Optical Ring Cavity Search for Axion Dark Matter

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We propose a novel experiment to search for axion dark matter which differentiates the phase velocities of the left and right-handed polarized photons. Our optical cavity measures the difference of the resonant frequencies between two circular-polarizations of the laser beam. The design of our cavity adopts double-pass configuration to realize a null experiment and give a high common mode rejection of environmental disturbances. We estimate the potential sensitivity to the axion-photon coupling constant $g_{a\gamma}$ for the axion mass $m \lesssim 10^{-10}$ eV. In a low mass range $m \lesssim 10^{-15}$ eV, we can achieve $g_{a\gamma} \lesssim 3 \times 10^{-16}$ GeV$^{-1}$ which is beyond the current bound by several orders of magnitude.

I. INTRODUCTION

Axion is one of the most known particles in the extended theories beyond the standard model of particle physics. It was originally introduced by Peccei and Quinn to solve the strong CP problem in QCD [1]. Moreover, string theory and supergravity generically predict a plethora of particles (ALPs) which can have a broad range of the mass [2]. Especially, the axion with a small mass $m \ll 1$ eV is well motivated by cosmology, since it behaves as a non-relativistic matter fluid in our universe and is a good candidate for dark matter. Axion dark matter may weakly interact with known standard model particles, so that we can explore axion dark matter through the direct search experiments.

It has been known that if axion is coupled to photon, the axion-photon conversion under static magnetic fields takes place [3]. Making use of this conversion process, many different types of experiments have been considered such as axion haloscopes [4], axion helioscopes [5, 6], “light shining through a wall” experiments [7, 8] and magnetometers [9, 10] (for more details, see recent reviews [11] and references therein). They put the constraints on the photon-axion coupling constant $g_{a\gamma}$ for a vast range of the ALPs mass. Astronomical observations can be also used to limit the axion-photon conversion. For the low mass range, the absence of gamma-ray emission from SN1987A [12, 13] and the spectral of cosmic rays from galaxy clusters [14, 15] are discussed to put significant bounds on $g_{a\gamma}$.

Here, we propose another way to find the coupling of photon to axion dark matter without using the axion-photon conversion. The dark matter axion whose field value oscillates around the minimum of its potential provides a small difference in the phase velocity between the left-handed and the right-handed photon. Optical cavity is useful to detect such a small deviation of the phase velocity. The authors in [16] recently suggested a experiment with a Michelson interferometer. On the other hand, ring cavity experiments have emerged to test the parity-odd Lorentz violation in the photon sector [18]. They have measured the variation of the resonant frequency depending on the direction of the light path. Similar technique can be applied for our purpose, because the resonant frequency of the cavity shifts depends on the polarization of photon, provided that the dark matter axion is coupled to photon. The dark matter axion predicts the phase velocities of the left and right-handed polarized photon shift with the opposite signs and the same magnitude. Therefore such shifts of the resonant frequencies of the polarized laser in the optical cavity are the measurement target in our experiment. We estimate the reach of our cavity experiment and obtain the potential sensitivity.

This paper is organized as follows. In Section 2, we derive the difference in the phase velocity of polarized photons in the presence of axion dark matter and estimate its magnitude. In Section 3, we describe the experimental method to probe the axion-photon coupling with our designed cavity. In Section 4, we show the potential sensitivity of our experiment and give a short discussion. Finally, we conclude the result of this work in Section 5.

In this paper, we set the unit $\hbar = c = 1$.

II. PHASE VELOCITIES OF PHOTONS

In this section, we present the equations of motions (EoMs) for two circular-polarized photons coupled with the axion dark matter and estimate their phase velocities. We consider the axion-photon coupling term

$$\frac{g_{a\gamma}}{4} A F_{\mu \nu} \tilde{F}^{\mu \nu} = g_{a\gamma} A_{\mu} \epsilon_{ijk} \partial_j A_k + \text{(total derivative)}, \quad (1)$$

where dots denotes the time derivative, $a(t)$ is the axion field value, $A_{\mu}$ is the vector potential, $F_{\mu \nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$ and $\tilde{F}_{\mu \nu} \equiv \epsilon_{\mu \nu \rho \sigma} \partial_\rho A_\sigma / (2\sqrt{-g})$. Here, we choose the temporal gauge $A_0 = 0$ and the Coulomb gauge $\nabla \cdot A = 0$. Then the EoM for gauge field reads

$$\dot{A}_i - \nabla^2 A_i + g_{a\gamma} \dot{a} \epsilon_{ijk} \partial_j A_k = 0. \quad (2)$$

The present background axion field is written as

$$a(t) = a_0 \cos(m t + \delta_a(t)). \quad (3)$$
with its constant amplitude $a_0$, its mass $m$ and a phase factor $\delta_\tau(t)$. In this experiment, we search for the axion dark matter with the mass $m \lesssim 10^{-10}$ eV and the corresponding frequency is given by

$$m \simeq 7 \text{ Hz} \left( \frac{m}{10^{-10} \text{ eV}} \right).$$

(4)

The phase factor $\delta_\tau$ can be assumed to be a constant value within the coherence timescale of dark matter $\tau$.

