Int J Theor Phys (2008) 47: 1911–1918
DOI 10.1007/s10773-007-9635-4

Proca Effects of Axion-Like Particle-Photon Interactions on Light Polarization in External Magnetic Fields

Cheng-De Li · Yan-Fu Cheng

Received: 23 September 2007 / Accepted: 10 December 2007 / Published online: 21 December 2007

Abstract Photon can mix with the axion-like particles (ALPs) on light polarization when the laser beam travels through a magnetic field. Since there is no conclusive evidence of an exact zero rest mass for the photon in various experiments and observations, we study the Proca effects in various ALP-photon regeneration experiments and develop a formalism which can be adopted to study the evolution of a massive photon in the presence of external magnetic fields. We find that the Proca effects are much smaller than the effects of the standard QCD axions. But if the masses of such particles are comparable, the Proca effects can not be neglected. Furthermore, we get the implied photon mass limit and discuss the feasibility of extending the search for the *photon mass* limit in this area.

Keywords Proca effect · Photon · Axion-like particle · Birefringence · Dichroism

1 Introduction

There are many proposals in the literature to embed the standard model of particle physics into a more general, unified framework. They predict many new particles which are very light and very weakly coupled to ordinary matter. Typically, such light particles arise if there is a global continuous symmetry that is spontaneously broken in the vacuum. A well known example is the axion [26, 27], a pseudoscalar particle arising from the breaking of Peccei-Quinn symmetry [17] which is introduced to explain the absence of CP violation in strong interactions. Axions could provide many interesting physical, astrophysical and cosmological effects, among them the possible solution to the Cold Dark Matter candidate and the early evolution of the universe [13, 21, 30]. Other examples of light spin-zero bosons beyond the standard model are familons [28], majorons [3, 7], the dilaton, and moduli, to name just a few. We call them axion-like particles, ALPs, in the following.

C.-D. Li (✉) · Y.-F. Cheng
College of Electronic Information Engineering, South-Central University for Nationalities, Wuhan 430074, People's Republic of China
e-mail: lcd8912@163.com

On the other hand, the enormous successes of quantum electrodynamics (QED) have led to an almost total acceptance of the photon with exactly zero rest mass. However, despite this acceptance, a substantial experimental effort has been made to determine whether the photon rest mass is zero or nonzero. Up to now, there is no conclusive evidence of an exact zero rest mass for the photon in various experiments and observations, with the results instead yielding more stringent upper bounds on the limit of it. Certainly, failure to find a finite photon mass in any one experiment or class of experiments is not proof that it is identically zero [24]. Even as the experimental limits move more closely towards the fundamental bounds of measurement uncertainty, new experimental and theoretical consideration of the photon rest mass continue to appear [14, 15, 23]. Generally, there are classical and quantum approaches to the determination of the photon mass limit. This limit has been usually determined by using a classical approach, such as the limit of Luo et al. [14, 15]. Boulware and Deser [1] proposed a quantum approach based on the Aharonov-Bohm effect to determine the photon mass limit. Moreover, recent developments of the effects of the Aharonov-Bohm type has allowed Spavieri and Rodriguez [23] to reach or even improve the limit of Luo et al., exploiting the quantum approach of Boulware and Deser. So, now the quantum approaches can compete with classical approaches. From a theoretical perspective, if the rest mass of the photon was found to be nonzero, classical electromagnetism and QED would remain untroubled in spite of the loss of gauge invariance. At the same time, there are also some far-reaching implications of a massive photon, such as variation of the speed of light, deviations in the behaviors of static electromagnetic fields, longitudinal electromagnetic radiation and even questions of gravitational deflection. Moreover, a finite photon mass is perfectly compatible with the general principles of elementary particle physics, and an answer to the question of its size can be found only through experiments or observations. Hence, unless we find the conclusive evidence of the photon rest mass in various experiments or observations, we can not avoid discussing the effects of nonzero photon rest mass, namely the Proca Effect, theoretically in the literature. Considering this, we propose to study the Proca Effect in various ALP-photon interaction experiments which are also devoted to characterize quantum vacuum and to discover the existence of ALPs with mass below the energy of the photons of the laser beam they used. Moreover, we also want to explore the feasibility of extending the search for the *photon mass* limit in this area.

