

DARK MATTER AXION SEARCH WITH RING CAVITY EXPERIMENT DANCE: CURRENT SENSITIVITY

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Dark matter Axion search with riNg Cavity Experiment (DANCE) was proposed. To search for axion-like particles, we aim to detect the rotation and oscillation of optical linear polarization caused by axion-photon coupling with a bow-tie cavity. DANCE can improve the sensitivity to axion-photon coupling constant $g_{a\gamma}$ for axion mass $m_a < 10^{-10}$ eV by several orders of magnitude compared to the best upper limits at present. A prototype experiment DANCE Act-1 is in progress to demonstrate the feasibility of the method and to investigate technical noises. We assembled the optics, evaluated the performance of the cavity, and estimated the current sensitivity. If we observe for a year, we can reach $g_{a\gamma} \simeq 9 \times 10^{-7} \text{ GeV}^{-1}$ at $m_a \simeq 10^{-13}$ eV. The current sensitivity was believed to be limited by laser intensity noise at low frequencies and by mechanical vibration at high frequencies.

1 Introduction

Axions are pseudo-scalar fields originally proposed to solve the strong CP problem in QCD physics. Moreover, string theory and supergravity generically predict a plenitude of axion-like particles. Hereafter we collectively call them “axions”. Axions are one of the well-motivated candidates for dark matter since axions typically have a small mass $m_a \ll \text{eV}$ and behave like non-relativistic classical wave fields in the present universe. High energy physics predicts that axions may weakly interact with photons¹.

A small coupling between axions and photons provides a good chance to detect axions through direct search experiments by using well-developed photonics technology. Recently, several novel methods were proposed to observe axion-photon coupling using carefully designed optical cavities^{2 3 4 5 6}. These laser interferometric searches can be done without a strong magnetic field, and have good sensitivity in the low mass region. In this paper, we review our Dark matter Axion search with riNg Cavity Experiment (DANCE) proposal, and report the current sensitivity of the prototype experiment, DANCE Act-1.

2 Principle of DANCE

The axion-photon interaction gives a phase velocity difference between left- and right-handed circularly polarized light¹. The phase velocity difference $\delta c = |c_L - c_R| = \delta c_0 \sin(m_a t + \delta_\tau(t))$ with axion mass m_a and a phase factor $\delta_\tau(t)$ for a wavelength of light $\lambda = 2\pi/k$ is estimated to be

$$\delta c_0 = \frac{g_{a\gamma} a_0 m_a}{k} = 1.8 \times 10^{-24} \left(\frac{\lambda}{1064 \text{ nm}} \right) \left(\frac{g_{a\gamma}}{10^{-12} \text{ GeV}} \right). \quad (1)$$

Here, we assumed axion energy density equals local dark matter density, $\rho_a = m_a^2 a_0^2 / 2 \simeq 0.3 \text{ GeV/cm}^3$.

This phase difference between circular polarizations is equivalent to a rotation of linearly polarized light¹. Small signal sidebands are generated as a linearly polarized laser propagates in the presence of axions⁴. Optical path length can be effectively increased using an optical cavity and the amplitude of the sidebands is enhanced for detection. The polarization flip upon mirror reflection have to be taken into account when designing the optical cavities. A bow-tie ring cavity is proposed to prevent the linear polarization from inverting since the laser beam is reflected twice at both ends³.

The fundamental noise source of DANCE would be quantum shot noise. The one-sided amplitude spectral density of the shot noise is given by

$$\sqrt{S_{\text{shot}}(\omega)} = \sqrt{\frac{\hbar \lambda}{4\pi c P_{\text{trans}}} \left(\frac{1}{t_c^2} + \omega^2 \right)}, \quad (2)$$

where ω is the fourier angular frequency and P_{trans} is the transmitted laser power. The averaged storage time of the cavity t_c is given by $t_c = L\mathcal{F}/(\pi c)$, where L is the cavity round-trip length and \mathcal{F} is the finesse. Assuming $L = 10 \text{ m}$, $\mathcal{F} = 10^6$, and $P_{\text{trans}} = 100 \text{ W}$, we can reach $g_{a\gamma} \simeq 3 \times 10^{-16} \text{ GeV}^{-1}$ for $m_a < 10^{-16} \text{ eV}$ (see purple dotted line in Figure 2). Here, we set $\lambda = 1064 \text{ nm}$ and the integration time $T = 1 \text{ year}$. Simultaneous resonance of both carrier and sidebands beams is also important for good sensitivity at low frequencies.

