Energy shift experiment in photonic crystal medium

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Abstract. We propose experimental confirmation of the new effect of the electron mass changes in photonic crystal medium, which was recently predicted. The method consists in measuring the Lamb shift in hydrogen atoms placed in the medium of photonic crystal. We discuss the experimental scheme based on the Lamb and Retherford experiment as well as the requirements for the samples of photonic crystals.

1. Introduction

Since the pioneering works of Yablonovitch [1] and John [2] photonic crystals (PCs) attract much attention of researchers. This materials have many potential technological applications ranging from high performance light-emitting diodes and optical fibers to low-power microlasers and optical microchips [3]. These applications are mainly based on the photonic band gap effect. However, band gap is not the only effect that follows from the periodic changing of the refractive index in the photonic crystal. It has been shown that the periodic change of the photon-matter interaction in PC medium gives rise to the fact that the mass of an electron in the PC must differs from its mass in vacuum [4–8]. Actually, this is a novel type QED effect. The origin of the effect under study is the fact that the interaction of a charged particle in the PC with its own radiation field differs from that in vacuum. The matter of fact is that the physical mass of the electron for example is the sum of the ”bare” mass and the electromagnetic mass being the electron rest energy arising from processes in which a photon is emitted and then reabsorbed by the electron. The effect should manifest itself in the modification of the spectra of atoms placed in PC medium. For today there are studies where the photoluminescence spectrum of the rare earth ions embedded in inverse opal was observed [9]. The authors detected shifts that was called the Lamb shifts. However, in [7] it was shown that this is not the case and the observed spectral features could be explained by the effect of the change of the mass of an electron. However some straightforward experimental proof of the effect is needed. For this purpose it is important to use the simplest hydrogen atoms, which are unique in their use for comparison between theory and experiment of bound-state energy level structures. We propose to measure the shifts of energy levels of the hydrogen atoms placed in photonic crystal medium. In this paper we discuss ideas for the experimental verification of the effect, based on the Lamb and Retherford experiment [10].
2. Influence of environment on the electromagnetic mass of an electron

It was shown in [4] that a new type of quantum-electrodynamical (QED) effect occurs in PCs when the electron rest mass changes. An explanation of this effect is contained in the concept of mass itself: the QED electron rest mass is the sum of its "bare" mass $m_0$ (the mass an electron might have if its interaction with the vacuum were negated) and the electromagnetic mass $m_{em}$, written as

$$ m_e = m_0 + m_{em}. \tag{1} $$

Electromagnetic mass $m_{em}$ is a result of an electron always interacting with the vacuum; it creates and then reabsorbs a photon, at which point electron-positron pairs and more complex combinations of virtual particles can arise. Such interaction never ceases.

The problem consists in the fact that the value of the electromagnetic mass of an electron in PC medium should differ from that in vacuum, and therefore the result of adding this electromagnetic mass to its "bare" mass will not be the physical mass. Obviously, the change of the value of the electron mass $\delta m_{pc}$ is the difference between the values of the electromagnetic masses in PC medium $m_{em}^{pc}$ and the electromagnetic mass $m_{em}$ in vacuum

$$ \delta m_{pc} = m_{em}^{pc} - m_{em}. \tag{2} $$

Thus, the influence of PC medium on the interaction of an electron with its own radiation field results in the change in its mass: $m_e \rightarrow m_{pc} = m_e + \delta m_{pc}$. Here we assume that the electron is in an air void of the PC.

The PC medium correction $\delta m_{pc}$ to the electron rest mass is given by the equation (in the unit system where $\hbar = c = \varepsilon_0 = 1$) [4]

$$ \delta m_{pc} = \frac{\alpha}{\mathbf{p}^2 \pi^2} \left[ \sum_n \int_{FBZ} d^3k \sum G |\mathbf{p} \cdot \mathbf{E}_{kn}(\mathbf{G})|^2 - \int \frac{d^3k}{2k^2} \sum_{\lambda=1}^2 |\mathbf{p} \cdot \varepsilon_{\lambda}(\mathbf{k})|^2 \right] \tag{3} $$

with $\mathbf{E}_{kn}(\mathbf{G})$ being the coefficients in the plane-wave expansion $\mathbf{E}_{kn}(\mathbf{r}) = \sum_{\mathbf{G}} \mathbf{E}_{kn}(\mathbf{G}) e^{i(\mathbf{k}+\mathbf{G}) \cdot \mathbf{r}}$ of the Bloch eigenfunctions $\mathbf{E}_{kn}(\mathbf{r})$. Here $\mathbf{G}$ is the reciprocal lattice vector of the photonic crystal ($\mathbf{G} = N_1 \mathbf{b}_1 + N_2 \mathbf{b}_2 + N_3 \mathbf{b}_3$ where $\mathbf{b}_i$ are primitive basis vectors of the reciprocal lattice). Thus, in contrast to the Lamb shift, the PC medium correction to the electron mass does not depend on the position of the electron in a PC’s air void. At the same time, this correction depends on the direction unit vector $\mathbf{\hat{p}} = \mathbf{p}/|\mathbf{p}|$ of the electron momentum.