2 The Proca Effects in the ALP-Photon Interaction Experiments

The photon rest mass is ordinarily assumed to be exactly zero in Maxwell's electromagnetic field theory, which is based on gauge invariance. The Proca equation for photon is the natural extension of the Maxwell equation to the case of the nonzero photon rest mass [16]. If gauge invariance is abandoned, a mass term can be added to the Lagrangian density for the electromagnetic field in a unique way [11, 24]

$$L_m = -\frac{1}{4}\boldsymbol{F}_{\mu\nu}\boldsymbol{F}^{\mu\nu} - j_\mu \boldsymbol{A}^\mu + \frac{1}{2}m_\gamma^2 \boldsymbol{A}_\mu \boldsymbol{A}^\mu, \tag{1}$$

where m_γ is the nonzero photon rest mass, $\boldsymbol{F}_{\mu\nu}$ is the electromagnetic field strength tensor with dual $\widetilde{\boldsymbol{F}}^{\mu\nu} = \frac{1}{2}\varepsilon^{\mu\nu\alpha\beta}\boldsymbol{F}_{\alpha\beta}$ ($\varepsilon^{0123} = 1$); $\boldsymbol{A}_\mu$ and j_μ are the four-dimensional vector potential $(\boldsymbol{A}, i\phi/c)$ and four-dimensional vector current density $(\boldsymbol{J}, ic\rho)$, with ϕ and $\boldsymbol{A}$ denoting the scalar and vector potentials, and ρ and $\boldsymbol{J}$ are the charge and current densities, respectively. The variation of the Proca Lagrangian density written by (1) with respect to $\boldsymbol{A}_\mu$ yields the Proca equations [4, 16].

In the presence of an external magnetic field in ALP-photon interaction experiments which will be discussed here, $\rho = 0$, $\boldsymbol{J} = 0$. Correspondingly, $\boldsymbol{F}_{\mu\nu}$ is the sum of the contributions from the external magnetic field and the field of real photons. It takes the form

$$\boldsymbol{F}_{\mu\nu} = \boldsymbol{F}^{ext}_{\mu\nu} + \partial_\mu \boldsymbol{A}_\nu - \partial_\nu \boldsymbol{A}_\mu. \tag{2}$$

So, the Proca Lagrangian density for the massive electromagnetic field in this letter can be written as

$$L_0 = -\frac{1}{4}\boldsymbol{F}_{\mu\nu}\boldsymbol{F}^{\mu\nu} + \frac{1}{2}m_\gamma^2 \boldsymbol{A}_\mu \boldsymbol{A}^\mu. \tag{3}$$

We stress that all equations in this letter are written in terms of natural, rationalized electromagnetic units (natural Lorentz-Heaviside units) where $\hbar = c = 1$. These units are commonly employed in field theory and have been used in the axion literature.

At the lowest non-trivial order, the coupling of such an ALP, whose corresponding quantum field we denote by a, to massive photons is described by an effective Lagrangian

$$L = -\frac{1}{4}\boldsymbol{F}_{\mu\nu}\boldsymbol{F}^{\mu\nu} + \frac{1}{2}m_\gamma^2 \boldsymbol{A}_\mu \boldsymbol{A}^\mu + \frac{1}{2}(\partial_\mu a \partial^\mu a - m_a^2 a^2) + \frac{1}{4M}\boldsymbol{F}_{\mu\nu}\widetilde{\boldsymbol{F}}^{\mu\nu} a, \tag{4}$$

where m_a is the mass of the ALPs, M is the inverse coupling constant which has dimensions of energy. Due to the presence of the external magnetic field, a photon of energy ω may oscillate into an ALP with a small mass $m_a < \omega$, and vice versa [19, 22]. So in the ALP-photon interaction experiments, if a beam of photons is shone across a magnetic field, a fraction of these photons will turn into the ALPs. Since the ALPs coupling to the ordinary matter is very weak, this ALP beam could then propagate freely through an optical barrier without being absorbed, and finally another magnetic field located on the other side of the wall could transform some of these ALPs into photons. This mechanism, which is also associated with the Primakoff effect, is the basic idea behind the ALP-photon interaction experiments [6, 18, 25]. These ALPs can be best scrutinized in ALP-photon regeneration experiments, such as optical experiments like BFRT [2], PVLAS [29] and ALPS [20], one of which operates at DESY by the ALPS group [5].

