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A SEARCH FOR THE COHERENT PRODUCTION OF AXIONS IN THE MILLI eV RANGE*

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ABSTRACT

Axions provide a natural explanation for the absence of CP violation in the strong interaction. As weakly interacting light particles they are also candidates for the much sought after dark matter allegedly responsible for our lack of understanding of galactic dynamics. Beam dump, particle decay and astrophysical measurements carried out over the past decade have failed to provide positive evidence for their existence over a wide range of masses and coupling strengths.

This experiment attempts to produce and detect scalar and pseudoscalar particles coherently produced through the interaction of laser photons with the virtual photons of the magnetic fields of superconducting dipole magnets as manifested by small changes in the polarization state of the laser light. A limit on the coupling of the axion to 2 photons of $g_{a\gamma\gamma} < 6.67 \times 10^{-7}$ GeV^{-1} was achieved.

Aside from the purely technical problem of computational intractability, QCD has been a remarkably successful theory of the strong interaction. Unfortunately, non-perturbative effects violate P, CP, and T which would have significant but so far unobserved consequences such as a large neutron electric dipole moment if not suppressed. In 1977 Peccei and Quinn[1] proposed a solution to this "strong CP problem" in the form of a new chiral symmetry which is broken at a scale M and has the virtue of making the CP violating term in the QCD Lagrangian vanish in a natural way. Weinberg[2] and Wilczek[3] realized that the breaking of the Peccei-Quinn symmetry would give rise to a new Goldstone boson, the axion.

A wealth of experimental evidence has eliminated the axion as originally conceived and has led to the proliferation of axion variants including "invisible axions" whose coupling is extremely weak and mass small making it a suitable dark matter candidate. The window remaining for their existence is in the 10^{-6} to 10^{-3} eV regime.

This experiment[4] attempts to coherently produce axions through their coupling to 2 photons. This is realized by using the interaction of laser photons with the virtual photons of a magnetic field to produce axions which are subsequently detected

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through a measurable rotation of the polarization of the laser light as originally proposed by Maiani, Petronzio, and Zavattini.[5] For a pseudoscalar particle such as the axion, the interaction is described in the Lagrangian by $L = g_{a\gamma\gamma} E \cdot B \phi_a$ where $g_{a\gamma\gamma}$ is the strength of the pseudoscalar coupling to 2 photons, E and B, the laser electric field and the external magnetic field respectively, and ϕ_a the strength of the pseudoscalar field. If the photon energy ω exceeds the mass of the pseudoscalar, axion production implies that energy is removed from the component of the laser photon field polarized parallel to the magnetic field. The reduction in the amplitude of that component results in a small rotation of the polarization. The coherent transfer of energy to the axion field and back can occur even if $m_a > \omega$ which implies a phase lag of the parallel component resulting in an induced ellipticity of the laser light polarization. Following Raffelt & Stodolsky,[8] in the weak coupling case the rotation angle for $m_a^2 \ell^2 / 3 \ll 4\omega$ is $\epsilon = N g_{a\gamma\gamma}^2 B^2 \frac{\ell^2}{16} \sin 2\theta$ and the induced ellipticity is given by $\psi = N g_{a\gamma\gamma}^2 B^2 \frac{m_a \ell^3}{96\omega} \sin 2\theta$, ℓ is the magnetic field length, N is the number of times the light passes through the magnetic field region and θ is the angle between the light polarization direction and the magnetic field B.

Figure 1 indicates the arrangement of the experimental elements. The photon source, a Coherent INNOVA 90-5 Argon ion laser operates at a wave length of 514.5 nm with vertical polarization at a power level of 2 watts. The half wave plate rotates the polarization 45° where it is then polarized with high precision by a Glan-Thompson polarizer before entering a 12 meter optical cavity of which 8.8 meters were covered by the magnetic fields of 2 superconducting dipole magnets. The laser beam traversed the cavity some 500 times between the 2 high reflectivity mirrors of the cavity before exiting through the hole in the first mirror through which it entered. The polarization direction of the exiting light was then modulated by a Faraday cell consisting of a cylinder of BK7 glass inside a coil driven 260 Hz. The light then passed through a second high precision polarizer which was set for maximum extinction before being detected by a photodiode whose output signal was amplified and then Fourier analyzed by Hewlett-Packard fast Fourier transform analyzer.