3 Experimental Setups of DANCE Act-1

Figure 1 (left) shows the schematic of DANCE Act-1. The S-polarized beam (the carrier in this work) was fed into the bow-tie cavity, and the laser frequency was locked to the resonance by the Pound-Drever-Hall technique. Polarization of transmitted light was rotated with a half-wave plate (HWP) to introduce some P-polarization (the sidebands in this work), and then split into S- and P-polarization with a polarizing beam splitter (PBS). P-polarization can be measured with a photodetector (PD), and in this signal we can search for axions. The amount of S-polarization was also recorded with a PD in order to calibrate the signal.

A photo of the experimental setup of DANCE Act-1 is shown in Figure 1 (right). The optical table was surrounded by aluminum plates to stabilize frequency by reducing air turbulence and shield the optical setup from external light. The bow-tie cavity was constructed from four mirrors rigidly fixed on a spacer made of aluminum.

4 Results and Discussion of DANCE Act-1

We evaluated the performance of the bow-tie cavity by modulating the laser frequency and taking the cavity scan of transmitted light (see Table 1). Measured values of round-trip length and finesse for S-polarization were consistent with designed values. Current injected laser power was lower than designed power because we used a laser source with maximum power of 500 mW. Transmitted laser power was lower than injected power due to loss of light in the cavity. Measured resonant frequencies for two polarizations were different because S- and P-polarization

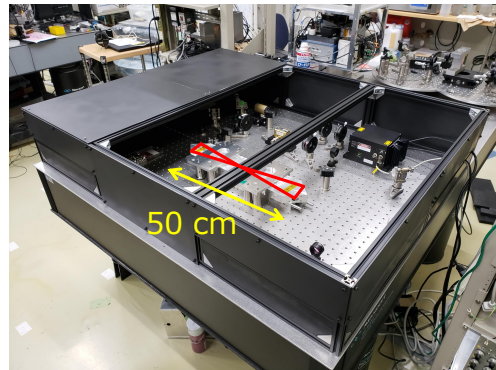
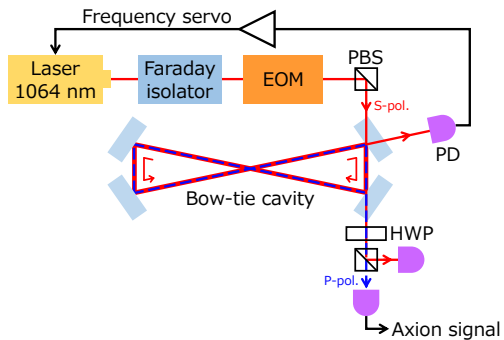


Figure 1 – The schematic of DANCE Act-1 (left), and a picture of DANCE Act-1 (right). S-polarized (P-polarized) beam is drawn as red (blue) lines. EOM: electro-optic modulator. PBS: polarizing beam splitter. PD: photodetector. HWP: half-wave plate.

Table 1: Summary of the performance evaluation of the bow-tie cavity.

	Designed values	Measured values
Round-trip length L	99.4 cm	97.1(4.5) cm
Injected laser power	1 W	274(14) mW
Transmitted laser power P_{trans}	1 W	158(8) mW
Finesse for S-polarization (carrier) \mathcal{F}_{car}	3×10^3	$2.80(34) \times 10^3$
Finesse for P-polarization (sidebands) $\mathcal{F}_{\text{side}}$	3×10^3	193(10)
Resonant frequency difference between polarizations δ_{res}	0 Hz	3.92(16) MHz

obtained non-zero phase shift from mirror coating layers at mirror reflections with non-zero incident angle. Measured finesse for P-polarization was smaller than the designed finesse because the mirrors had lower reflectivity for P-polarization. This was not an issue in this work since the sensitivity in low mass region gets better with smaller finesse for P-polarization when resonant frequency difference between polarizations is non-zero.

The amount of P-polarization $P_P(t)$ was measured for 50 minutes with a PD and calibrated to the rotation angle of linear polarization $\phi(t)$ by

$$\phi(t) = \sqrt{\frac{P_P(t)}{P_{\text{tot}}}} - 2\theta, \quad (3)$$

where P_{tot} is the averaged total amount of transmitted light and θ is the fixed angle of a HWP. Then, the spectrum of the rotation angle of linear polarization and the current estimated sensitivity were calculated. If we observe for a year, we can reach $g_{a\gamma} \simeq 9 \times 10^{-7} \text{ GeV}^{-1}$ at $m_a \simeq 10^{-13} \text{ eV}$ (see red solid line in Figure 2). Rotation angle of linear polarization in 0.1 Hz - 1 Hz correlated significantly with injected laser power, therefore the current sensitivity was believed to be limited by laser intensity noise. Whereas, rotation angle of linear polarization in 30 Hz - 5 kHz correlated significantly with error signal for frequency servo, therefore the current sensitivity was believed to be limited by mechanical vibration.

