Proposed Experiment to Produce and Detect Light Pseudoscalars

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We propose a laboratory experiment to produce and detect a light neutral pseudoscalar particle that couples to two photons. The pseudoscalar would be produced by a (real) photon from a laser beam interacting with a second (virtual) photon from a static magnetic field; it would be detected after it reconverts to a real photon in a duplicate magnetic field. The bounds on the coupling constant that could be obtained from a null result in such an experiment compete favorably with astrophysical limits and would substantially improve those from direct measurements.

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Light, weakly interacting bosons have been proposed as signatures of new physics at high mass scales and as candidates for dark matter. For example, the axion emerges in a solution to the strong *CP* problem as a manifestation of a new symmetry, the Peccei-Quinn (PQ) symmetry, that is broken at a mass scale v; the axion acquires a mass of $\sim f_\pi m_\pi / v \approx (0.013\ \mathrm{GeV}^2)/v$. As originally proposed,[1] $v \approx 250$ GeV was the weak scale, but the axion thereby implied has not been observed experimentally.[2] Other axion models with $v \gg 250$ GeV have been proposed.[3] These so-called "invisible" axions could make up the dark matter of the Universe. In such models, the coupling of the axion to specific quarks and leptons can be varied or even absent. In all of them, however, the axion couples to photons.[4] It is therefore of great interest to set stringent limits on the properties of a light neutral boson coupling to photons. For definiteness we take the boson to be a pseudoscalar, but other spin and parity choices could be explored by slight modifications of our proposal.

The best limits on the coupling of a light pseudoscalar to two photons follow from the consideration of energy loss in stars.[5] Blackbody x rays would produce pseudoscalars in collisions with charged particles in the star via the Primakoff effect. The pseudoscalars would then escape from the star before decaying. These limits have recently been weakened by the realization that plasma screening drastically reduces the Primakoff cross sections for low momentum transfers.[6] It is, however, imperative to perform controlled laboratory experiments. In this Letter we propose a terrestrial experiment to produce and detect such particles. A bound on the coupling to two photons of the order of the solar limit is feasible with a simple experiment; a refined experiment could yield a bound which exceeds the most stringent limits from stellar evolution. The experiment would have uniform sensitivity from truly massless pseudoscalars up to masses somewhat less than the energy of the incident photon.

The pseudoscalar couples to two photons through fermions via the well-known triangle anomaly. The corresponding term in the effective Lagrangean is $L_I = \frac{1}{4} g \phi_p F_{\mu\nu} \tilde{F}^{\mu\nu} = g \phi_p \mathbf{E} \cdot \mathbf{B}$, where $\tilde{F}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\lambda\rho} F^{\lambda\rho}$. The fermion loop can be quarks and/or leptons.

The experimental setup we envision is illustrated in Fig. 1. The initial photon of energy ω from the laser (we put $\hbar = c = 1$ throughout[7]) interacts with a virtual photon from the static magnetic field $\mathbf{B}_0 = \hat{\mathbf{z}} B_0$, to produce a pseudoscalar of energy ω and momentum $k_p (\omega^2 - m_p^2)^{1/2}$, where m_p is the pseudoscalar mass. The photon is polarized so that its electric field $\mathbf{E}(\mathbf{r},t) = \hat{\mathbf{z}} E_0 e^{i\omega(x-t)}$ is parallel to $\mathbf{B}_0$, maximizing the interaction with the pseudoscalar field for a given B_0 and laser intensity.[8] The photon beam is then blocked to eliminate everything except the pseudoscalars, which pass through because of their extremely weak interaction with ordinary matter. (Such shielding is straightforward for a low-energy laser beam.) The pseudoscalar then interacts with another virtual photon in the second magnet to produce a real photon of energy ω, whose detection is the signal for the production of the pseudoscalar. We note that this setup is conceptually similar to two of Sikivie's detectors[9] operated in tandem.

