# COHERENT PRODUCTION OF PSEUDOSCALARS (AXIONS) INSIDE A DIPOLE MAGNETIC FIELD

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We set a limit on the coupling of any light pseudoscalar that couples to two photons by looking at the induced optical rotation of a polarized laser beam inside a dipole magnetic field. The limit is $g_{a\gamma\gamma} < 2.5 \times 10^{-6}$ GeV$^{-1}$ for a particle of mass $m_a \leq 7 \times 10^{-3}$ eV.

## I. Theoretical motivation

The QCD Lagrangian contains a term that violates CP symmetry:

$$L_\theta = \frac{\theta}{32\pi^2} F^{\alpha\mu\nu} F_{\alpha\mu\nu} \tag{1}$$

where $F^{\alpha\mu\nu}$ is the gluon field and $\theta$ is an angular parameter with possible values ($0 \leq \theta < 2\pi$). This term violates the Parity (P) symmetry and conserves the charge (C) symmetry and therefore violates the combined CP symmetry. An experimental upper limit on the violation of CP symmetry in strong interactions exists[1] from the study of the electric dipole moment (EDM) of neutron. The limit of $4\times10^{-25}$e·cm limits $\theta$ to $|\theta| < 10^{-9}$ or $|\pi-\theta| < 10^{-9}$.

Because it is unlikely for $\theta$ to be so close to 0 or $\pi$ it is believed to be exactly 0 or $\pi$. In order to explain why $\theta$ choses to take the value 0 or $\pi$, Peccei and Quinn[2] first proposed a new theory in which $\theta$ gets the value 0 below the QCD energy scale, because the Lagrangian has an effective potential with minimum at that value. The Peccei-Quinn symmetry ($U(1)_{P.Q.}$ axial symmetry) corresponds to invariance in the Lagrangian under the transformations:

$$u_i \to e^{i\eta\gamma_5} u_i \quad , \quad \phi_u \to e^{-2i\eta}\phi_u$$

$$d_i \to e^{i\eta\gamma_5} d_i \quad , \quad \phi_d \to e^{-2i\eta}\phi_d \tag{2}$$

where $u_i$, $d_i$ refer to the SU(2) quarks, $\eta$ is a rotation angle (some arbitrary phase) and

$$\phi_u = \begin{bmatrix} \phi_u^0 \\ \phi_u^- \end{bmatrix} \quad , \quad \phi_d = \begin{bmatrix} \phi_d^+ \\ \phi_d^0 \end{bmatrix} \tag{3}$$

the two Higgs doublets of the standard $SU(3)\times SU(2)_L\times U(1)$ theory.

A breakdown of this symmetry gives rise to a pseudogoldstone boson, the axion, predicted by Weinberg and Wilczek.[3] The scale at which the symmetry breaks down first thought to be at the weak symmetry breaking scale and the mass of the axion at the MeV range. The axion mass depends on the symmetry breaking scale $f_a$: $m_a = \frac{\sqrt{2} f_\pi m_\pi}{f_a}$ with $f_\pi$ the pion form factor (94 MeV) and $m_\pi$ the pion mass (135 MeV).

The heavy mass axion was excluded by beam dump and branching ratio experiments.[4] An extension[5] of the Peccei-Quinn model was invented which includes an extra Higgs doublet with very high vacuum expectation value (VEV). $f_a$ in this case is proportional to the (VEV) of the third Higgs doublet and therefore the axion mass can be very small.

An experiment to look for very light pseudoscalars and/or scalars that couple to two photons was setup at Brookhaven National Lab. It uses a polarized laser light inside a dipole magnetic field. The Lagrangian that describes it is

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \left[\frac{1}{2}(\partial_\mu a \partial^\mu a - m_a^2 a^2) + \frac{1}{4M}F_{\mu\nu}\tilde{F}^{\mu\nu}a\right] + \frac{\alpha^2}{90 m_e^4}\left[(F_{\mu\nu}F^{\mu\nu})^2 + \frac{7}{4}(F_{\mu\nu}\tilde{F}^{\mu\nu})^2\right] \quad (4)$$

where the first term describes the propagation of the classical fields, the second term is referring to the axion coupled to two photons, and the third term describes the QED vacuum polarization.

## II. Axion induced rotation and ellipticity.

The interaction Lagrangian for the axion is

$$L_{int} = \frac{1}{M}\bar{E}\cdot\bar{B}\phi_a \quad (5)$$

with $g_{a\gamma\gamma} = \frac{1}{M}$ the coupling constant, $\bar{E}$ the electric field vector of the photon beam, $\bar{B}$ the external magnetic field, and $\phi_a$ the axion field. A polarized laser beam entering the magnetic field region undergoes rotation because only one component produces axions (and thus is attenuated) due to $\bar{E}\cdot\bar{B}$ nature of the interaction Lagrangian. The rotation angle is given by

$$\epsilon \approx N\frac{B_{ext}^2 l^2}{16M^2}\sin 2\theta \quad (6)$$

where N is the number of times the light passes through the magnetic field, $\theta$ the angle between $\bar{B}_{ext}\times\bar{k}$ and the electric field of the light beam, and $l$ the magnetic field length.

