Journal of Physics: Conference Series **2156** (2022) 012042 doi:10.1088/1742-6596/2156/1/012042

First observation and analysis of DANCE: Dark matter Axion search with riNg Cavity Experiment

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Abstract. Dark matter Axion search with riNg Cavity Experiment (DANCE) was proposed to search for axion dark matter [*Phys. Rev. Lett.* **121**, 161301 (2018)]. 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 ongoing to demonstrate the feasibility of the method and to investigate technical noises. The optics was assembled and the performance of the cavity was evaluated. The first 12-day observation was successfully performed in May 2021. We reached 3×10^{-6} rad/$\sqrt{\mathrm{Hz}}$ at 10 Hz in the one-sided amplitude spectral density of the rotation angle of linear polarization.

1. Introduction

Various experiments and observations have been performed to search for dark matter, but dark matter has yet to be detected. Axions are one of the well-motivated candidates for dark matter since axions behave like non-relativistic classical wave fields in the present universe [1–4]. Axions may weakly interact with photons [5, 6], and this axion-photon coupling 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 [7–12]. These laser interferometric searches can be done without a strong magnetic field, and have good sensitivity in the low mass region $m_a < 10^{-10}$ eV. In this paper, we review the Dark matter Axion search with riNg Cavity Experiment (DANCE) proposal, and report the status of the prototype experiment, DANCE Act-1.

2. Designed sensitivity of DANCE

The axion-photon interaction gives a phase velocity difference between left- and right-handed circularly polarized light [5,6]. The phase velocity difference $\delta c = |c_{\rm L} - c_{\rm R}| = \delta c_0 \sin(m_a t + \delta_\tau(t))$ 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

$$\delta c_0 = \frac{g_{a\gamma} a_0 m_a}{k} \simeq 2.1 \times 10^{-24} \left(\frac{\lambda}{1064\,{\rm nm}}\right) \left(\frac{g_{a\gamma}}{10^{-12}\ {\rm GeV}^{-1}}\right). \quad (1)$$

Here, we assumed axion energy density equals local dark matter density, $\rho_a = m_a^2 a_0^2/2 \simeq 0.4\ {\rm GeV/cm}^3$.

This phase difference between circular polarizations is equivalent to a rotation of linearly polarized light [5]. Small signal sidebands are generated as a linearly polarized laser light propagates in the presence of axions [9]. 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 used to prevent the linear polarization from inverting since the laser beam is reflected twice at both ends (see Figure 2 (a)) [8].

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

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

where ω is the fourier angular frequency and $P_{\rm trans}$ 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. Simultaneous resonance of both carrier and sidebands beams is also important for good sensitivity at low frequencies.

The signal-to-noise ratio improves with the measurement time $T^{1/2}$ as long as the axion oscillation is coherent for $T \lesssim \tau$, where τ is the coherent timescale of axion dark matter. When the measurement time becomes longer than this coherence time $T \gtrsim \tau$, the growth of the signal-to-noise ratio with the measurement time changes as $(T\tau)^{1/4}$.

Assuming $L = 10\,{\rm m}$, $\mathcal{F} = 10^6$, and $P_{\rm trans} = 100\,{\rm W}$, we can reach $g_{a\gamma} \simeq 3 \times 10^{-16}\ {\rm GeV}^{-1}$ for $m_a < 10^{-16}$ eV (see red line in Figure 1). Here, we set $\lambda = 1064\,{\rm nm}$ and the integration time $T = 1$ year.

3. Prototype experiment DANCE Act-1

3.1. Experimental setups

Since April 2019, we are continuing the prototype experiment DANCE Act-1 [18–20]. Figure 2 (a) shows the schematic of DANCE Act-1. The s-polarized beam (the carrier in this work) was fed into the bow-tie cavity by putting a polarizing beam splitter (PBS) and a polarizer in front of the cavity. The laser frequency was locked to the resonance of the bow-tie cavity 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 p- and s-polarization with a Glan laser polarizer (GLP). The amount of p- and s-polarization was recorded with photodetectors PD2 and PD3.