It is straightforward to calculate the probability of the conversion and the reconversion of the initial photon, to lowest order in g^2, with use of quantum field theory. The result so obtained, however, coincides with the result of the solution to the classical field equations,

$$L=-\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}+\tfrac{1}{2}(\partial_\mu\phi_p\partial^\mu\phi_p-m_p^2\phi_p^2)-\tfrac{1}{4}g\phi_pF_{\mu\nu}\tilde{F}^{\mu\nu}, \quad (1)$$

$$\partial_\mu F^{\mu\nu}=g\,\partial_\mu(\phi_p\tilde{F}^{\mu\nu}),\quad (\partial_\mu\partial^\mu+m_p^2)\phi_p=g\mathbf{E}\cdot\mathbf{B}. \quad (2)$$

By neglecting the modification of the electromagnetic field due to the presence of the pseudoscalar field [through the right-hand side of the first equation of (2)] and solving for ϕ_p in the second equation of (2), one obtains the solution to lowest order in gB_0l, where l is the linear dimension associated with the extent of the magnetic field:

$$\phi^{(\pm)}(\mathbf{r},t)=e^{-i\omega t}\int d^3r'\frac{1}{4\pi}\frac{e^{\pm ik_p|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|}g\mathbf{E}(\mathbf{r}')\cdot\mathbf{B}(\mathbf{r}'). \quad (3)$$

The $(\pm)$ indicate the boundary conditions on ϕ_p. If we specialize to our experimental configuration and take the transverse extent of the magnetic region to be much larger than that of the laser beam, the problem becomes one dimensional, with

$$\phi_p^{(+)}(\mathbf{r},t)=iE_0(gB_0l/2k_p)F(q)e^{i(k_px-\omega t)}. \quad (4)$$

Here l is now the extent of the magnetic field in the x (beam) direction, $q=\omega-k_p$ is the momentum transfer to the magnet, and $F(q)=\int dx\,e^{-iqx}B(x)/lB_0$ is a form factor for the magnetic region. For the rectangular shape we have considered, $F(q)=\sin\frac{1}{2}ql/\frac{1}{2}ql$ and, in general, $F(0)=1$ This solution implies that the number of pseudoscalars produced per incident photon is

$$\Pi=\tfrac{1}{4}(\omega/k_p)(gB_0l)^2F^2(q), \quad (5)$$

which we interpret as the probability of conversion of a photon into a pseudoscalar as it goes through the magnet. For $m_p/\omega\ll 1$, we have $\omega/k_p\simeq 1$; $q=m^2/2\omega$, and therefore $F^2\omega/k_p\simeq 1$, if $m^2l/4\omega$ is also small. In this case, $\Pi\simeq(gB_0l)^2/4$. It is easy to show that the probability for the reverse process coincides exactly with this result, so that the number of signal photons can be obtained by the multiplication of the number of incident photons by Π^2.

The region excluded by a null experiment would depend variously on the implementation of the basic idea:

(i) *Simple photon counting.*— Here, as shown in Fig. 1(a), visible photons would simply be counted by a phototube at the rear of the second magnet. A null experiment would yield a 90%-confidence-level upper limit for very light pseudoscalars of

$$g<(4.7\times10^{-9}\,\mathrm{GeV}^{-1})\left(\frac{10\,\mathrm{T}}{B_0}\frac{10\,\mathrm{m}}{l}\right)\left(\frac{\omega}{2.5\,\mathrm{eV}}\frac{1\,\mathrm{kW}}{P}\frac{0.1}{\epsilon}\right)^{1/4}\left(\frac{100\,\mathrm{d}}{t}\frac{v}{0.01\,\mathrm{Hz}}\frac{\delta}{1.0\times10^{-4}}\right)^{1/8}, \quad (6)$$

where benchmark experimental parameters have been left manifest. Here P is the average power of the laser, ϵ is the efficiency of the photon detector, t is the duration of the experiment, v is the counting rate due to noise, and δ is the duty cycle of the laser. The limit weakens for higher masses because of the form factor $F(q)$, where $ql/2\approx[(2.5\,\mathrm{eV})/\omega][m_p/(4.4\times10^{-4}\,\mathrm{eV})]^2$.