So, in the presence of a static magnetic field and real photons in these ALP-photon regeneration experiments, (4) reduces to

$$L = -\frac{1}{4}\boldsymbol{F}_{\mu\nu}\boldsymbol{F}^{\mu\nu} - \frac{1}{2}m_\gamma^2 \boldsymbol{A}_\mu \boldsymbol{A}^\mu + \frac{1}{2}(\partial_\mu a \partial^\mu a - m_a^2 a^2) + \frac{1}{M}(\boldsymbol{E} \times \boldsymbol{B}_{ext})a. \tag{5}$$

By utilizing the Euler-Lagrange equations, the resulting equations of motion to first order in the photon field $\boldsymbol{A}$ and the ALP field a are

$$\begin{cases} \left[\nabla^2 - \dfrac{\partial^2}{\partial(ct)^2} + m_\gamma^2\right]\boldsymbol{A} + \dfrac{1}{M}\dot{\boldsymbol{a}} \cdot \boldsymbol{B}_{ext} = 0, \\ \left[\nabla^2 - \dfrac{\partial^2}{\partial(ct)^2} + m_a^2\right]a - \dfrac{1}{M}\dot{\mathbf{A}} \cdot \boldsymbol{B}_{ext} = 0 \end{cases} \tag{6}$$

where the gauge condition $\nabla \cdot \boldsymbol{A} = 0$ is used, along with $A^0 = 0$ (the external field is transverse). In the case of zero photon rest mass, solutions of such equations have been given by Raffelt and Stodolsky [19]. We will give the solutions in the case of the nonzero photon rest mass, so as to get the Proca effects of the ALP-Photon interactions on light polarization in external magnetic fields. We derive the evolution equation for a plane-wave light beam propagating in the z direction and perpendicularly to $\boldsymbol{B}_{ext}$ in this new case. Assuming for the fields plane-wave solutions, we find the stationary wave equation which can be written in matrix form for particles propagating along the z axis as

$$\begin{pmatrix} \omega^2 + \partial_z^2 - m_\gamma^2 & 0 & 0 \\ 0 & \omega^2 + \partial_z^2 - m_\gamma^2 & -i B_{ext}\omega/M \\ 0 & B_{ext}\omega/M & \omega^2 + \partial_z^2 - m_a \end{pmatrix} \begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix} = 0, \tag{7}$$

where a, $A_\perp$ and $A_\parallel$ are the amplitudes of the ALPs, the components orthogonal and parallel to the external magnetic field $\boldsymbol{B}_{ext}$, respectively. Generally, we can assume that the variation of the magnetic field in space occurs on much larger scales than the photon and ALPs wavelength. Then we use the expansion $\omega^2 + \partial_z^2 = (\omega + i\partial_z)(\omega - i\partial_z) \approx (\omega + k)(\omega - i\partial_z) = 2\omega(\omega - i\partial_z)$ for propagation in the positive z direction. Since in our case always $|n-1| \ll 1$, the dispersion relation can be written as $k = n\omega$ and we can approximate $\omega + k = 2\omega$, and $\partial_z = -i\omega$. The resultant errors which are higher order in small parameters are not to be considered here.

When the laser beam in such ALP-photon interaction experiments is propagating in the vacuum through a transverse magnetic field, the polarization of the light will be modified by the interactions of the photons of the light beam with the virtual photons of the external magnetic field. Photon-photon interactions producing a real particle, such as ALPs, deplete the original light beam. This kind of pseudoscalar particle is produced only because the amplitude of the component of the photons with the electric field direction parallel to the external magnetic field are absorbed. The component of the polarized light beam with polarization parallel to the magnetic field $A_\parallel$ is reduced, while the orthogonal component $A_\perp$ remains unchanged and then the outcoming light beam has the polarization plane slightly rotated (vacuum magnetic induced dichroism) with a small angle ε. In addition, we should emphasize that Maxwell's equations imply a photon that can be polarized in either of two directions, both of which are orthogonal to the photon's direction of motion. But a nonzero rest mass of the photon as described by the Proca equations would result in a third state of polarization, in which the vector of the electric field points along the line of motion and the particle is called a 'longitudinal photon' [11]. However, if the photon has a nonzero rest mass, it must be very tiny, so the effect of longitudinal photons has been too small to be considered up to the present [8–10, 24]. Moreover, the component of the longitudinal photon is also orthogonal to the external intensive magnetic field $\boldsymbol{B}_{ext}$ and the laser beam polarization plane, so we need not to consider it. So, the matrix equation for the two coupled components takes the form

$$\left[\begin{pmatrix} \omega - i\partial_z & 0 \\ 0 & \omega - i\partial_z \end{pmatrix} + \begin{pmatrix} \Delta_\gamma & -i\Delta_M \\ i\Delta_M & \Delta_a \end{pmatrix}\right] \begin{pmatrix} A_\parallel \\ a \end{pmatrix} = 0, \tag{8}$$

where

$$\Delta_a = \frac{-m_a^2}{2\omega}; \qquad \Delta_\gamma = \frac{-m_\gamma^2}{2\omega}; \qquad \Delta_M = \frac{B_{ext}}{2M}. \tag{9}$$

