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ZERO-POINT ELECTROMAGNETIC FIELD AND NONLOCALITY

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Recently the problem of the experimental test of local quantum field theory, in particular, quantum electrodynamics (QED) at small distances has been of current interest because of introduction of the notion of the nonlocality, which can be characterized by some parameter ℓ of the dimension of length called the fundamental length (see refs.[1-3], for example). Very-high-precision measurements in the atomic physics, for example, the measurements of the anomaly of the muon (the electron) and the Lamb shift give the restrictions on the parameter $\ell \lesssim 10^{-15}$ cm ($\ell \lesssim 10^{-13}$ cm) and $\ell \lesssim 10^{-13}$ cm, respectively[2,4]. From high-energy experimental data it follows that $\ell \lesssim 10^{-16}$ cm[5].

It is well known that we detect at small distances with enormous price. Therefore, in order to detect at small distances in an optimal way, it is important to search for effective methods and new approaches to the construction of physical theory at small distances[6]. As a rule, the nonlocality in QED is introduced by modifications of quantities for lepton and photon proragators and vertex functions[7].

In this note we assume another approach to test the locality in physics, which is related with properties of vacuum fluctuations. The hypothesis of stochastic space[8] is reduced to the change $\rho(\omega) \to \rho_\ell(\omega)$ for the value of the spectum density of the zero-point electromagnetic field (ZPEMF) at small distances[9]. It appears that the change of the spectrum density of ZPEMF at small distances is very sensitive to the change of vertex functions and propagators of leptons and photons. We show this in the case of the Lamb shift for atomic Levels.

Random[10] or stochastic electrodynamics (SED)[11] (i.e., the theory of motion of charged particles in the presence of the electromagnetic vacuum) is constructed on the basic of the hypothesis about the existence of the zero-point random electromagnetic radiation field $\vec{E}$ with the spectrum density $\rho(\omega) = \hbar\omega^3/2\pi^2c^3$. The basic equation of SED is

$$m\ddot{\vec{r}} = m\tau\dddot{\vec{r}} + e\vec{E}, \qquad (1)$$

where $\tau = 2\alpha/3mc^3$, $\alpha = e^2/4\pi$. The fluctuation of the position of the electron due to the random electromagnetic field $\vec{E}$

makes the Lamb shift. Here, following Welton (see ref./12/), we give a qualitative description of the main effect. In this case only s-waves are affected and the n-th level is shifted by the amount

$$\Delta E(n) = \frac{(2mZ\alpha)^3}{12}\,\frac{\alpha}{n^3}\,\langle(\delta\vec{r})^2\rangle\,, \tag{2}$$

where $\delta\vec{r}$ satisfies equation (1). The Fourier component $\vec{E}_\omega$ with frequency ω of the ZPEMF contributes

$$m\,\delta\vec{r}_\omega = -\frac{e}{\omega^2}\,\frac{1}{1-i\,r\,\omega}\,\vec{E}_\omega$$

and assuming that there is no correlation between various modes

$$\langle(\delta\vec{r})^2\rangle = \frac{e^2}{m^2}\int_0^\infty \frac{d\omega}{\omega^4}\,\frac{1}{1+r^2\omega^2}\,\langle\vec{E}_\omega^{\,2}\rangle\,. \tag{3}$$

Here

$$\langle\vec{E}^2\rangle = \int d\omega\,\rho(\omega) = \int d\omega\,\langle\vec{E}_\omega^{\,2}\rangle.$$

Therefore

$$\langle(\delta\vec{r})^2\rangle = \frac{2\alpha}{\pi m^2}\int_0^\infty \frac{d\omega}{\omega(1+r^2\omega^2)}\,. \tag{4}$$

An infrared cutoff is usually chosen of the order $\omega_{min} \sim c/a$, $a \sim \langle\hbar/mc\rangle/\alpha$. As has been shown by N.Bogolubov and S.Tyablikov, vacuum fluctuations lead to some effective spreading (nonlocality) of the point-like electron and as a result, the value of the corresponding radius turns out to be a geometric mean of the electron classical radius and the Compton wavelength (see ref./14/, for example)

$$r_a = \langle\hbar/mc\rangle = \sqrt{\frac{e^2}{4\pi m c^2}\cdot\frac{\hbar}{mc}} = \sqrt{\alpha}\cdot\frac{\hbar}{mc}.$$

So we get

$$\Delta E(n,L) = \frac{4}{3}\,\frac{mZ^4\alpha^5}{\pi n^3}\,\frac{1}{2}\ln\left(\frac{1+r^2\omega_{min}^2}{r^2\omega_{min}^2}\right)\delta_{L0}\,. \tag{5}$$

For the level n=2 of the hydrogen atom the calculated shift $2S_{1/2} - 2P_{1/2}$ is

$$\Delta E = 1043\ \mathrm{MHz}$$

in agreement with the observed shift of 1057, 912±0 011 MHz. We recall that here relativistic effects are not taken into account. So, we believe that local SED as QED describes the Lamb shift at the present experimental level of accuracy.

Now we calculate the Lamb shift within the framework of a nonlocal SED[9] in which the density of energy is finite and acquires the following form

$$<\vec{E}^2> = \int_0^\infty d\omega <\vec{E}^2_\omega> = \frac{\hbar}{c^3} \int \frac{d\omega}{2\pi^2} \omega^3 f(\ell\omega),$$

where $f(\ell\omega)$ is some form factor, in particular, $f(\ell\omega) = 1 - \mathrm{erf}(\ell\omega)$, $\mathrm{erf}(x)$ is the error function. In this case the expression (5) is:

$$\Delta E(n,L) = \frac{4}{3} \frac{mZ^4\alpha^5}{\pi n^3} \{ \frac{1}{2} \ln \frac{1+r^2\omega^2_{min}}{r^2\omega^2_{min}} - \sqrt{\pi}\frac{\ell}{cr} + O(\frac{\ell^2}{c^2 r^2}) \} \delta_{LO}. \qquad (6)$$

In view of the above deduction it is natural to suppose that the nonlocal contributions calculated here should be of the order of or less than the experimental errors. It makes it possible to establish the following restrictions on the parameter ℓ : $\ell \lesssim 8 \cdot 10^{-18}$ cm. We see that by introduction of the nonlocality into the spectum of ZPEMF there can be gained three orders of the length with respect to low-energy tests of QED at small distances.

Thus, a treatment of experimental data on testing the locality, if possible, by means of the nonlocal vacuum fluctuations may be interesting and what is more, the present result[13] of the calculations of the zero-point (Casimir) energy of gluon and fermion fields in bag models shows that, in our opinion, it is necessary to reproduce these results within the framewort of the nonlocality of zero-point fields. In view of the physical idea it is not difficult to realize this program, the mathematical problem of which is not trivial.

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