The length between mirrors M1 and M2 as well as M3 and M4 was 45 cm, and that between M2 and M3 as well as M4 and M1 was 4.7 cm. Incident angles at all the four mirrors were 42 deg. Mirrors M1-M4 were custom-made by Layertec. All the four mirrors are concave mirrors with 1 m radius of curvature. The power reflectivity for s-polarization of M1 and M4 was designed to be 99.90(2)% and that of M2 and M3 larger than 99.99%, which results in the designed finesse of 3×10^3. We did not specify the reflectivity for p-polarization.

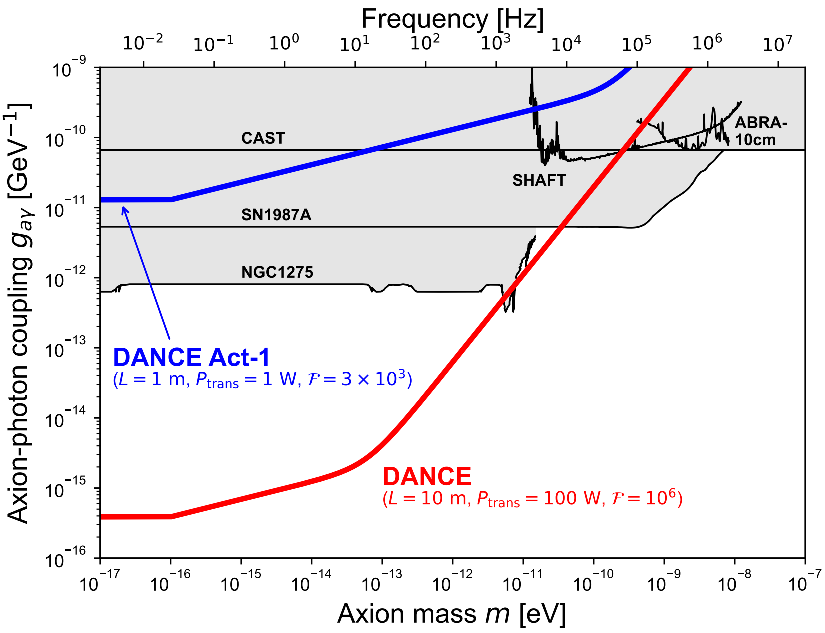

Figure 1. The sensitivity curves for the axion-photon coupling constant $g_{a\gamma}$. The blue (red) lines represent the designed shot noise limited sensitivity of DANCE Act-1 (DANCE) with feasible (optimistic) parameters if we observe for a year. The grey lines with shaded region are current bounds obtained from CAST [13], SHAFT [14], and ABRACADABRA-10cm [15] experiments, and the astrophysical constraints from the gamma-ray observations of SN1987A [16] and the X-ray observations of NGC1275 galaxy [17].

A photo of the experimental setup of DANCE Act-1 is shown in Figure 2 (b). The optical table is surrounded by aluminum plates to stabilize the frequency control by reducing air turbulence and to shield the optical setup from external light. The bow-tie cavity is constructed from four mirrors rigidly fixed on a spacer made of aluminum.