5 Conclusion

A new table-top experiment, DANCE, was proposed to search for axion dark matter with an optical cavity. We aim to detect the rotation and oscillation of a linear polarization caused by axion-photon coupling with a bow-tie cavity. DANCE can improve the sensitivity beyond the current bounds of axion-photon coupling constant $g_{a\gamma}$ for axion mass $m_a < 10^{-10} \text{ eV}$ by several

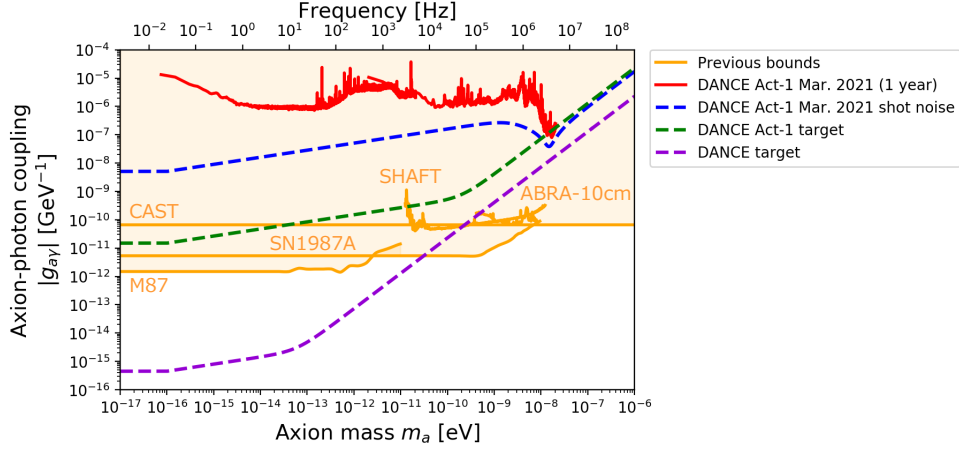


Figure 2 – The sensitivity curves for the axion-photon coupling constant $g_{a\gamma}$. The orange solid lines with shaded region are current bounds obtained from CAST⁷, SHAFT⁸, and ABRACADABRA-10cm⁹ experiments, and the astrophysical constraints from the gamma-ray observations of SN1987A¹⁰ and the X-ray observations of M87 galaxy¹¹. The red solid line shows the current estimated sensitivity of DANCE Act-1 if we observe for a year. The dotted lines represent the expected shot noise limited sensitivity of DANCE Act-1 with current setup parameters (blue; the cavity round-trip length of $L = 1$ m, transmitted laser power of $P_{\text{trans}} = 158$ mW, finesse for carrier (S-polarization in this work) of $\mathcal{F}_{\text{car}} = 2.80 \times 10^3$, finesse for sidebands (P-polarization in this work) of $\mathcal{F}_{\text{side}} = 193$, and resonant frequency difference between polarizations of $\delta_{\text{res}} = 3.92$ MHz), DANCE Act-1 target (green; $L = 1$ m, $P_{\text{trans}} = 1$ W, $\mathcal{F}_{\text{car}} = \mathcal{F}_{\text{side}} = 3 \times 10^3$, and $\delta_{\text{res}} = 0$ Hz), and DANCE target (purple; $L = 10$ m, $P_{\text{trans}} = 100$ W, $\mathcal{F}_{\text{car}} = \mathcal{F}_{\text{side}} = 10^6$, and $\delta_{\text{res}} = 0$ Hz) with one-year integration time.

orders of magnitude. A prototype experiment DANCE Act-1 is underway to demonstrate the feasibility of the method. We finished the assembly of the optics, the performance evaluation of the cavity, and the estimation of the current sensitivity. If we observe for a year, we can reach $g_{a\gamma} \simeq 9 \times 10^{-7} \text{ GeV}^{-1}$ at $m_a \simeq 10^{-13} \text{ eV}$. The current sensitivity was believed to be limited by laser intensity noise at low frequencies and by mechanical vibration at high frequencies.

We plan to observe for a week and analyze the data in May 2021. Furthermore, we plan to build a new setup to improve the sensitivity by injecting higher input laser power and by canceling out resonant frequency difference between polarizations with an auxiliary cavity⁶.

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