Photon Regeneration from Pseudoscalars at X-Ray Laser Facilities

Raúl Rabadán,[1,*] Andreas Ringwald,[2,†] and Kris Sigurdson[1,‡]
[1]Institute for Advanced Study, Einstein Drive, Princeton, New Jersey 08540, USA
[2]Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, D-22607 Hamburg, Germany

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Recently, the PVLAS Collaboration reported an anomalously large rotation of the polarization of light in the presence of a magnetic field in vacuum. As a possible explanation, they consider the existence of a light spin-zero particle coupled to two photons. We propose here a method of independently testing this result using a high-energy photon regeneration experiment (the x-ray analogue of "invisible light shining through walls") using the synchrotron x rays from a free-electron laser. With such an experiment the region of parameter space implied by PVLAS could be probed in a matter of minutes.

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Many models beyond the standard model predict the existence of light pseudoscalar particles which are very weakly coupled to ordinary matter. Such particles would arise if there were a global continuous symmetry in the theory that is spontaneously broken in the vacuum—a notable example being the axion [1] arising from the breaking of a U(1) Peccei-Quinn symmetry [2], introduced to explain the absence of strong *CP* violation.

Pseudoscalars may couple to two photons via the interaction

$$\mathcal{L}_{\phi\gamma\gamma} = -\tfrac{1}{4} g\phi F_{\mu\nu}\tilde{F}^{\mu\nu} = g\phi\vec{E}\cdot\vec{B}, \qquad (1)$$

where g is the pseudoscalar-photon coupling, ϕ is the field corresponding to the pseudoscalar, and $F_{\mu\nu}$ ($\tilde{F}^{\mu\nu}$) is the (dual) electromagnetic field strength tensor. Correspondingly, in the presence of a magnetic field $\vec{B}$, a photon of frequency ω may oscillate into a pseudoscalar particle of small mass $m_\phi < \omega$, and vice versa. The exploitation of this result is the basic idea behind photon regeneration [3,4] (sometimes called "invisible light shining through walls" experiments). Namely, if a beam of light with N_0 photons is shone across a magnetic field, a fraction of these photons will turn into pseudoscalars. This pseudoscalar beam can then propagate freely through a wall or another obstruction without being absorbed, and finally another magnetic field located on the other side of the wall can transform some of these pseudoscalars into N_f photons—apparently regenerating these photons out of nothing. This type of experiment was carried out in Brookhaven using two prototype magnets for the Colliding Beam Accelerator and was used to exclude values of the pseudoscalar-photon coupling $g < 6.7 \times 10^{-7}$ GeV^{-1} for $m_\phi < 10^{-3}$ eV [5].

Recently the PVLAS collaboration has reported an anomalous signal in measurements of the rotation of the polarization of photons in a magnetic field in vacuum [6]. One *a priori* possible explanation of this apparent vacuum magnetic dichroism is the production of a pseudoscalar coupled to photons through Eq. (1), according to which photons polarized parallel to the magnetic field disappear, leading to a rotation of the polarization plane [7]. The region quoted in Ref. [6] that might explain this signal is 1.7×10^{-6} GeV$^{-1} < g < 1.0 \times 10^{-5}$ GeV^{-1} for 0.7×10^{-3} eV $< m_\phi < 2.0 \times 10^{-3}$ eV, obtained from a combination of previous limits on g vs m_ϕ from a similar, but less sensitive polarization experiment in Brookhaven [5] and the g vs m_ϕ curve corresponding to the PVLAS signal. In minimal models a pseudoscalar-photon coupling in this region of parameter space is in contradiction with limits derived from pseudoscalar production in stars [8], particularly in the Sun [9,10]. However, in principle one can try to find nonminimal models where, through extra interactions or other physical effects, the absence of pseudoscalar production in stars can be made compatible with the laboratory result [11] [which only involves the interaction shown in Eq. (1)].

The main motivation of this Letter is to suggest an independent laboratory probe of the $g\phi\vec{E}\cdot\vec{B}$ interaction without reference to a specific model of pseudoscalar production in stars (see Refs. [12,13]). Given the unexpected and surprising results found in the neutrino sector we believe this type of laboratory cross-check is certainly warranted. Specifically, we consider the possibility of exploiting a powerful x-ray free-electron laser in a photon regeneration experiment [14] to probe the region where the PVLAS signal could be explained in terms of a pseudoscalar coupling to a light particle [16]. One of the novel features of our proposal compared to lower-frequency optical regeneration experiments is that, through the use of x-ray energies, larger masses can be probed before incoherent effects are encountered.