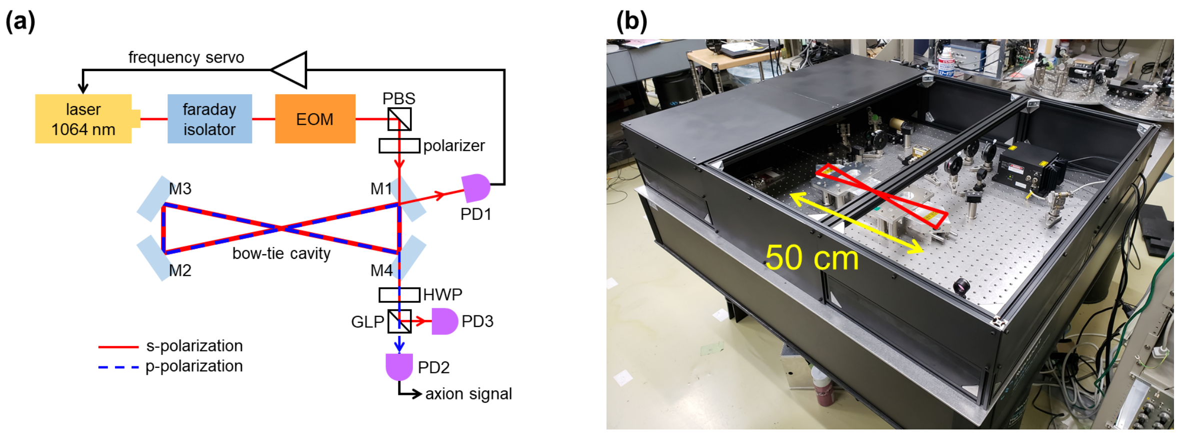

Figure 2. (a) The schematic of DANCE Act-1. S-polarized (p-polarized) beam is drawn as red solid (blue dashed) lines. EOM: electro-optic modulator. PBS: polarizing beam splitter. GLP: Glan laser polarizer. PD: photodetector. HWP: half-wave plate. (b) A picture of DANCE Act-1.

3.2. Performance evaluation of the bow-tie cavity

We evaluated the performance of the bow-tie cavity by modulating the laser frequency and taking the cavity scan of transmitted light. Results are summarized in Table 1. We injected laser power of around 200 mW into the cavity, which is lower than the designed power. Transmitted laser power was lower than injected power due to loss of light in the cavity. Measured finesse for s-polarization was consistent with the designed finesse. Measured resonant frequencies for two polarizations were different because p- and s-polarization obtained a non-zero phase shift from mirror coating layers when reflecting at oblique incident angles. This resonant frequency difference degrades the sensitivity of axion-photon coupling by two orders of magnitude in the low mass region $m_a < 10^{-10}$ eV. Note that smaller finesse for p-polarization is not an issue in this work since the sensitivity in low mass region gets better with smaller finesse for p-polarization when the resonant frequency difference between two polarizations is non-zero.

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

	Designed values	Measured values
Injected laser power	1 W	242(12) mW
Transmitted laser power	1 W	153(8) mW
Finesse for s-polarization (carrier)	$3.2(8) \times 10^3$	$2.85(5) \times 10^3$
Finesse for p-polarization (sidebands)	–	195(3)
Resonant frequency difference between polarizations	0 Hz	2.52(2) MHz

3.3. First observation and sensitivity

The first data was taken for 12 days in May 2021. The amount of p-polarization $P_{\rm p}(t)$ was observed with PD2, and in this signal we can search for axions. The amount of s-polarization was also measured with PD3 for calibration. We calibrate the data to the rotation angle of linear polarization $\phi(t)$ by

$$\phi(t) = \sqrt{\frac{P_{\rm p}(t)}{P_{\rm tot}}} - 2\theta, \tag{3}$$

where $P_{\rm tot}$ is the averaged total amount of transmitted light and θ is the fixed angle of the HWP. The one-sided amplitude spectral density of the rotation angle of linear polarization is plotted in Figure 3 by calculating with 10-hour data. We reached 3×10^{-6} rad/$\sqrt{\rm Hz}$ at 10 Hz.

Rotation angle of linear polarization in 0.1 Hz − 1 Hz correlated significantly with injected laser power, therefore the current sensitivity is believed to be probably 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 seems to be limited by mechanical vibration.