We decompose $A_i$ into two helicity modes with wave number $k$:

$$A_i(t, x) = \sum_{\lambda = \pm} \int \frac{d^3k}{(2\pi)^3} A_i^\lambda(t) e^{i\lambda(x)} e^{ik \cdot x},$$

(5)

where $e^{i\lambda(x)} e^{i\lambda(x)} = \delta^{\lambda\lambda}$ and $e^{i\lambda(x)} e^{i\lambda(x)}(k) = \pm i k e^{i\lambda(x)}$. Then one finds EoMs for the two polarization modes as

$$\ddot{A}_k^\pm + \omega_\pm^2 A_k^\pm = 0,$$

(6)

with

$$\omega_\pm^2 = k^2 \left( 1 \pm \frac{g_{a\gamma} a_0 m}{k} \sin(mt + \delta_\tau) \right).$$

(7)

From (6), we obtain their phase velocities as

$$c_\pm = \frac{\omega_\pm}{k} = \left( 1 \pm \frac{g_{a\gamma} a_0 m}{k} \sin(mt + \delta_\tau) \right)^{1/2},$$

(8)

and define their difference as $\delta c \equiv |c_+ - c_-|$. The tiny coupling $g_{a\gamma}$ allows us to approximate $\delta c$ by

$$\delta c \simeq \frac{g_{a\gamma} a_0 m}{k} \sin(mt + \delta_\tau) \equiv \delta c_0 \sin(mt + \delta_\tau).$$

(9)

Assuming the laser light with the wavelength $\lambda = 2\pi/k = 1550$ nm, we can estimate

$$\delta c_0 \simeq 3 \times 10^{-24} \left( \frac{g_{a\gamma}}{10^{-12} \text{ GeV}^{-1}} \right).$$

(10)

where we used the present energy density of the axion dark matter, $\rho_a = m^2 a_0^2/2 \approx 0.3$ GeV/cm$^3$.

III. SEARCH FOR AXION DARK MATTER USING OPTICAL RING CAVITY

In this section, we describe our experiment to detect $\delta c$ caused by the axion dark matter. The set up of our experiment is schematically illustrated in Figure 1. First, a laser beam which is circularly polarized by a 1/4 waveplate enters our bow-tie cavity. For the illustrative purpose, let us assume the incident beam has the left-handed polarization. The incident beam to the cavity is partially reflected by the input mirror and goes to the photodetector A, while the other part enters the cavity. Since the reflection off of a mirror flips the circular-polarization of photon, the beam changes its polarization each time it is reflected by a mirror. It should be noted that the beam that enters the cavity from the left has the right-handed polarization most of the time, because the bow-tie optical path is stretched in the longitudinal direction. It eventually goes to either the photodetector A or the mirror on the far right. The beam which is reflected from the mirror on the far right is partially reflected into the photodetector B or re-enters the cavity. Then it has the left-handed polarization most of the time while traveling inside the cavity in the opposite direction. Finally some part of the beam goes into the photodetector B.

From each photodetector, we can obtain the signal which is proportional to the frequency difference between the laser frequency and the cavity resonant frequency using, for example, Pound-Drever-Hall method [19]. Using this error signal taken by the photodetector A, the incident laser frequency is stabilized to the resonance of the (almost) right-handed polarized beam. We can also obtain the second error signal from the photodetector B, which is proportional to the resonant frequency difference between (almost) left-handed and right-handed beams. Without the phase velocity modulation $\delta c$ given by the axion dark matter, the resonant frequency would not depend on the circular-polarizations. Therefore our setup works as a null-experiment sensitive to the axion-photon coupling.