The limit improves most rapidly if B_0 or l is increased, because the production and detection are both coherent. The second factor in (6) comes from the rate of incident photons and the detection efficiency. It enters in the limit on g to the $\frac{1}{4}$ power because of the production-detection nature of the experiment. For visible photons, detection efficiencies of 0.1 are easily achieved. The third factor comes from the upper limit on the rate of detected photons, which enters only as the $\frac{1}{8}$ power in the limit on g. The additional square root appears because the upper limit on the photon signal goes as the square root of the noise rate, and the inverse root of the operating time. Noise rates of 0.01 Hz for single-photon detection are routinely available with cooled phototubes

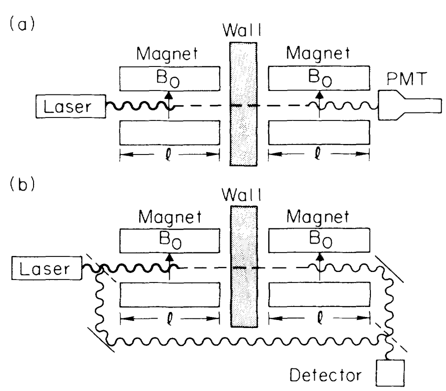

FIG. 1. Experimental setups. (a) Photons from a laser are shone into the bore of a dipole magnet. There the real laser photons interact with the virtual photons from the magnetic fields, producing pseudoscalars. The weakly interacting pseudoscalars penetrate the wall and then convert in the second magnet. The resulting photon is detected in the phototube (PMT). (b) A similar experiment, except that interference is used to increase the signal-to-noise ratio.

having small-area (≈ 0.06 cm^2) photocathodes and low-activity glass.[10]

(ii) *Interference techniques.*— Interference of a relatively strong signal split from the laser with the possible signal from a light pseudoscalar, as shown in Fig. 1(b), would make the signal-to-noise ratio independent of noise sources intrinsic or extrinsic to the detector, and allow single-quantum detection. This arrangement is similar to homodyning from a local oscillator.[11] One could perform the experiment in the far infrared, and obtain higher average power of the CO_2 laser, more photons per unit power, and unit detector efficiencies. Again for very small masses, a null experiment would yield a 90%-confidence-level upper limit of

$$g < (1.1\times10^{-11}\,\mathrm{GeV}^{-1})\left[\frac{6.6\,\mathrm{T}}{B_0}\frac{500\,\mathrm{m}}{l}\right]\left[\frac{\omega}{1\,\mathrm{eV}}\frac{100\,\mathrm{kW}}{P}\frac{1}{\epsilon}\frac{100\,d}{t}\right]^{1/4}. \tag{7}$$

Note the changes in the benchmark values from (6), not only in ω, P, and ϵ, but also in B_0 and l, where we have considered the use of 60 magnets of the type designed for the Superconducting Super Collider (SSC), of length 16.6 m and field strength 6.6 T. The time t in this case can be thought of as $1/\Delta\nu$, where $\Delta\nu$ is the narrowest bandwidth one can achieve, and in practice would probably be limited by $1/f$ noise in the apparatus.

(iii) *Wigglers.*— Segmentation of the magnetic field into regions of alternating polarity gives a form factor that peaks at a nonzero value of q, thereby giving sensitivity to higher-mass pseudoscalars. If N identical magnets of length L, such that $l=NL$, are segmented into n subgroups of alternating polarity, we have

$$F(q)=[(\sin\tfrac{1}{2}ql)/\tfrac{1}{2}ql]\tan(qNL/2n). \tag{8}$$

The limits attainable from null experiments of types (i) and (ii), with the mass dependence from the form factor, are shown in Fig. 2. We have also exhibited the region that one could exclude by alternating $N=30$ SSC magnets with n from 2 to 30, as discussed in (iii).

