PROCEEDINGS OF SCIENCE

Axion Polarimeteric Experiment (APE)

Qazal Rokn,[a,*] **Laura Roberts,**[a] **Aldo Ejlli**[a] **and Guido Mueller**[a,b]

[a] *Max–Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and Leibniz Universität Hannover, Hannover, Germany*

[b] *Department of Physics, University of Florida Gainesville, USA*

E-mail: Qazal.rokn@aei.mpg.de

The interaction of axions and axion-like particles with photons would induce a time-varying rotation of the polarization of linearly polarized laser light. This paper presents a highly sensitive setup for detecting the polarization rotation using a polarimetric setup with two quarter-wave plates inside a Fabry-Pérot cavity. This configuration allows exploration of a previously untested region in the parameter space, covering coupling constants in the range of $(5 \cdot 10^{-13}$ - $10^{-11})$ GeV^{-1} and axion masses from $(10^{-16}$-$10^{-12})$ eV.

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1. Theoretical Background

Axions and axion-like particles (ALPs) are modeled as oscillating classical fields, represented by the sinusoidal function [1]:

$$a(t) = a_0 \sin(\omega_a t + \delta(t)), \tag{1}$$

where $\omega_a = \frac{m_a c^2}{\hbar}$ is the angular frequency, and $a_0 = \frac{\hbar\sqrt{2\rho_{local}}}{m_a}$ is the field amplitude, which depends on the local dark matter density ρ_{local} and the axion mass m_a. The interaction of axions and photons induces a change in the polarization of light. Here, the polarization angle, denoted by β, represents a rotation of the linear polarization and its first-order approximation for small time intervals $\tau \ll \frac{1}{\omega_a}$ is given by [2]:

$$\beta(\omega_a, \tau, t) \approx g_{a\gamma\gamma} a_0 \omega_a \tau \sin(\omega_a t). \tag{2}$$

2. Experimental Setup

In this section, we outline a method to detect axion-induced polarization changes in linearly polarized light. First, as shown in Fig 1, p-polarized monochromatic laser light enters a Fabry-Pérot cavity through a polarizer. At the frequency of axion field ν_a, a part of the p-polarized component converts within the cavity into an s-polarized component ($\mathbf{E}_a$). The axion-induced signal would cancel out after a round trip in an empty cavity. Two quarter-wave plates (QWPs) will be added into the cavity in order to prevent this [2]. With every pass, these QWPs induce a $\pi/2$ phase shift between the p- and s-polarized components, which leads to the accumulation of axion-induced s-polarization inside the cavity and resulting in an elliptical polarization state at the cavity exit.

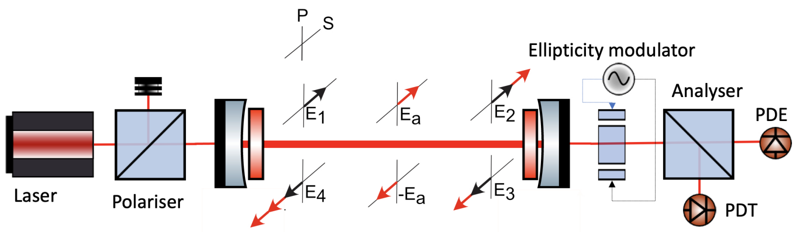


Figure 1: The polarimetry method with QWPs inserted into the cavity. The s-polarized field accumulation is represented by the field vectors at the left (input) ($\mathbf{E}_1$, $\mathbf{E}_4$) and right (output) ($\mathbf{E}_2$, $\mathbf{E}_3$) couplers. The axion-induced signal is modulated and detected by a photodiode (PDE).

The intensity of the signal at the extinguished port is proportional to the square of the rotation angle $\beta(t)$, which makes detection challenging. Using heterodyne detection, we modulate the ellipticity with a photoelastic modulator (PEM), $\eta = \eta_0 \cos(2\pi\nu_{PEM} t)$, and detect the signal via a photodetector. The relative intensity at the extinguished port is:

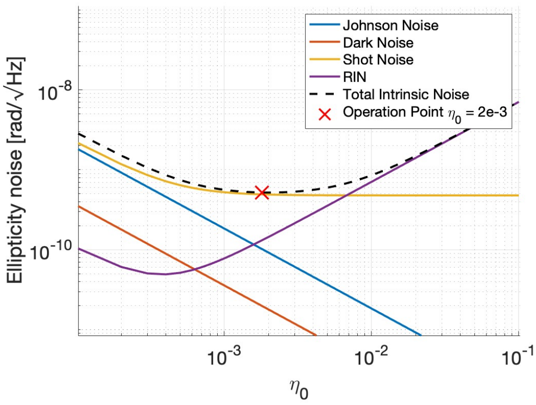
$$\frac{I^{ext}}{I_0}(\beta) \approx \sigma^2 + \eta^2 - \left(\frac{1+R}{1-R}\right)\eta\frac{\beta}{2} + O[\beta^2]. \tag{3}$$

