

**An Experiment to Produce and Detect
Light Pseudoscalars ***

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Abstract

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 $O(f_\pi m_\pi/v \approx 0.013 \text{ GeV}^2/v)$. As originally proposed,¹ $v \approx 250 \text{ GeV}$ was the weak scale, but the axion thereby implied has not been observed experimentally.² Other axion models with $v \gg 250 \text{ GeV}$ 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-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 Black body X-rays would produce pseudoscalars in collisions with charged particles in the star via the Primakoff effect. The pseudoscalars would then escape the star before decaying. These limits have recently been weakened by the realization that plasma screening drastically reduces the Primakoff cross section 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 pseudoscalar couples to two photons through fermions via the well known triangle anomaly. The corresponding term in the effective Lagrangean is $L_I = -(1/4)g\phi_p F_{\mu\nu} \tilde{F}^{\mu\nu} = g\phi_p \vec{E} \cdot \vec{B}$, 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 Figure 1. The initial photon of energy ω from the laser (we put $\hbar = c = 1$ throughout⁷) interacts with a virtual photon from the static magnetic field $\vec{B}_0 = \hat{z}B_0$, to produce a pseudoscalar of energy ω and momentum $k_p = \sqrt{\omega^2 - m_p^2}$, where m_p is the pseudoscalar mass. The photon is polarized so that its electric field $\vec{E}(\vec{r}, t) = \hat{z}E_0 e^{i\omega(x-t)}$ is parallel to \vec{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 detectors⁹

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 , using quantum field theory. The result so obtained, however, coincides with the result of the solution to the classical field equations,

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

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

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:

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

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

$$\phi^{(+)}_p(\vec{r}, t) = iE_0 \frac{gB_0l}{2k_p} F(q) e^{i(k_px - \omega t)}. \quad (4)$$

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 $F(q) = \sin(ql/2)/(ql/2)$ and, in general $F(0) = 1$. This solution implies that the number of pseudoscalars produced per incident photon is

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

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 multiplying 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 Figure 1a, visible photons would simply be counted by a phototube at the rear of the second magnet. A null experiment would yield a 90% confidence upper limit for very light pseudoscalars of

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

where benchmark experimental parameters have been left manifest. Here P is the average power of the laser, ϵ the efficiency of the photon detector, t the duration of the experiment, ν the counting rate due to noise, and δ the duty cycle of the laser. The limit weakens for higher masses due to the form factor $F(q)$, where $ql/2 \approx (2.5\text{eV}/\omega)(m_p/4.4 \times 10^{-4}\text{eV})^2$.

The limit improves most rapidly if B_0 or l are 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 one-fourth 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 one-eighth 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 having small-area ($\approx .06\text{cm}^2$) photocathodes and low activity glass.¹⁰

(ii) *Interference techniques.* Interfering a relatively strong signal split from the laser with the possible signal from a light pseudoscalar, as shown in Figure 1b, 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

$$g < 1.1 \times 10^{-11} \frac{1}{\text{GeV}} \left(\frac{6.6\text{T}}{B_0} \frac{500\text{m}}{l} \right) \left(\frac{\omega}{0.1\text{eV}} \frac{100\text{kW}}{P} \frac{1}{\epsilon} \frac{100\text{days}}{t} \right)^{1/4} \quad (7)$$

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 meters 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 non-zero 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,

$$F(q) = \frac{\sin(ql/2)}{ql/2} \tan(qNL/2n) \quad (8)$$

The limits attainable from null experiments of types (i) and (ii), with the mass dependence from the form factor, are shown in Figure 2. We have also exhibited the region 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} /day 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 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 $\sqrt{l/l_c}$, if $l_c < l$.

In Figure 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 $g \lesssim 1.0 \times 10^{-10} \text{ GeV}^{-1}$ inferred from helium burning stars.⁶

The best terrestrial limits on light pseudoscalars coupling to photons presumably come from searches for $e^+e^- \rightarrow \gamma + \text{nothing}$ 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 $g < 2.5 \times 10^{-4} \text{ GeV}^{-1}$, some five orders of magnitude worse than our proposed experiment. Beam dumps, reactor experiments, and searches for nuclear de-excitation via axion emission in general do not limit pseudoscalars in the domain of the proposed experiment, because the pseudoscalar would escape the apparatus before decaying.

Axion models predict⁴ $g \approx 0.1 - 10 \times 10^{-10} \text{ GeV}^{-1} \times (m_p/\text{eV})$, 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 assumption¹³ that axions contribute most of the galactic dark matter, providing a density of some 10^{14} axions/cm³ 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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FIGURE CAPTIONS

1. **Experimental Setups.** (a) Photons from a laser would be shone into the bore of a dipole magnet. There, the real laser photons would interact with the virtual photons from the magnetic fields, producing pseudoscalars. The weakly interacting pseudoscalars would penetrate the wall, then convert in the second magnet. The resulting photon would be detected in the phototube (PMT). (b) a similar experiment, except interference is used to increase signal to noise.
2. **Limits on Light Pseudoscalars.** The proposed laser experiments would exclude regions in the upper left corner of this plot. *Dashed* – the region a null experiment of type (i), show in Figure 1a, could exclude. The ripples come from the form factor, $F(q)$. *Solid* – the region a null experiment of type (ii), using SSC dipoles, a CO_2 laser, and interference could exclude. *Dot-dashed* – region that could be excluded by an experiment of type (iii) where magnet polarity is alternated. Also shown are the solar limit,⁶ and the expectations from a variety of axion models.⁴