4. Conclusion

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

A prototype experiment DANCE Act-1 is ongoing. The assembly of the optics as well as the performance evaluation of the cavity has been completed. Measured finesse for s-polarization (carrier) was consistent with the designed finesse, while the resonant frequency

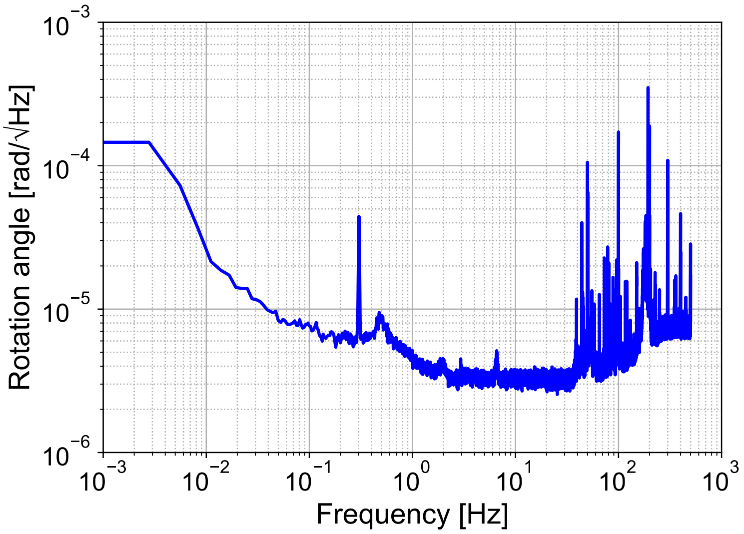

Figure 3. The one-sided amplitude spectral density of the rotation angle of linear polarization.

difference between p- and s-polarizations was non-zero. This leads to the degradation of the sensitivity by two orders of magnitude in the low mass region $m_a < 10^{-10}$ eV. We took the first data for 12 days in May 2021 and the data analysis is underway. We have found candidate peaks for axions, but most of them turned out to be noise peaks. We are working on further veto procedures and calibration to the coupling constant.

Acknowledgments
We would like to thank Shigemi Otsuka and Togo Shimozawa for manufacturing the mechanical parts, and Ching Pin Ooi for editing this paper. This work was supported by JSPS KAKENHI Grant Nos. 18H01224, 20H05850, 20H05854 and 20H05859, and JST PRESTO Grant No. JPMJPR200B.

References

[1] Preskill J, Wise M B and Wilczek F 1983 *Phys. Rev. B* **120**, 127
[2] Abbott L F and Sikivie P 1983 *Phys. Rev. B* **120**, 133
[3] Dine M and Fischler W 1983 *Phys. Rev. B* **120**, 137
[4] Arias P *et al* 2012 *J. Cosmol. Astropart. Phys.* **06**, 013
[5] Carroll S M, Field G B and Jackiw R 1990 *Phys. Rev. D* **41**, 1231
[6] Carroll S M 1998 *Phys. Rev. Lett.* **81**, 3067
[7] DeRocco W and Hook A 2018 *Phys. Rev. D* **98**, 035021
[8] Obata I, Fujita T and Michimura Y 2018 *Phys. Rev. Lett.* **121**, 161301
[9] Liu H, Elwood B D, Evans M and Thaler J 2019 *Phys. Rev. D* **100**, 023548
[10] Nagano K, Fujita T, Michimura Y, Obata I 2019 *Phys. Rev. Lett.* **123**, 111301
[11] Martynov D and Miao H 2020 *Phys. Rev. D* **101**, 095034
[12] Nagano K *et al* 2021 *Phys. Rev. D* **104**, 062008
[13] CAST Collaboration 2017 *Nature Physics* **13**, 584
[14] Gramolin A V *et al* 2021 *Nature Physics* **17**, 79
[15] Salemi C P *et al* 2021 *Phys. Rev. Lett.* **127** 081801.
[16] Payez A *et al* 2015 *J. Cosmol. Astropart. Phys.* **02** 006.
[17] Reynolds C S *et al* 2020 *Astrophys. J.* **890** 59.
[18] Michimura Y *et al* 2020 *J. Phys.: Conf. Ser.* **1468**, 012032
[19] Oshima Y *et al* 2021 arXiv:2105.06252 [hep-ph]
[20] Fujimoto H *et al* 2021 arXiv:2105.08347 [physics.ins-det]