Two facilities have designed and, in fact, are about to commence construction of powerful free-electron lasers (FEL) in the x-ray range: the Linac Coherent Light Source (LCLS) at SLAC [19] and the European X-Ray Laser XFEL at DESY [20]. The LCLS is a free-electron x-ray laser that will use the last kilometer of the SLAC linear accelerator. It will be capable of producing intense pulses of x-ray photons at energies between 0.8 and 8 keV. Project completion is expected in 2008 and the first experiments involving the LCLS will be running in 2009. The XFEL at DESY starting in 2012 will have several lasers with similar characteristics with photon energies in the 1–10 keV range and an average flux of photons of approximately 10^{17}–10^{19} photons per second. Already running at the DESY TESLA Test Facility is the VUV-FEL which provides tunable radiation from the vacuum-ultraviolet (10 eV) to soft x rays (200 eV), with an average flux of about 10^{18}–10^{19} photons per second [21,22].

Our benchmark proposal uses a photon regeneration set up with two equal magnets of magnetic field B and length L. The first of them converts the x-ray photons from the laser beam into pseudoscalars and the second, on the other side of the "wall," converts the high-energy pseudoscalars into x-ray photons again (see Fig. 1). We consider the sensitivity of two experimental setups: a superconducting magnet of $L = 10$ m and $B = 10$ T and a conventional magnet with $L = 20$ m and $B = 1$ T. The first setup is more appropriate for the DESY FEL facilities because of the availability of superconducting magnets after the decommissioning of the electron-proton collider HERA in mid-2007 [23,24].

The probability of photon-pseudoscalar conversion in a constant magnetic field of length L is

$$P = \frac{1}{4} g^2 B^2 L^2 j_0^2\left(\frac{qL}{2}\right) = g^2 B^2 \frac{\sin^2(\frac{qL}{2})}{q^2}, \tag{2}$$

where $q = \omega - \sqrt{\omega^2 - m_\phi^2}$ is the difference between the momentum of the pseudoscalar and the photon. When the mass of the pseudoscalar is much smaller than the photon energy, we can approximate $q = m_\phi^2/2\omega$. For the magnets and pseudoscalar masses we are considering, we have $qL \ll 1$, so that $j_0 \rightarrow 1$ and the conversion probability simplifies to

$$P = \frac{1}{4} g^2 B^2 L^2. \tag{3}$$

Using magnets of a length of 10 m $= 5.07 \times 10^7$ eV^{-1} and a magnetic field of 10 T $= 1.95 \times 10^3$ eV^2, the probability of converting a photon into a pseudoscalar is

$$P = 2.4 \times 10^{-9}\left(\frac{g}{10^{-6}\ \mathrm{GeV}^{-1}}\right)^2\left(\frac{B}{10\ \mathrm{T}}\right)^2\left(\frac{L}{10\ \mathrm{m}}\right)^2. \tag{4}$$

An x-ray laser facility may produce on average as many as $N_0 \simeq \mathcal{N}_{17} \times 10^{17}$ photons per second (where $\mathcal{N}_{17} \simeq$ 1–100). The number of pseudoscalar particles that are produced per second is $N_\phi = PN_0$. The number that will be transformed back into photons is just $N_f = PN_\phi = P^2 N_0$. Thus we find the photon regeneration rate as

$$N_f = 0.6\ \mathrm{s}^{-1}\mathcal{N}_{17}\left(\frac{g}{10^{-6}\ \mathrm{GeV}^{-1}}\right)^4\left(\frac{B}{10\ \mathrm{T}}\right)^4\left(\frac{L}{10\ \mathrm{m}}\right)^4. \tag{5}$$

We immediately see that the PVLAS result can be tested in a matter of minutes. We summarize the full mass dependence of these potential bounds and the values of the pseudoscalar-photon coupling that can be probed in this way for various running times in Fig. 2. For the superconducting magnet and single day experiment, the region $g > 8.9 \times 10^{-8}$ GeV^{-1} could be probed at 95% confidence, while in a year the limit could be improved to $g > 2.0 \times 10^{-8}$ GeV^{-1}.

