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Axion interpretation of the PVLAS data?[1]

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Abstract. The PVLAS collaboration has recently reported the observation of a rotation of the polarization plane of light propagating through a transverse static magnetic field. Such an effect can arise from the production of a light, $m_A \sim$ meV, pseudoscalar coupled to two photons with coupling strength $g_{A\gamma} \sim 5 \times 10^{-6}$ GeV^{-1}. Here, we review these experimental findings, discuss how astrophysical and helioscope bounds on this coupling can be evaded, and emphasize some experimental proposals to test the scenario.

There are various proposals in the literature in favour of the existence of light pseudoscalar particles beyond the Standard Model which have, so far, remained undetected, due to their weak coupling to ordinary matter. Such light particles would arise if there was a global continuous symmetry in the theory that is spontaneously broken in the vacuum. A well known example is the axion [1], which arises from a natural solution to the strong CP problem. It appears as a pseudo Nambu-Goldstone boson of a spontaneously broken Peccei-Quinn symmetry [2], whose scale f_A determines its mass, $m_A = [z^{1/2}/(1+z)]\, m_\pi f_\pi / f_A = 0.6\,\text{meV} \times (10^{10}\,\text{GeV}/f_A)$ in terms of the mass m_π and decay constant f_π of the pion and the current quark mass ratio $z = m_u/m_d$. Only invisible axion models [3, 4], where $f_A \gg 247$ GeV, are viable experimentally [5].

Clearly, it is of great interest to set stringent constraints on the properties of such light pseudoscalars. The interactions of axions and similar light pseudoscalars with Standard Model particles are model dependent, i.e. not a function of $1/f_A$ only. The most stringent constraints to date come from their coupling to photons, $g_{A\gamma}$, which arises via the axial anomaly [6],

$$\mathcal{L}_{\text{int}} = -\frac{1}{4}\, g_{A\gamma}\, A\, F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{A\gamma}\, A\, \mathbf{E}\cdot\mathbf{B}\,; \qquad g_{A\gamma} = -\frac{\alpha}{2\pi f_A}\left(\frac{E}{N} - \frac{2}{3}\,\frac{4+z}{1+z}\right), \tag{1}$$

where A is the pseudoscalar field, $F_{\mu\nu}$ ($\tilde{F}^{\mu\nu}$) the (dual) electromagnetic field strength tensor, α the fine-structure constant, and E/N the ratio of electromagnetic over color anomalies. As illustrated in Fig. 1, two quite distinct invisible axion models, namely the KSVZ [3] (or hadronic) and the DFSZ [4] (or grand unified) one, lead to quite similar $g_{A\gamma}$. The strongest constraints currently involve cosmological and astrophysical considerations. Only the laser experiments in Fig. 1 aim also at the production of axions in the laboratory.

Let us discuss such laser experiments in some detail. The most straightforward ones exploit photon regeneration. They are based on the idea [13] to send a polarized laser beam, with

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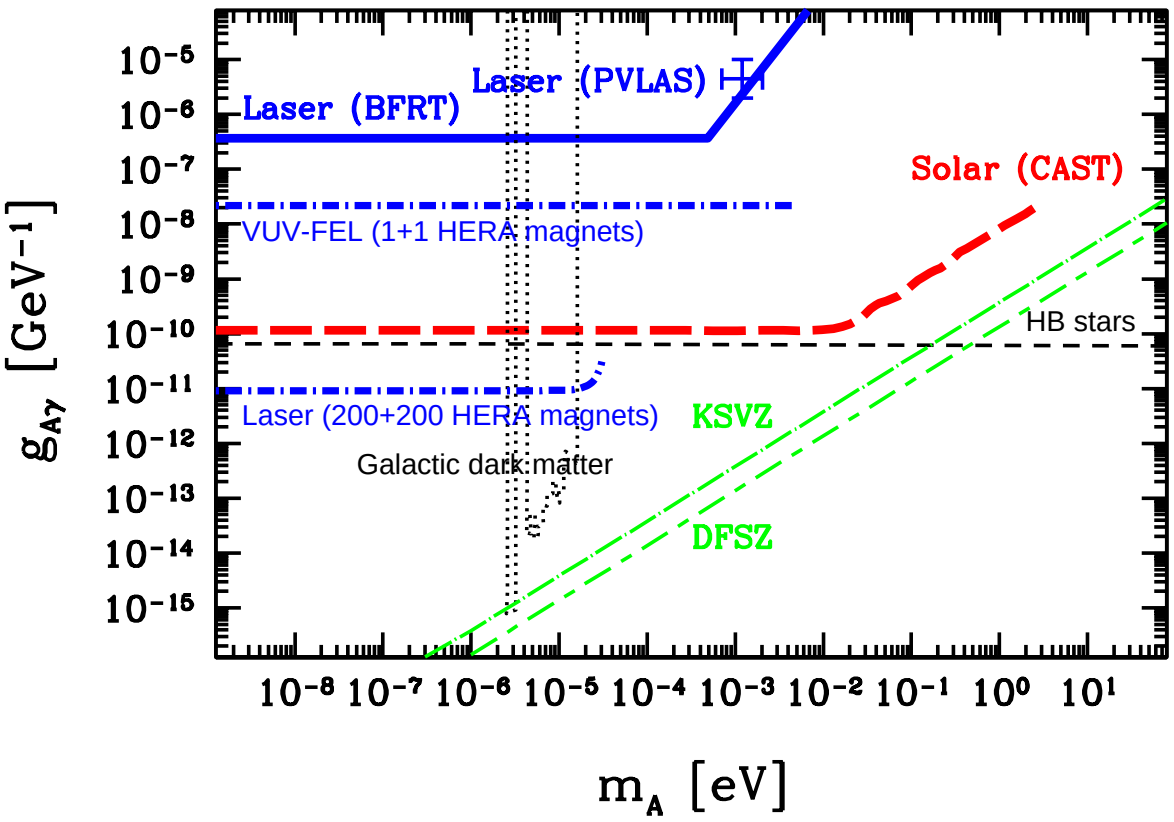