In case that the axion, that is produced inside the magnetic field, interacts with a virtual photon from the magnetic field, it recombines giving back the original photon.

Because axions acquire mass, they travel slower that the speed of light in vacuum and therefore there is a phase difference between the parallel and orthogonal components. This translates to an ellipticity given by

$$\psi_a = \frac{N}{2}\left(\frac{B_{ext}\omega}{Mm_a^2}\right)^2\left\{\frac{m_a^2 l}{2\omega} - \sin\left(\frac{m_a^2 l}{2\omega}\right)\right\}\sin 2\theta. \tag{7}$$

There is also ellipticity induced from QED vacuum polarization[6] which is given by

$$\psi = N\frac{\alpha^2 B_{ext}^2 \omega l}{15 m_e^4}\sin 2\theta \tag{8}$$

where $\alpha \approx 1/137$ is the fine structure constant, $\omega$ the photon energy (green light, 2.41 eV) and $m_e$ the electron mass in eV. In these units (natural Heaviside-Lorentz) a magnetic field of 1T is equal to 195 $eV^2$, and a length of 1 cm equal to $5 \times 10^4$ $eV^{-1}$.

## III. Experiment[7]

An Ar ion laser (2 Watt single line) is used as the source of the polarized photons (fig. 1). The light goes through a telescope that transforms the beam characteristics in order to match the cavity (see below). The half wave plate (HWP) rotates the polarization plane so that the polarization can have the desired angle with the external magnetic field. After the light passes through some steering mirrors (P.S.: periscope, M1: mirror) it enters the vacuum vessel.

Very high quality polarizers are used to polarize (P) and analyze (A) the light. The delay line method is used where the laser beam travels in the magnetic field region several hundred times. After exiting from the magnetic field region the light is heterodyned with a Faraday cell (F.C.). In case the sought after effect is ellipticity the QWP is used to convert the ellipticity into rotation. Two superconducting dipole magnets from the CBA[8] project are used. Each is about 4.5 meters long and can deliver 5 T maximum magnetic field.

The photodiode after the analyzer sees a current that is proportional to

$$I_T = I_o\{\sigma^2 + \alpha^2 + 2\alpha\eta_o\cos(2\pi f_F t + \phi_F) + \frac{\eta_o^2}{2}\cos(4\pi f_F t + 2\phi_F)$$

$$+\eta_o\epsilon_o\cos[2\pi(f_F - f_M)t + (\phi_F - \phi_M)] + \eta_o\epsilon_o\cos[2\pi(f_F + f_M)t + (\phi_F + \phi_M)]\} \quad (9)$$

with $\sigma^2 \approx 10^{-7}$ the extinction between the two polarizers, $\alpha \approx 10^{-6}$ the misalignment between the polarizer and analyzer from the perfect crossing, $\eta_o \approx 10^{-3}$ the Faraday rotation amplitude, $\epsilon_o$ the rotation (or ellipticity) amplitude induced by the magnetic field, $\phi_F$, $\phi_M$ are the Faraday cell and rotation phases respectively, and $f_F$ = 260 Hz, $f_M$ = 39.0625 mHz are the Faraday cell and the magnet modulation frequencies respectively. The photodiode current is amplified by a charge sensitive amplifier and the rotation is found by Fourier analyzing the resulting voltage from the formula

$$\epsilon_o = \frac{\eta_o}{2}\frac{I_{f_F \pm f_M}}{I_{2f_F}} \quad (10)$$

where $I_{f_F \pm f_M}$ is the power at the signal frequency, and $I_{2f_F}$ the power at twice the Faraday cell frequency.

In fig. 2 rotation data is shown.[9] The number of reflections were 790, the modulated magnetic field was $B^2$ = 1.65 $T^2$ and the pressure inside the cavity was better than $10^{-5}$ Torr. We also run the experiment with the QWP in place, and observed peaks at the magnet frequency of the same order as the rotation, but with 38 reflections. Treating these signals as a background of unknown origin we set a limit on the axion coupling constant to two photons. We are continuing the efforts in resolving the origin of these signals by performing various tests in the system.