Here we utilize the Jacobi method to calculate the eigenvalue of the matrix equation, so the matrix in (8) can be diagonalized by rotating the original fields through a mixing angle θ

$$\begin{pmatrix} A'_\parallel \\ a' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A_\parallel \\ a \end{pmatrix}, \tag{10}$$

where the strength of mixing angle θ is defined by the ratio of the off-diagonal term in (10) to the difference of the diagonal terms:

$$\frac{1}{2}\,\mathrm{tg}\,2\theta = \frac{\Delta_M}{\Delta_\gamma - \Delta_a}\Delta' = \frac{\Delta_\gamma + \Delta_a}{2} \pm \frac{\Delta_\gamma - \Delta_a}{2\cos 2\theta}. \tag{11}$$

We have $\frac{1}{2}\,\mathrm{tg}\,2\theta \approx \theta$ for $\theta \ll 1$, the weak mixing case. Turning to the dispersion relation for the diagonal fields $A'_\parallel$ and a' we find

$$\Delta' = \frac{\Delta_\gamma + \Delta_a}{2} \pm \frac{\Delta_\gamma - \Delta_a}{2\cos 2\theta}, \tag{12}$$

where the plus sign refers to $\Delta'_\parallel$ and the minus sign to Δ'_a. Hence, The Proca effect of the refractive indices of the mixed modes are given as

$$n' = 1 + \Delta'/\omega. \tag{13}$$

The eigenvalue of (10) is

$$\lambda_\pm = \frac{(\Delta_\gamma - \Delta_a) \pm \sqrt{(\Delta_\gamma - \Delta_a)^2 + 4\Delta_M^2}}{2}, \tag{14}$$

which also can be described by the term of θ respectively as

$$\lambda_+ = \frac{\Delta_a - \Delta_\gamma}{2}\left(1 - \frac{1}{\cos 2\theta}\right), \tag{15}$$

$$\lambda_- = \frac{\Delta_a - \Delta_\gamma}{2}\left(1 + \frac{1}{\cos 2\theta}\right). \tag{16}$$

We consider the laser beam of frequency ω propagating in the z direction and we measure the phase of all modes relative to the unmixed $A_\parallel$ component, neglecting a common phase $e^{i(\omega t - kz - \Delta_\gamma z)}$. Then the discussion is simplified and the mixing components take the form

$$\begin{aligned}\begin{pmatrix} A_p(z) \\ a(z) \end{pmatrix} &= T(z)\begin{pmatrix} A_p(0) \\ a(0) \end{pmatrix} \\ &= \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} e^{-i\lambda_+ z} & 0 \\ 0 & e^{-i\lambda_- z} \end{pmatrix}\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} A_p(0) \\ a(0) \end{pmatrix}.\end{aligned} \tag{17}$$

The mixing matrix $T(z)$ can be written as

$$T(z) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} e^{-i\lambda_+ z} & 0 \\ 0 & e^{-i\lambda_- z} \end{pmatrix}\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}. \tag{18}$$

We now take the external homogeneous field to be sufficiently weak so that $\theta \ll 1$ the weak mixing case applies. Then we can expand the mixing matrix $T(z)$ in θ to the second order as

$$T(z) = T_0(z) + \theta T_1(z) + \theta^2 T_2(z). \tag{19}$$

We work to the relevant order in θ in the exponential, and then we find the expansion of the mixing matrix

$$T_0 = \begin{pmatrix} 1 & 0 \\ 0 & e^{-i(\Delta_a-\Delta_\gamma)z} \end{pmatrix}, \tag{20}$$

$$T_1 = \begin{pmatrix} 1 & 1-e^{-i(\Delta_a-\Delta_\gamma)z} \\ 1-e^{-i(\Delta_a-\Delta_\gamma)z} & e^{-i(\Delta_a-\Delta_\gamma)z} \end{pmatrix}, \tag{21}$$

$$T_2 = \begin{pmatrix} e^{-i(\Delta_a-\Delta_\gamma)z}-1+i(\Delta_a-\Delta_\gamma)z & 0 \\ 0 & e^{-i(\Delta_a-\Delta_\gamma)z}-1-i(\Delta_a-\Delta_\gamma)z \end{pmatrix}. \tag{22}$$