The energy of the hydrogen state in free space $|a\rangle = |n, j, l, m\rangle$ may be written as $E_a = m_e + \epsilon_a$ with $\epsilon_a = - \frac{1}{2} \frac{\alpha^2 m_e}{\hbar^2} + O(\alpha^4)$. The frequency $\omega_{ab}$ of the transition between the state $|a\rangle$ and the state $|b\rangle$ is given by $\omega_{ab} = \epsilon_a - \epsilon_b$. Since the mass correction (3) depends on the electron momentum direction the energy gets the correction

$$ \langle \delta m_{pc} \rangle = \int d^3p \Psi^*_{njlm}(\mathbf{p}) \delta m_{pc}(\mathbf{\hat{p}}) \Psi_{njlm}(\mathbf{p}), \tag{4} $$

that depends only on the orbital angular momentum and the absolute value of the angular-momentum $z$-component $m$. As a result, the rest energy parts of the total energies of the states $|a\rangle$ and $|b\rangle$ contribute to the transition frequency

$$ \omega_{ab}^{pc} = (\delta m_{pc})_a - (\delta m_{pc})_b + \epsilon_a^{pc} - \epsilon_b^{pc}. \tag{5} $$

Thus, we expect that the customary difference between the $2S_{1/2}$ and $2P_{1/2}$ energy levels will change. Moreover each component of the $2P$ doublet will split into two levels corresponding to the values of $m = 0; \pm 1$. 

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3. Experimental evidence of the electron mass changes

The effect under study will very much depend on the structure quality of photonic crystals and many other parameters, including the effective refractive index. Using the model proposed in [4] for the inverse opal PC with parameters $n_{eff} = 1.15$, $\omega_0 = 1$ eV, $h_0 = 0.8$, $\sigma_0 = 0.1$ eV (the last 3 parameters are characterizing the position, the depth and the width of band gap) we expect that the wavelength of the $2S_{1/2} - 2P_{1/2}$ transition will be in the range $200 - 600 \mu m$. The relation between the observed Lamb shift and the mass correction to the energy levels is shown in the figure 1. Using this relation we can obtain the values of the correction to the mass from experiment.

![Figure 1](image)

**Figure 1.** The relation between wavelength of the observed $2S_{1/2} - 2P_{1/2}$ Lamb shift and the mass correction to the $S$-state (solid line) and the $P$-state with $m = 0$ (dashed line).

Depending on the PC parameters the shifted lines could be detected in a wide range from a microwaves, up to infrared region (IR). If the energy shifts caused by the effect are in the microwave range, it is natural to use a modified variant of the Lamb and Retherford experiment on the observation of the Lamb shift in hydrogen atoms.

The main distinguishing feature of our experiment is that the hydrogen atoms placed in our voids of the photonic crystal will be exposed to electromagnetic radiation (figure 2). To detect excited atoms it is proposed to use the devices based on electron multipliers, such as the channeltron. Observation of a significant correction to the Lamb shift between the $2S_{1/2}$ and $2P_{1/2}$ energy levels should be an experimental confirmation of the effect under study. The proposed experiment consists of two following steps:

1) Confirmation of the effect of the electron mass changes. To do this, first the Lamb shift of hydrogen atoms will be measured without the photonic crystal. Thus, the frequency of electromagnetic radiation corresponding to the difference between the $2S_{1/2}$ and $2P_{1/2}$ energy levels ($\sim 1058$ MHz) will be determined and no excited atoms will reach the detector. Then, the photonic crystal is introduced into the scheme in accordance with figure 2. The appearance of excited atoms in the detector will indicate that the value of the Lamb shift is already different from 1058 MHz. As a result, the effect of the electron mass changes in PC medium will be confirmed.

2) Measurement of the new Lamb shift by tuning the frequency of the electromagnetic radiation. As a result of this step the corrections to the energy levels of hydrogen placed in the PC medium will be measured.
Certainly there are some issues to be solved. For example, it is necessary to ensure that the atoms from the outside of the photonic crystal will not be exposed to electromagnetic radiation. In this connection it is necessary to concentrate the electromagnetic radiation only in PC using waveguides or antennas. Also, it may be necessary to use IR spectroscopy instead of the microwave generator. In addition, there are many requirements to the photonic crystal, which are necessary for the implementation of our experiment. The structure of the photonic crystal cavities should allow hydrogen atoms to pass through the PC medium. For this purpose, photonic crystals based on inverse opals [11] are best suited. Such materials are obtained by assembling of spherical microparticles in a periodic close-packed structure (synthetic opal) followed by filling of desired substance into the voids between the particles and removing the initial particles. However, it is very difficult to obtain such structures with the required quality.

4. Conclusion
The way to experimental confirmation of the effect of the electron mass changes in photonic crystal medium has been proposed. The proposed scheme is based on the Lamb-shift experiment in hydrogen atoms. It is expected that the change in the Lamb shift in photonic crystal will be observed, as well as the corrections to the energy levels in the hydrogen atoms will be measured.

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References
[1] Yablonovitch E 1987 Phys. Rev. Lett. 58 2059
[2] John S 1987 Phys. Rev. Lett. 58 2486
[3] Krauss T F and De La Rue R M 1999 Progr. Quantum Electronics 23(2) 51–96
[4] Gainutdinov R Kh, Khamadeev M A and Salakhov M Kh 2012 Phys. Rev. A 85 053836
[5] Gainutdinov R Kh, Salakhov M Kh and Khamadeev M A 2012 Bull. Russ. Acad. Sci. Phys. 76(12) 1301–1305
[6] Gainutdinov R Kh, Khamadeev M A and Salakhov M Kh 2013 Bull. Russ. Acad. Sci. Phys. 77(12) 1440–1443
[7] Gainutdinov R Kh, Khamadeev M A and Salakhov M Kh 2014 Bull. Russ. Acad. Sci. Phys. 78(3) 193–195
[8] Gainutdinov R Kh, Khamadeev M A and Salakhov M Kh 2013 J. Phys.: Conf. Ser. 478 012017
[9] Liu Q et al 2010 Opt. Lett. 17 2898
[10] Lamb W E and Retherford R C 1947 Phys. Rev. 72(3) 241–243
[11] Khokhlov P E, Sinitskii A S and Tretyakov Yu D 2006 Dokl. Chem. 408 61–64