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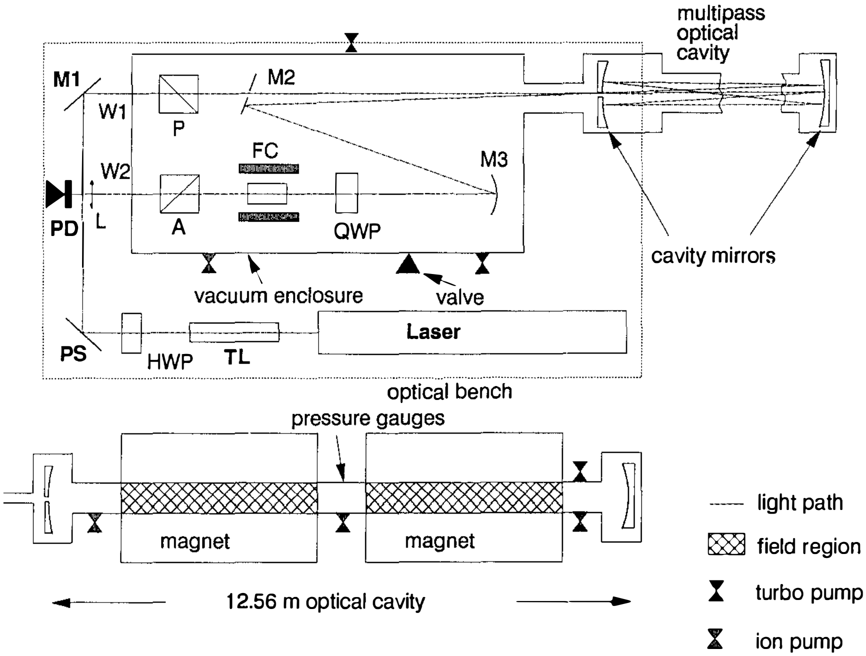


Fig. 1 The apparatus; A: analyzer; FC: Faraday cell; M1: steering mirror; P: polarizer; PD: photodiode; PS: periscope; QWP: quarter-wave plate; and TL: telescope.

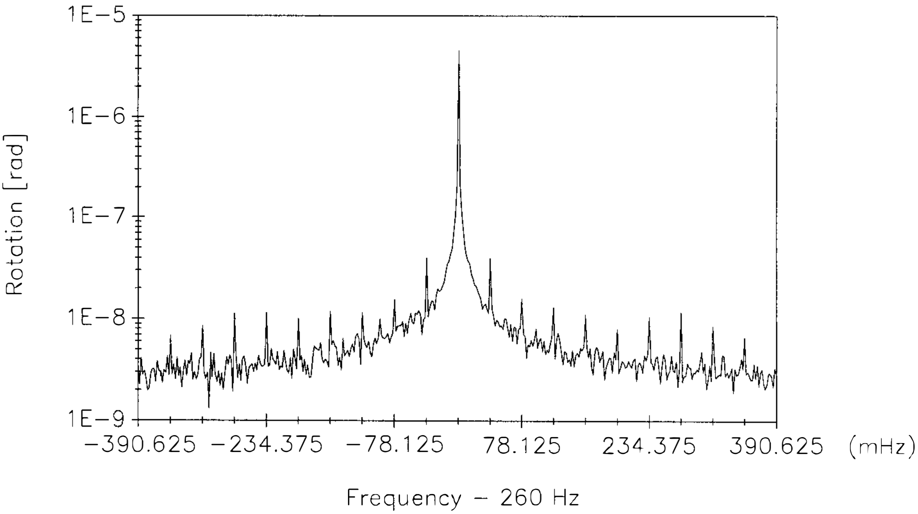


Fig. 2 Rotation data in vacuum.

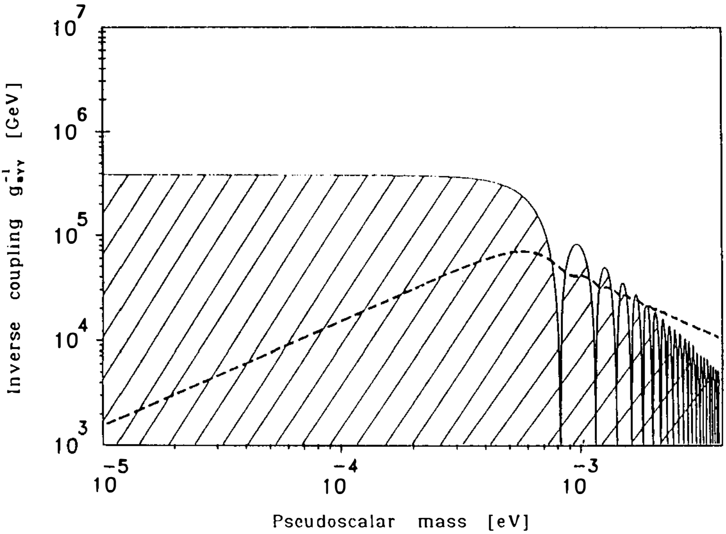


Fig. 3 Excluded regions for the inverse coupling to two photons. The shaded region is a result of the rotation data and the dashed curve of the ellipticity data.