum theory of photodetection starts with an appropriate light-matter interaction hamiltonian. Hence the probability of photon absorption is derived using time-dependent perturbation theory and taking, at some stage, the limit of infinite time. Afterwards it is argued that microscopic times are so short that the resulting rule ”detection probability per unit time proportional to the light intensity” may be used whatever is the time dependence of the intensity. The procedure usually provides very good approximation, but it is obviously inconsistent. Indeed, if the probability per unit time is finite and the time goes to infinity, the total probability would surpass unity. The problem is that the use of infinite time intervals hides all the difficulties derived from the ZPF. In fact, it is trivial to get detection models able to subtract efficiently the fluctuations of the ZPF if the detection time is large enough, as we shall comment in the following section. But for actual quantum-optical experiments (e.g. tests of Bell’s inequality) the detection time is short, typically of the order of nanoseconds. I conjecture that a refined quantum theory of detection, which might require short enough detection times and the use of high order perturbation theory, would give a better understanding of the quantum vacuum fluctuations.

The point which I want to emphasize is that the difficulties for reaching an intuitive picture of how detectors subtract the ZPF probably do not derive from quantum theory itself, but from the use of idealizations like first-order perturbation theory or infinite detection time. I have conjectured elsewhere that excesive idealizations might be at the origin of the difficulties for un-
dersanding intuitively the paradoxical aspects of quantum physics. Indeed, although simplifications are extremely useful for calculations, they tend to obscure the physics. In the case of photon counting we might attempt to understand the removal of the ZPF by working a refined quantum theory of detection, but here I shall use the alternative route of studying detection models without explicit appeal to quantum theory. However I stress that these models do not necessarily contradict quantum theory.

II. Critical analysis of recent detection models

Several models of photodetection have been proposed recently resting upon the idea that there exists a "detection time", T, independent of the light intensity and such that the probability of a count depends on the radiation (including the zeropoint field, ZPF) which enters the detector during the time T. It proved necessary to "filter" the incoming field by means of some temporal and spatial Fourier transform in order to reduce the noise. A general feature of these models is that the "filtered" intensity of the ZPF has a gaussian distribution, whose dispersion I shall label σ. Finding a suitable filtering is the difficult problem in the construction of a model because it would not work if σ is not smaller than the typical light intensities to be detected. In the particular model of the quantity σ was rather sensitive to the assumed depth of the active zone of the photodetector, a fact which has been proved incompatible with experiments. However, there are experiments which refute, not only that particular model, but the whole family of models involving a fixed detection time T (see above) as we show in the following.

In the mentioned family of models we start calculating the probability distribution of the total radiation energy which enters the detector during the time T. (As the energy is proportional to the beam intensity, I shall not distinguish between energy and intensity in the present section.) In the most simple case, where the incoming beam consists of a signal with constant intensity, I_s, superimposed to the ZPF, the probability distribution is

$$\rho(I) = K \exp \left( \frac{(I - I_0 - I_s)^2}{2\sigma^2} \right), \quad (2)$$

K being a normalization constant and I_s the mean intensity of the ZPF.
In order that the model predictions do not depart too much from the quantum predictions, the detection probability should be roughly proportional to the intensity (except at high intensities where there should appear saturation effects). Then it is plausible to assume that the probability, \( Q \), of a count when the energy \( I \) has entered the detector during the "detection time" \( T \), is given by

\[
Q(I) = \xi (I - I_0) \Theta (I - I_0 - I_m),
\]

(3)

\( I_m (I_m > 0) \) being a threshold, \( \Theta () \) the Heavside step function and \( \xi \) a constant related to the detector efficiency. The first factor, if alone, would give the quantum rule "counting probability proportional to the intensity", but the second factor is necessary in order to ensure that \( Q \geq 0 \), as it should \( Q \) being a probability.