By demodulating the signal, the magnitude of $|\beta(\nu)|$ can be estimated as:

$$|\beta(\nu)| = \frac{I^{\text{ext}}_{@\nu_{\text{PEM}}}}{N h_T(\nu) I_0 \eta_0}. \tag{4}$$

3. Analysis of Noise Sources and Sensitivity Calculation

The several noise sources that impact the polarimetry experiment are identified in this section. These sources include shot noise, Johnson noise, dark current noise, relative intensity noise (RIN), and seismic noise. The total ellipticity noise is the quadrature sum of these components and is dominated by shot and seismic noise at the operation point of $\eta_0 = 2 \times 10^{-3}$. Fig 2 shows the variations in ellipticity noise with respect to the modulation depth (η_0) of the PEM and the table contains the polarimeter parameters.



Cavity output power	I_0	1 W
PD Responsivity	q	0.7 A/W
PD gain	G_{PD}	10^6 Ω
Extinction ratio	σ^2	10^{-7}
Dark noise	i_{Dark}	25 $\text{fA}_{\text{rms}}/\sqrt{\text{Hz}}$
PEM modulation depth	η_0	2×10^{-3}
Modulation frequency	ν_{PEM}	50 kHz
RIN	$\text{RIN}_{@\nu_{\text{PEM}}}$	$3 \times 10^{-7}/\sqrt{\text{Hz}}$
Number of trips inside the cavity	N	13,000
Temperature	T	300 K

Figure 2: Ellipticity noises as a function of the modulation depth (η_0) of the PEM. The parameters for the polarimeter are listed in the accompanying table.

4. Sensitivity to Axion

The total noise and the cavity losses determine the sensitivity to axion and ALPs. The transmittance of the mirrors designed to be $T_2 = 50\,\text{ppm}$ (input mirror) and $T_1 = 150\,\text{ppm}$ (output mirror), the total losses from the QWP and mirrors are assumed to be around 100 ppm. The following represents the sensitivity to the axion-photon coupling constant:

$$g_{a\gamma} = \frac{s_\beta^{\text{tot}}}{2\tau}\sqrt{\frac{(l_{\text{tot}} + T_2 + T_1)^2 + 4\sin^2(\pi\nu_a\tau)}{2\rho_{\text{local}}}} \tag{5}$$

where τ is the cavity round-trip travel time and ρ_{local} is the local axion density.

5. Conclusion

The presented experimental setup has the potential to surpass the performance of existing experiments for direct ALPs search, such as CAST, with sensitivity in the mass range of (10^{-15}

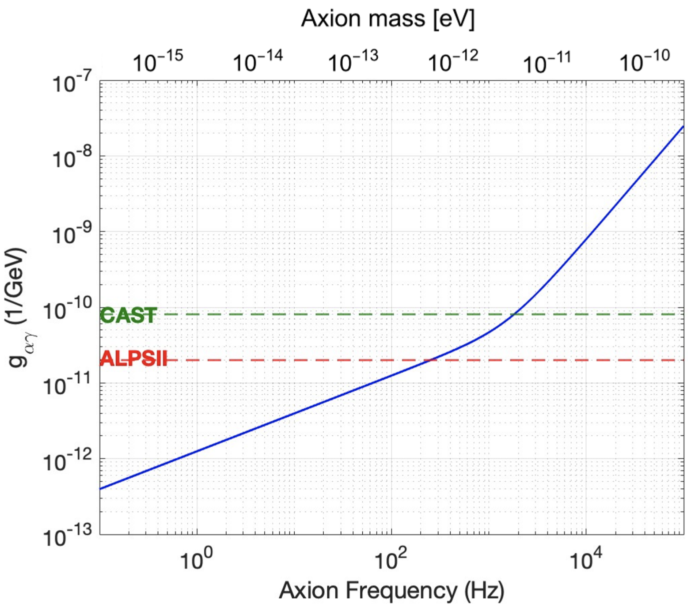


Figure 3: The sensitivity of the experiment to the axion-photon coupling coefficient, with time integration up to the ALPs coherence time $t_{\text{int}} = \frac{10^6}{\nu_a}$(shown by the blue solid line), was evaluated using a polarimetry setup with two quarter-wave plates in a 1.5-meter cavity, limited by shot noise. The parameters used for this plot include a total loss factor of $l_{\text{tot}} = 100$ ppm and a number of trips inside the cavity N= 13,000. For comparison, the current sensitivity of CAST (green) [3] and the design sensitivity for ALPS II (red) [4] are also shown.

-10^{-12}) eV, corresponding to an ALPs frequency range of (1-10) kHz. This setup is currently being constructed at the Max Planck Institute for Gravitational Physics in Hannover, Germany. Further improvements in sensitivity can be achieved by extending the cavity length, leading to an enhancement in signal detection proportional to the cavity length.

Acknowledgment

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