Figure 1. Exclusion region in mass m_A vs. axion-photon coupling $g_{A\gamma}$ for various current and future experiments. The laser experiments [7, 8, 9, 10] aim at axion production and detection in the laboratory. The galactic dark matter experiments [5] exploit microwave cavities to detect axions under the assumption that axions are the dominant constituents of our galactic halo, and the solar experiments search for axions from the sun [11]. The constraint from horizontal branch (HB) stars [5, 12] arises from a consideration of stellar energy losses through axion production.

average power $\langle P \rangle$ and frequency ω, along a superconducting dipole magnet of length ℓ, such that the laser polarization is parallel to the magnetic field. In the latter, the photons may convert into axions via a Primakoff process. If another identical dipole magnet is set up in line with the first magnet, with a sufficiently thick wall between them to absorb the incident laser photons, then photons may be regenerated from the pure axion beam in the second magnet and detected with an efficiency ϵ. The expected counting rate of such an experiment is given by

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}t} = \frac{\langle P \rangle}{\omega} \, \frac{N_r + 2}{2} \, \frac{1}{16} \, (g_{A\gamma} \, B \, \ell)^4 \sin^2 \left(\frac{m_A^2 \, \ell}{4 \, \omega} \right) \left(\frac{m_A^2 \, \ell}{4 \, \omega} \right)^2 \approx \frac{\langle P \rangle}{\omega} \, \frac{N_r + 2}{2} \, \frac{1}{16} \, (g_{A\gamma} \, B \, \ell)^4 \, \eta \,, \quad (2)$$

if one makes use of the possibility of putting the first magnet into an optical cavity with a total number N_r of reflections. For $m_A \ll \sqrt{2 \, \pi \, \omega / \ell} = 4 \times 10^{-4} \, \mathrm{eV} \sqrt{(\omega / 1 \, \mathrm{eV})(10 \, \mathrm{m} / \ell)}$, the approximate sign in (2) applies and the expected counting rate for a photon regeneration experiment is independent of the axion mass. A pilot photon regeneration experiment was performed by the Brookhaven-Fermilab-Rutherford-Trieste (BFRT) collaboration [7]. It employed an optical laser of wavelength $\lambda = 2\pi/\omega = 514$ nm and power $\langle P \rangle = 3$ W for $t = 220$ minutes in an optical cavity with $N_r = 200$, and used two superconducting dipole

magnets with $B = 3.7$ T and $\ell = 4.4$ m. No signal of photon regeneration was found, which leads, taking into account a detection efficiency of $\eta = 0.055$, to a $2\,\sigma$ upper limit of $g_{A\gamma} < 6.7 \times 10^{-7}$ GeV^{-1} for axion-like pseudoscalars with mass $m_A < 10^{-3}$ eV.