After that the counting rate as a function of the incoming deterministic part of the intensity, \( I_s \), is

\[
R(I_s) = \frac{1}{T} \int \rho(I) Q(I) dI.
\]

(4)

Whatever are the values of the parameters \( I_m \) and \( \sigma \) (the value of \( I_0 \) is irrelevant) the curve \( R(I_s) \) has the following features. At high intensity we have \( R \propto I_s \) in agreement with the quantum rule, but for \( I_s = 0 \) there is some unavoidable "dark rate". We may reduce the dark rate by increasing the threshold \( I_m \), but if \( I_m \) is high the departure of \( R(I_s) \) from linearity is big. This is because the curve lies well below the linear asymptote (tangent at infinite) whenever \( I_s \) is not substantially larger than \( \sigma \), that is

\[
R \ll \xi I_s \text{ for } I_s \lesssim \sigma, \text{ where } \xi = \lim_{I_s \to \infty} \left( \frac{R}{I_s} \right).
\]

(5)

When one goes from singles counts to (correlated) coincidence counts, it can be shown that the following inequality holds (\( R_1 \) labels singles rate and \( R_{12} \) coincidence rate)

\[
R_{12} < \left( 1 + \left( \frac{\sigma}{I_s} \right)^2 \right) T R_1^2.
\]

(6)

This implies that either \( T \) should be very large (i.e. \( T \gg R_{12}/R_1^2 \)) or the correlation in coincidence counts may be observed only when the intensity is
so low that the function $R_1(I_s)$ is nonlinear (i.e. $I_s \ll \sigma$, see eq.(3)). High 
correlation exists, for instance, when there is high visibility in the polarization 
correlation measured in order to test the Bell inequalities. This conclusion is 
not compatible with empirical evidence. In fact Fig.4 of the recent article by 
Kurtsiefer et al.\cite{9} shows an essentially linear counting rate, $R$, as a function 
of the intensity, $I_s$, along two orders of magnitude, and the paper reports a 
visibility of 98% for the highest intensity of this linear region. In order that 
these results are compatible with (3) we should have $T \gtrsim 1/R_1$, which is 
absurd.

We conclude that the whole class of models considered in the present 
section are incompatible with empirical evidence.

III. Detection models with varying detection time

Instead of fixing the detection time, $T$, we may assume that a count is 
produced when the radiation energy accumulated in the detector surpasses 
some threshold. This means that when the photocounter is ready to detect 
(this will happen some ”dead time” after a count is produced, but we will 
neglect the dead time here), the detector begins to accumulate the radiation 
energy entering in it. If $I_{\text{tot}}(t)$ is the total intensity entering the detector at 
time $t$, the accumulated energy at time $T$ will be

$$E(T) = A \int_0^T I_{\text{tot}}(t)dt,$$

where $A$ is the entrance area of the detector (in the following we shall put $A = 1$ for the sake of simplicity). Our assumption is that a new count will 
be produced when $E(T)$ surpasses some threshold $E_t$ (this threshold may 
depend on the value of $T$). According to our essential assumption that the 
ZPF has the same nature as the signal and it is indistinguishable from it, we 
may write the intensity in the form

$$I_{\text{tot}}(t) = I_0 + I(t),$$

where $I_0$ is the mean of the ZPF entering the detector. Taking eqs.(7) and 
(8) into account we define the threshold in the form

$$E_t = I_0T + E_m.$$
Thus our model assumption is: a detection event is produced at a time \( T \), after the previous count, when \( T \) is such that

\[
\int_0^T I(t)dt = E_m, \tag{10}
\]

where \( I(t) \) is the radiation intensity entering the detector, once the average intensity of the ZPF has been subtracted, and \( E_m \) is a parameter characteristic of the detector.

The use of eq.\((10)\) is cumbersome due to the fluctuations of the ZPF (and maybe also fluctuations of the signal). Indeed constructing a detailed detection model on the basis of that equation would require using the theory of ”first passage time” for the stochastic process \( I(t) \). In the following we shall solve, using rough approximations, the case of a deterministic signal with constant intensity \( I_s \). In this case \( I(t) \) is the sum of the ZPF part, \( I_{ZPF}(t) \), plus \( I_s \) and eq.\((10)\) may be written

\[
E_m = E_0(T) + I_s T \approx \Sigma \sqrt{T} + I_s T, E_0(T) \equiv \int_0^T I_{ZPF}(t)dt. \tag{11}
\]

There are two approximations in the second equality. The first one is to treat the stochastic process \( I_{ZPF}(t) \) as a Wiener (”white noise”) one. The approximation may be justified if the coherence time of the incoming radiation is much shorter than \( T \), which we shall assume here. The second approximation is to assume that the first time at which the stochastic process \( E_0(T) \) takes some fixed value, say \( E_1 \), is proportional to the time needed for the equality

\[
\langle E_0^2 \rangle = E_1^2
\]

to hold. These approximations give a first passage time proportional to \( \sqrt{T} \), which lead us to eq.\((11)\)giving a detection model which contains two parameters, \( E_m \) and \( \Sigma \), characteristic of the detector. From eq.\((11)\) it is easy to get \( T \), whence the counting rate becomes

\[
R = \frac{1}{T} = \frac{4I_s^2}{(\sqrt{\Sigma^2 + 4I_s E_m} - \Sigma)^2}. \tag{12}
\]