Let us summarize why we believe our proposal is of interest. First, high frequency photons are able to avoid pseudoscalar-photon incoherent effects, which set in for $m_\phi^2 L \approx 2\pi\omega$, and can probe pseudoscalar masses [26] $m_\phi < 0.05$ eV, beyond the capability of optical photons. Second, x-ray detection can be very efficient, with an efficiency $\eta \simeq 1$, and with backgrounds in the laboratory very much under control. They can be reduced by utilizing the directionality, the pulsed time structure, and the small bandwidth of the signal and comparing the backgrounds when the magnets are on with the background when the magnets are off. Note that even after accounting for a realistic detector efficiency and backgrounds the main conclusions of this work will remain unchanged. Thirdly, superconducting magnets are not mandatory and so, in principle, one can use long ordinary magnets that are more cost effective. Moreover, a remarkable feature of this proposal is that, if the initial conversion magnet is placed before a target that is the subject of other experiments, it is possible to perform both experiments simulta-

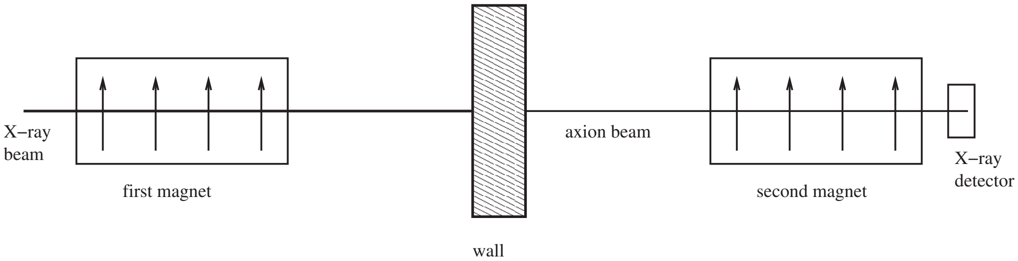

FIG. 1. Schematic figure of the regeneration experiment.

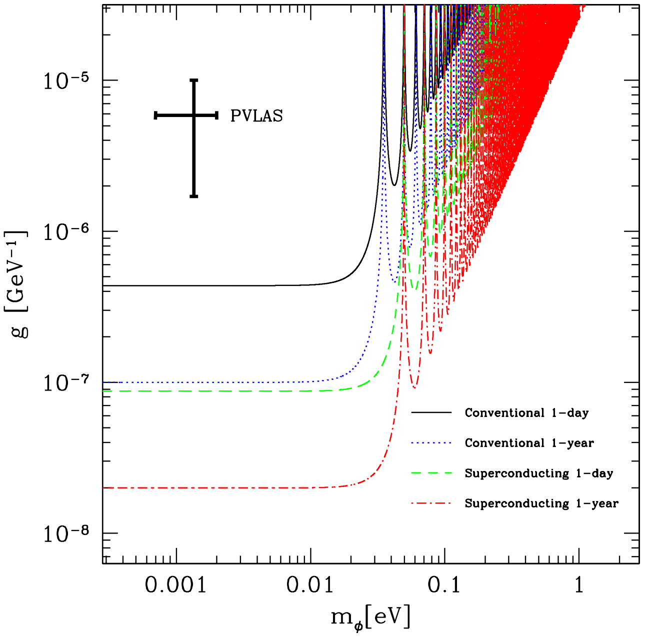

FIG. 2 (color online). 95% confidence level exclusion region for different running times: 1 d and 1 yr for two different magnets (a conventional magnet with $L = 20$ m and $B = 1$ T and a superconducting magnet with $L = 10$ m and $B = 10$ T). We have assumed efficient (perfect) x-ray detection and an x-ray beam with $N_0 = 10^{17}$ s^{-1} and $\omega = 10$ keV. Note that photons with energies as low as ~30 eV would be adequate for testing PVLAS without being limited by incoherent effects.

neously, since the pseudoscalar beam will propagate unimpeded through the target.

This experiment could probe the region of parameter space relevant to PVLAS in less than a day. The pseudoscalar vs scalar nature of the interaction can be tested by varying the direction of the magnetic field with respect to the polarization of the laser or measuring the polarization of the regenerated photons. The possibility of tuning the frequency of the FEL for fixed photon flux would allow a precision determination of m_ϕ. A first experiment could be done within this year with the VUV-FEL at the TESLA Test Facility [27]. This could serve also as a first step towards an ambitious large scale photon regeneration experiment [23,24], based on the XFEL and the recycling of HERA's 400 superconducting dipole magnets ($B = 5$ T, $L = 200 \times 10$ m), to reach within a year an unprecedented sensitivity of $g > 2.0 \times 10^{-10}$ GeV^{-1}, comparable to the limits involving model-dependent astrophysical considerations [8–10].

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*Electronic address: rabadan@ias.edu
†Electronic address: andreas.ringwald@desy.de
‡Electronic address: krs@ias.edu

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