So, we can use these results to deduce some applications of the mixing formulism with the Proca effects indicated by a term of $\Delta_\gamma = \frac{-m_\gamma^2}{2\omega}$ respectively as follows:

(1) The phase shift of the component of the polarized laser beam with polarization parallel to the magnetic field$A_\parallel$ is

$$\Delta\varphi = -\mathrm{Im}(T_{11}) = \theta^2[-(\Delta_a-\Delta_\gamma)z + \sin(\Delta_a-\Delta_\gamma)z]. \tag{23}$$

(2) The reduction of the amplitude of the laser beam with polarization parallel to the magnetic field$A_\parallel$ is

$$\delta = 1-\mathrm{Re}(T_{11}) = 2\theta^2\sin[(\Delta_a-\Delta_\gamma)z/2]. \tag{24}$$

(3) The slightly rotated (vacuum magnetic induced dichroism) angle of the polarization plane of the outcoming laser beam is

$$\varepsilon = \left[\frac{\omega B_{ext}}{M(m_a^2-m_\gamma^2)}\right]^2 \sin^2\left[\frac{(m_a^2-m_\gamma^2)l}{4\omega}\right],$$

where l is the length of the magnetic field region. The effective length of the magnetic field region can be increased by multiply reflecting the laser beam through the magnets. However, since the ALPs do not reflect, coherence is lost at every reflection. The rotation is cumulative upon reflection, so that for N reflections the values of ε is increased by a factor of N.

$$\varepsilon = N\left[\frac{\omega B_{ext}}{M(m_a^2-m_\gamma^2)}\right]^2 \sin^2\left[\frac{(m_a^2-m_\gamma^2)l}{4\omega}\right]. \tag{25}$$

(4) The probability of the conversion from a photon to an ALP can be found from the off-diagonal elements of the same matrix equation. The probability of the conversion is

$$P_{\gamma\to a} = 4\left[\frac{\omega B_{ext}}{M(m_a^2-m_\gamma^2)}\right]^2 \sin^2\left[\frac{(m_a^2-m_\gamma^2)l}{4\omega}\right]. \tag{26}$$

3 Discussion

Since there is no conclusive evidence of an exact zero rest mass for the photon in various experiments and observations, we compute the Proca effects in various ALP-photon regeneration experiments and develop a formalism which can be adopted to study the evolution of a massive photon in the presence of external magnetic fields. The applications of the mixing formulism with the Proca effects indicated by the term of Δ_γ are given. We find that the applications can return to the Raffelt and Stodolsky's solutions [19] when $m_\gamma = 0$. If $m_\gamma \neq 0$, the applications of the mixing formulism are changed since the Proca effects are introduced in those equations.

In the limit of $\sin\frac{(m_a^2-m_\gamma^2)l}{4\omega} \ll 1$, $|m_a^2 - m_\gamma^2| \ll 4\omega/l$, we get the approximate expressions of the mixing formulism following from expanding the sine function respectively as

$$\varepsilon = N\left[\frac{\omega B_{ext}}{M(m_a^2 - m_\gamma^2)}\right]^2 \sin^2\left[\frac{(m_a^2 - m_\gamma^2)l}{4\omega}\right] \approx N\frac{B_{ext}^2 l^2}{16M^2}.$$

As the case of Cameron [2], $M > \sqrt{N\frac{B_{ext}^2 l^2}{16\varepsilon}} = 0.68 \times 10^8$ GeV valid for $\varepsilon \sim 10^{-12}$ rad, $m_a < 8 \times 10^{-4}$ eV ($m_a \approx \frac{2\pi}{\alpha M \times 0.72\xi \times 10^{-7}} \times 0.62$ eV $\propto \frac{1}{M}$). The implied photon mass limit $m_\gamma < 10^{-4}$ eV is much higher than those of Luo et al. [14, 15] and Spavieri et al. [23]. The Particle Data Group finds the currently accepted upper limit on the photon rest mass to be $m_\gamma \leq 2 \times 10^{-16}$ eV [12]. Hence, the Proca effects are much smaller than the effects of ALPs which have the mass limits around the ordinary bounds of the standard QCD axions 10^{-6} eV $\sim 10^{-3}$ eV. But this is only the case of the QCD axion. If the masses of some ALPs are comparable with the photon mass limit, such as $m_a \sim 10^{-16}$ eV, the Proca effects can not be neglected and the photon mass limit $m_\gamma \sim 10^{-16}$ eV can be reached. At the same time, the value of B_{ext}, l, N and the sensitivity of the rotation angleε must be increased in such experiments, so as to improve the magnitude of M. It may be not easy for such experiments at present. For example, if we want to obtain the photon mass limit near 10^{-12} eV with this method, we must achieve the sensitivity of the measurement of M near 10^{16} GeV. So, the feasibility of extending the search for the *photon rest mass* limit in this area of physics relies on the improvement of the magnitude of the measurement of M.