If light pseudoscalars exist at the limit of (7), some 10^{14}/d would be produced in the first magnet. We have considered other methods to detect their production. For example, if one tried to measure the disappearance of photons from the laser beam, one would be limited at best by counting statistics and would achieve an upper limit similar to (7). We have concluded that the production-detection scheme is difficult to improve upon. We have emphasized the use of a laser as the light source for conceptual simplicity and because of the long spatial coherence lengths available. Use of a light source of coherence length l_c degrades (6) by a factor of $(l/l_c)^{1/2}$, if $l_c < l$.

In Fig. 2 we also plot the most reliable astrophysical limit in this regime: that from the sun.[6] This limit is valid to pseudoscalar masses of approximately 1 keV, where threshold effects in the Primakoff cross section weaken it. Decay of the pseudoscalar in the sun provides the boundary for very large values of g. One sees that an experiment of type (i) would compare favorably with the solar limit for masses $< 10^{-4}$ eV; an experiment of type (ii) would exceed by an order of magnitude the limit of $g \lesssim 1.0\times10^{-10}$ GeV^{-1} inferred from helium-burning stars.[6]

The best terrestrial limits on light pseudoscalars coupling to photons presumably come from searches for $e^+e^- \to \gamma + nothing$ at storage rings.[2,12] The light pseudoscalar would escape detection if its mass were less than ≈ 20 MeV. None of the experiments have interpreted their data with this process, but we estimate that they limit $g < 2.5\times10^{-4}$ GeV^{-1}, some 5 orders of magnitude worse than our proposed experiment. Beam dumps, reactor experiments, and searches for nuclear deexcitation via axion emission in general do not limit pseudoscalars in the domain of the proposed experiment, because the pseudoscalar would escape from the apparatus before decaying.

Axion models predict[4]

$$g \approx [(0.1-10)\times10^{-10}\,\mathrm{GeV}^{-1}][m_p/(1\,\mathrm{eV})],$$

some 2–4 orders of magnitude smaller than the sensitivity the experiments we describe could achieve. We note that microwave-cavity experiments that claim sensitivity to very light axions are dependent on the assumption[13] that axions contribute most of the galactic dark matter,

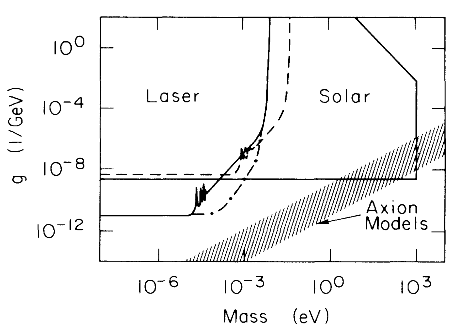

FIG. 2. Limits on light pseudoscalars. The proposed laser experiments could exclude regions in the upper-left-hand corner of this plot. Dashed line: Region that a null experiment of type (i), shown in Fig. 1(a), could exclude. The ripples come from the form factor, $F(q)$. Solid line: Region that a null experiment of type (ii), with use of SSC dipoles, a CO_2 laser, and interference, could exclude. Dot-dashed line: Region that could be excluded by an experiment of type (iii), where magnet polarity is alternated. Also shown are the solar limit (Ref. 6) and the expectations from a variety of axion models (Ref. 4).

providing a density of some 10^{14} axions/cm^3 and a monochromaticity of 1 part in 10^7. While observation of a signal in one of these detectors would provide marvelous support for the theories that motivate this assumption, Nature might not provide light neutral pseudoscalars that satisfy it.

In summary, we have described a method to produce and detect light pseudoscalars that would produce a limit competitive with those from astrophysical considerations. An experiment is being designed for implementation.

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