The bow-tie configuration of our optical cavity can-
els the Sagnac effect from, for example, the spin of Earth [20]. Most of the environmental noises are also cancelled due to the double-pass configuration [21], because the second error signal observes only the difference in the resonant frequency between the two counter-propagating optical paths in the cavity and their common fluctuations become irrelevant. The difference of the resonant frequencies between the two optical paths is given by

\[ \frac{\delta \nu}{\nu} = \frac{\delta c}{c} = 3 \times 10^{-24} \left( \frac{g_{a\gamma}}{10^{-12} \text{ GeV}^{-1}} \right) \sin(mt + \delta_\tau), \]

and hence the second error signal is expected to be oscillating. This oscillatory behavior is advantageous for the signal extraction.

IV. SENSITIVITY TO THE AXION-PHOTON COUPLING

In this section, we calculate the sensitivity of our experiment to the axion-photon coupling constant. By virtue of the double-pass configuration, most of the noises from the environmental disturbance are in principle cancelled out by the common mode rejection. Then the primary source of noise is the quantum shot noise. One-sided spectrum of the shot noise of an optical ring cavity is written as [22]

\[ \sqrt{S_{\text{shot}}} = \sqrt{\frac{\lambda}{4\pi P} \left( \frac{1}{t^2} + \omega^2 \right)}, \]

where \( \lambda \) is the laser wavelength, \( P \) is the input power, and \( \omega \) is the angular frequency which is the axion mass \( m \) in our case. Note that the quantum radiation pressure noise is cancelled out by our double-pass configuration. Averaged round-trip time \( t_\tau \) is

\[ t_\tau = \frac{L\mathcal{F}}{\pi}, \]

where \( L \) is the cavity round-trip length and \( \mathcal{F} \) is the finesse.

If our measurement is limited by the shot noise, the signal-to-noise ratio (SNR) improves with the measurement time \( T \) as

\[ (\text{SNR}) = \frac{\sqrt{T}}{2\sqrt{S_{\text{shot}}}} \frac{\delta c_0}{c}. \]

Therefore the sensitivity to \( \delta c_0/c \) is limited by

\[ \frac{\delta c_0}{c} \lesssim \begin{cases} \frac{2}{\sqrt{T}} \frac{S_{\text{shot}}}{2} & (T \lesssim \tau) \\ \frac{1}{(T\tau)^{1/4}} \frac{S_{\text{shot}}}{2} & (T \gtrsim \tau) \end{cases}. \]

It can be translated into the sensitivity to \( g_{a\gamma} \) as

\[ g_{a\gamma} \lesssim \begin{cases} \frac{10^{12} \sqrt{S_{\text{shot}}}}{T} [1/\text{GeV}] & (T \lesssim \tau) \\ \frac{10^{12} S_{\text{shot}}^{1/2}}{(T\tau)^{1/2}} [1/\text{GeV}] & (T \gtrsim \tau) \end{cases}. \]

Figure 2 shows the sensitivity of our experiment to the axion-photon coupling constant for different configurations. Here we set \( \lambda = 1550 \text{ nm} \) and assumed \( T = 1 \text{ year} = 3 \times 10^7 \text{ sec} \). With feasible parameters we can achieve a sensitivity level \( g_{a\gamma} \approx 3 \times 10^{-13} \text{ GeV}^{-1} \) for \( m \lesssim 10^{-16} \text{ eV} \), which is below the current constraints from axion helioscope experiments, SN1987A and Chandra X-ray observations. Moreover, with more optimistic
parameters, our cavity can reach $g_a \gamma \approx 3 \times 10^{-16} \text{ GeV}^{-1}$ for $m \lesssim 10^{-16} \text{ eV}$ which will be the best sensitivity among the proposed axion search experiments in this mass range.

We note here that the technical noises at low frequency should be further investigated to determine the sensitivity for lower mass range of the axion, $m \lesssim 10^{-17} \text{ eV}$. Also, it would be interesting to consider an optical cavity which is sensitive to the axion-photon coupling at higher frequencies, because our cavity does not have much sensitivity at larger mass region $m \gtrsim 10^{-10} \text{ eV}$. We leave these issues for future work.

V. CONCLUSION

In this letter, we proposed a novel experiment to probe the coupling of the axion dark matter to photon with a resonant cavity. We consider the double-pass cavity which aims to detect the difference in the resonant frequencies of the laser beam with the two circular-polarizations. Due to the oscillation of the axion dark matter, the resonant frequencies are expected to periodically change in time and we can extract the signal from the irreducible noises. The sensitivity curve is in principle determined only by quantum shot noise by virtue of the double-pass configuration and hence we can achieve the great sensitivity level for the detection of the axion-photon coupling constant. In the concrete estimation of the sensitivity, we adopted two sets of parameters, feasible one and optimistic one. We have demonstrated that both of them can reach sensitivities beyond the current constraints by several orders of magnitude.

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