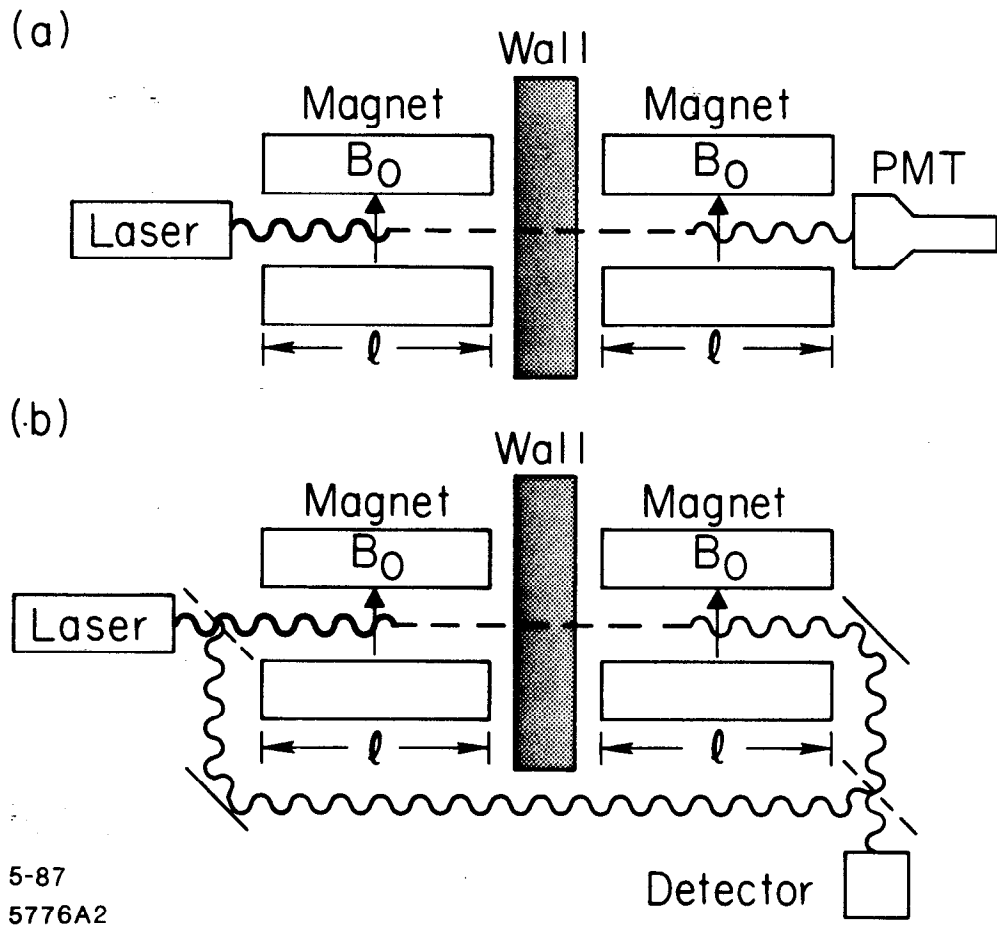


Fig. 1

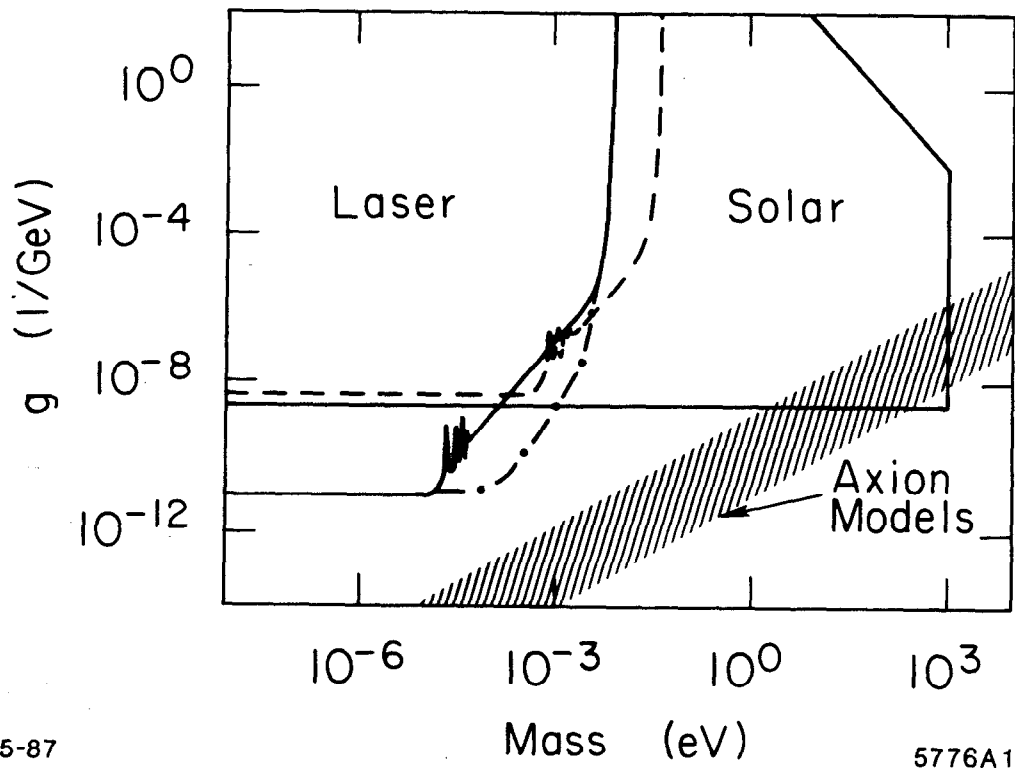


Fig. 2