The interesting case is that of high intensity, which suggests an expansion in powers of the small parameter \( \Sigma/\sqrt{I_s E_m} \). We get

\[
R \approx \frac{I_s}{E_m} + \frac{\Sigma \sqrt{I_s}}{\sqrt{E_m}} + \frac{\Sigma^2}{2E_m^2}. \tag{13}
\]
From this result we see that there exists a counting rate even without signal, given by the last term, which we may considered as a part of the dark rate. The existence of a fundamental dark rate is an unavoidable consequence of the fluctuation of the ZPF. On the other hand the function \( R(I_s) \) is almost linear with a slowly decreasing slope. This behaviour fits qualitatively the results reported in the experiment (see Fig. 4 of the quoted paper).  

If our model is correct we are able to make some specific predictions which might be tested experimentally. For instance a fit of our curve eq. (13) to the empirical data gives our prediction for the dark rate to be 

\[
R_{\text{dark}} \gtrsim \frac{\sigma^2}{2E_m^2} \approx 30 \text{s}^{-1},
\]

for that experiment. We cannot make a comparison with the empirical dark rate because this is not given in the paper. Another straightforward prediction of our model is that the coincidence rate should decrease more quickly than the single rate when the intensity decreases. This is what happens in Fig. 4 of the mentioned paper. Indeed from the highest to the lowest intensity the slope of the singles count curve, \( R(I_s) \), decreases by about 25%, but the decrease in the slope of the coincidence curve is almost 40%. The explanation of this behaviour is that the "detection time" \( T \) increases as the signal intensity decreases (see eq. (11)). Now, the fluctuations of the energy accumulated during a time \( T \) are less relevant as the time \( T \) increases. On the other hand the correlation between two beams is just a correlation of the fluctuations (this is true at least for the correlated beams produced in the process of parametric down conversion, PDC, which was used in the commented experiment.) Consequently it is expected that the measured correlation is weaker as the correlated beams are less intense, although we are not able to give a quantitative prediction for the moment. More accurate predictions will be possible when a detailed detection model is made along the lines presented in this section, a work which is in progress.  

I finish this section stressing that our model goes beyond, although not necessarily against, quantum mechanics. In fact, the analysis of quantum-optical experiments is typically made starting from the quantum predictions for the ideal case. Afterwards these predictions are modified by introducing some empirical parameters like efficiencies of detectors, polarizers, etc., in order to fit actual laboratory situations. The nonidealities are attributed to technical imperfections of the set-up and are not analyzed further. Here I
have studied a part of the nonidealities, namely those relative to detectors. This is why I say that our model goes beyond standard quantum mechanics.

IV. Conclusion

Our analysis shows that quantum vacuum fluctuations of the electromagnetic field (or ZPF) are a possible source of nonidealities in the behaviour of optical photon counters. This is specially important when it is necessary to measure coincidence counting rates with short time windows, as is frequent in quantum optical experiments (e.g. optical tests of Bell’s inequality). In contrast they are probably irrelevant for measurements lasting for long times, as is usually the case in astronomical observations.

The main effect of the ZPF on photon counters is that the response to the incoming intensity becomes nonlinear, as is shown by our eq. (13). In particular the ZPF gives rise to a fundamental, nonthermal, dark rate and a decrease in the effective efficiency of the detector with increasing beam intensity. I may conjecture that the nonidealities will dramatically increase when the detection efficiency is high. In fact, if our eq. (13) is correct, at least as a rough approximation, then the increase in efficiency could be reached only by lowering the parameter $E_m$, which will lead to a big departure from the ideal behaviour. It must be taken into account that the parameter $\Sigma$, which essentially measures the intensity of the ZPF fluctuations, could not be reduced too much with the design of the photocounters.

Our results provide a possible explanation for the difficulties of performing loophole-free tests of Bell’s inequality using optical photons. As is well known all performed experiments suffer from the ”detection loophole” and I conjecture that the cause might be the existence of fundamental nonidealities in the behaviour of photon counters.

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