Virtually, a nonzero photon rest mass may have no impact on the bulk of terrestrial laboratory physics. However, for physics on scales comparable with the Compton wavelength of the photon, the importance of the Proca effects would be profound since this is the region of astrophysics and cosmology where many doubts and suspicions await resolution, including ALPs. Determining a nonzero photon rest mass or the existence of such ALPs would be very meaningful for the components of the universe, such as Cold Dark Matter candidates, and the early evolution of stars [13, 21, 30]. Hence, the problem of the photon rest mass and the existence of ALPs is ultimately of interest in both fundamental physics and applied physics.

References

1. Boulware, D.G., Deser, S.: Phys. Rev. Lett. **63**, 2319 (1989)
2. Cameron, R., et al.: Phys. Rev. D **47**, 3707 (1993)
3. Chikashige, Y., Mohapatra, R.N., Peccei, R.D.: Phys. Lett. B **98**, 265 (1981)
4. De Broglie, L.: La Méchanique Ondulatoire du Photon, Une Nouvelle Théorie de Lumière, vol. 1, pp. 39–40. Hermann, Paris (1940)
5. Ehret, K., et al.: hep-ex/0702023
6. Gasperini, M.: Phys. Rev. Lett. **59**, 396 (1987)
7. Gelmini, G.B., Roncadelli, M.: Phys. Lett. B **99**, 411 (1981)
8. Goldhaber, A.S., Nieto, M.M.: Phys. Rev. Lett. **21**, 567 (1968)
9. Goldhaber, A.S., Nieto, M.M.: Rev. Mod. Phys. **43**, 277 (1971)
10. Goldhaber, A.S., Nieto, M.M.: Phys. Rev. Lett. **91**, 149101 (2003)
11. Greiner, W., Reinhardt, J.: Field Quantization. Springer, New York (1996)

12. Haginara, et al.: Phys. Rev. D **66**, 010001 (2002)
13. Kim, J.E.: Phys. Rep. **150**, 1 (1987)
14. Luo, J., Tu, L.C., Hu, Z.K., Luan, E.J.: Phys. Rev. Lett. **90**, 081801 (2003)
15. Luo, J., Tu, L.C., Hu, Z.K., Luan, E.J.: Phys. Rev. Lett. **91**, 149102 (2003)
16. Proca, A.: J. Phys. Radium **7**, 347 (1936)
17. Peccei, R.D., Quinn, H.R.: Phys. Rev. Lett. **38**, 1440 (1977)
18. Primakoff, H.: Phys. Rev. **81**, 899 (1951)
19. Raffelt, G., Stodolsky, L.: Phys. Rev. D **37**, 1237 (1988)
20. Ringwald, et al.: Phys. Rev. D **75**, 035011 (2007)
21. Rosenberg, L.J., Bibber, K.A.: Phys. Rep. **325**, 1 (2000)
22. Sikivie, P.: Phys. Rev. Lett. **51**, 1415 (1983)
23. Spavieri, G., Rodriguez, M.: Phys. Rev. A **75**, 052113 (2007)
24. Tu, L.C., Luo, J., Gillies, G.T.: Rep. Prog. Phys. **68**, 77 (2005)
25. Van Bibber, K., et al.: Phys. Rev. Lett. **59**, 759 (1987)
26. Weinberg, S.: Phys. Rev. Lett. **40**, 223 (1978)
27. Wilczek, F.: Phys. Rev. Lett. **40**, 279 (1978)
28. Wilczek, F.: Phys. Rev. Lett. **49**, 1549 (1982)
29. Zavattini, E., et al.: Phys. Rev. Lett. **96**, 110406 (2006)
30. Zioutas, K., et al.: Phys. Rev. Lett. **94**, 121301 (2005)