Another possibility to probe $g_{a\gamma}$ is to measure changes in the polarization state when photons have traversed a transverse magnetic field [14]. In particular, the real production of axions leads to a rotation of the polarization plane of an initially linearly polarized laser beam by an angle

$$\epsilon \;=\; N_r \, \frac{g_{A\gamma}^2 \, B^2 \, \omega^2}{m_A^4} \, \sin^2 \left(\frac{m_A^2 \, \ell}{4\,\omega} \right) \sin 2\,\theta \approx \frac{N_r}{16} \, (g_{A\gamma} \, B \, \ell)^2 \, \sin 2\,\theta \,, \tag{3}$$

where θ is the angle between the light polarization direction and the magnetic field component normal to the light propagation vector. The BFRT collaboration has also performed a pilot polarization experiment along these lines, with the same laser and magnets described before. For $\ell = 8.8$ m, $B = 2$ T, and $N_r = 254$, an upper limit on the rotation angle $\epsilon < 3.5 \times 10^{-10}$ rad was set, leading to a limit $g_{A\gamma} < 3.6 \times 10^{-7}$ GeV^{-1} at the 95 % confidence level, provided $m_A < 1$ meV [7]. Similar limits have been set from the absence of ellipticity in the transmitted beam. The overall envelope of the constraints from the BFRT collaboration [7] is shown in Fig. 1 and labelled by "Laser (BFRT)" (cf. Ref. [5]).

Recently, the PVLAS experiment [8], consisting of a Fabry-Pérot cavity of very high finesse ($N_r \approx 44\,000$), immersed in a magnetic dipole with $\ell = 1$ m and $B = 5$ T, reported the observation of a rotation of the polarization plane of light propagating through a transverse static magnetic field [8]. If interpreted in terms of the production of a light neutral pseudoscalar, the PVLAS collaboration finds a region $1.7 \times 10^{-6}\,\text{GeV}^{-1} \lesssim g_{A\gamma} \lesssim 1.0 \times 10^{-5}\,\text{GeV}^{-1}$ for $0.7\,\text{meV} \lesssim m_A \lesssim 2.0\,\text{meV}$, from a combination of the $g_{A\gamma}$ vs. m_A curve corresponding to the PVLAS rotation signal (cf. Eq. (3)) with the BFRT limits on the same quantities.

Clearly, a pseudoscalar with these properties is hardly compatible with a genuine QCD axion. For the latter, a mass $m_A \sim 1\,\text{meV}$ implies a symmetry breaking scale $f_A \sim 6 \times 10^9\,\text{GeV}$. According to (1), one needs then an extremely large ratio $|E/N| \sim 3 \times 10^7$ of electromagnetic and color anomalies in order to arrive at an axion-photon coupling in the range suggested by PVLAS. This is far away from the predictions of any model conceived so far [15]. Moreover, such a pseudoscalar must have very peculiar properties in order to evade the strong constraints on $g_{A\gamma}$ from stellar energy loss considerations ("HB stars" in Fig. 1) and from its non-observation in helioscopes such as the CERN Axion Solar Telescope ("Solar (CAST)" in Fig. 1) [16]. Pseudoscalar production in stars may be hindered, for example, if the $A\gamma\gamma$ vertex is suppressed at keV energies due to low scale compositeness of A [17] or if, in stellar interiors, A acquires an effective mass larger than the typical photon energy, $\sim$ keV [18].

In any case, an independent and decisive experimental test of the finding of PVLAS is urgently needed. One opportunity is offered by high luminosity e^+e^- colliders, e.g. a possible super-B factory at KEK, where one may search for events with a single photon plus missing transverse energy in the final state [19]. The best and most timely possibilities, however, are offered by dedicated photon regeneration experiments, either based on ordinary optical lasers (e.g. [20]) or on (soft) X-rays from free-electron lasers (FEL) at DESY and SLAC [9]. In fact, as can be seen in Fig. 1, the region of parameter space implied by PVLAS could be probed in a matter of minutes if one sets up a photon regeneration experiment exploiting the already operating FEL at DESY's TESLA Test Facility, which provides tunable radiation from the vacuum-ultraviolet (VUV) to soft X-rays, $\omega = 10$–200 eV, with an average power $\langle P \rangle = 20$–40 W, together with two superconducting dipole magnets of the type used in DESY's electron proton collider HERA ($B = 5$ T, $\ell = 10$ m) [9]. The tuning of the FEL for fixed photon flux would allow a precision determination of m_A. Such an experiment could also serve as a test facility for an ambitious large scale photon regeneration experiment with sensitivity exceeding CAST [10], based on the recycling of all the 400 dipole magnets of HERA after its decommissioning in mid of 2007.

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