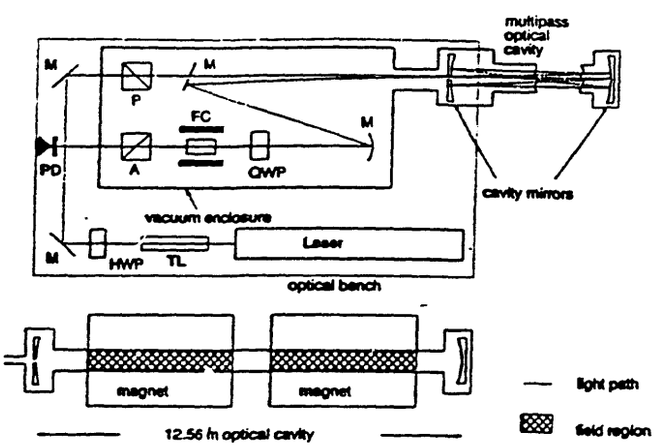

FIG. 1. Schematic diagram of the apparatus and optical path. A: analyzer; FC: Faraday cell; HWP: half-wave plate; M: mirror; P: polarizer; PD: photodiode; QWP: quarter-wave plate; and TL: telescope.

The use of the second polarizer which produced extinctions of approximately 10^{-8} transforms the measurement of polarization rotation into a null measurement and the modulation of this signal with the Faraday cell allows one to greatly improve the signal to noise by then modulating the magnetic field from 2.7T to 4T at a frequency of 32 mHz and searching for a signal within the narrow band width of the beat frequency.

Rotation data is shown in Fig. 2. Zero frequency corresponds to the 260 Hz carrier frequency of the Faraday cell. Calibration data is

based on the birefrigence of gasses in a magnetic field, which is known Cotton-Mouton effect. The high sensitivity achieved has led to the first detection and measurement of the Cotton-Mouton effect in He.[7]

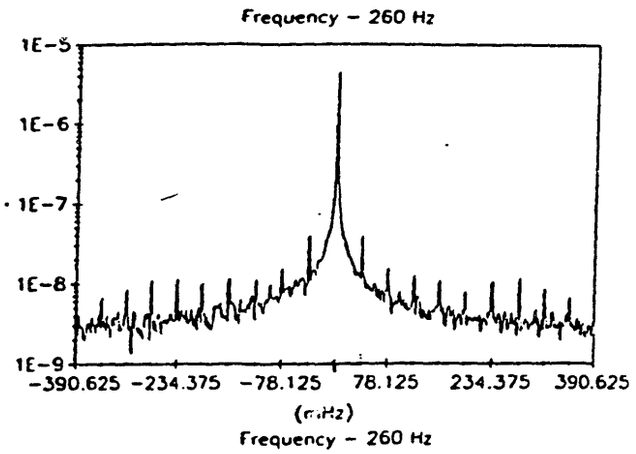

FIG. 2. Rotation data at a vacuum of 3.5×10^{-6} Torr.

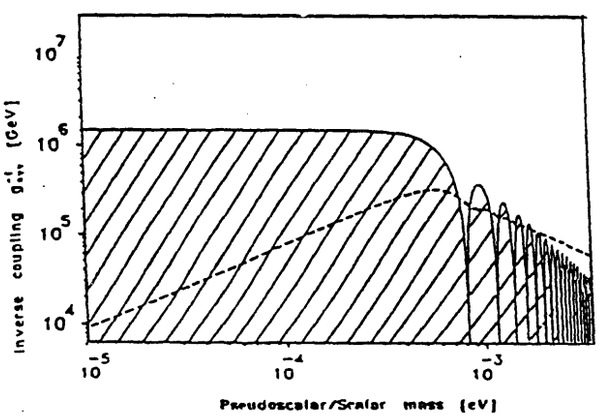

FIG. 3. Excluded regions for inverse coupling vs pseudoscalar mass. The shaded region is from the limit of the rotation data; the region bounded by the dashed curve from the limit on the ellipticity data.

Unfortunately this extraordinary sensitivity has also enabled us to observe signal peaks in vacuum. By exploiting the signal dependence on polarization direction with respect to the magnetic field for pseudoscalar or scalar production we were able to demonstrate that they were instrumental in origin and serial in appearance as the sensitivity improved.

Our present limits on the rotation angle and ellipticity are 1.0 x 10^{-8} rad and 1.74 x 10^{-9} respectively which imply an upper limit on the coupling of $g_{a\gamma\gamma}$ = 6.67 x 10^{-7} GeV^{-1}. The region of the inverse coupling vs pseudoscalar mass plane excluded by this experiment is presented in Fig. 3.

Progress in overcoming spurious signals and noise background is rapid. If it is possible to reach a level where the experiment is limited by 1/f noise, it may be possible to achieve an order of magnitude improvement in sensitivity by using high field magnets based on ultra-pure aluminum rather than superconducting coils where magnetic field ramp rates of 4T/sec have been achieved in model magnets.[8]

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