Tokyo Axion Helioscope

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A new search result of the Tokyo axion helioscope is presented. The axion helioscope consists of a dedicated cryogen-free 4T superconducting magnet with an effective length of 2.3 m and PIN photodiodes as x-ray detectors. Solar axions, if exist, would be converted into X-ray photons through the inverse Primakoff process in the magnetic field. Conversion is coherently enhanced even for massive axions by filling the conversion region with helium gas. The present third phase measurement sets a new limit of $g_{a\gamma\gamma} < 5.6\text{–}13.4 \times 10^{-10}\mathrm{GeV}^{-1}$ for the axion mass of $0.84 < m_a < 1.00\,\mathrm{eV}$ at 95% confidence level.

1 Introduction

The existence of axion is implied to solve the so-called strong CP problem [1, 2, 3, 4, 5]. Axions are expected to be produced in solar core through their coupling to photons with energies of order keV, and the so-called 'axion helioscope' technique may enable us to detect such axions directly [6, 7].

The differential flux of solar axions at the Earth is approximated by [8, 9]

$$\begin{aligned} \mathrm{d}\Phi_\mathrm{a}/\mathrm{dE} &= 6.020 \times 10^{10}[\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{keV}^{-1}] \\ &\quad \times \left(\frac{g_{a\gamma\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2 \left(\frac{E}{1\,\mathrm{keV}}\right)^{2.481} \exp\left(-\frac{E}{1.205\,\mathrm{keV}}\right), \end{aligned} \tag{1}$$

where $g_{a\gamma\gamma}$ is the axion-photon coupling constant. Their average energy is 4.2 keV reflecting the core temperature of the sun. Then, they would be coherently converted into X-rays through the inverse process in a strong magnetic field at a laboratory. The conversion rate in a simple case is given by

$$P_{a\to\gamma} = \left(\frac{g_{a\gamma\gamma}B_\perp L}{2}\right)^2 \left[\frac{\sin(qL/2)}{qL/2}\right]^2, \tag{2}$$

where $B_\perp$ is the strength of the transverse magnetic field, L is the length of the field along the axion path, $q = (m_\gamma^2 - m_a^2)/2E$ is the momentum transfer by the virtual photon, m_a is the axion mass, and m_γ is the effective mass of the photon which equals zero in vacuum.

If one can adjust m_γ to m_a, coherence will be restored for non-zero mass axions. This is achieved by filling the conversion region with gas. A photon in the X-ray region acquires a positive effective mass in a medium. In light gas, such as hydrogen or helium, it is well approximated by

$$m_\gamma = \sqrt{\frac{4\pi\alpha N_e}{m_e}}, \tag{3}$$

where α is the fine structure constant, m_e is the electron mass, and N_e is the number density of electrons. We adopted cold helium gas as a dispersion-matching medium. It is worth noting that helium remains at gas state even at 5–6 K, the operating temperature of our magnet. Since the bore of the magnet is limited in space, the easiest way is to keep the gas at the same temperature as the magnet. Moreover, axions as heavy as a few electronvolts can be reached with helium gas of only about one atmosphere at this temperature.

2 Experimental apparatus

The schematic figure of the axion helioscope is shown in Fig. 1. Its main components are identical to the ones used in the first [10] and second phase measurements [11] of the Tokyo Axion Helioscope performed in 1997 and 2000, respectively. It is designed to track the sun in order to achieve long exposure time. It consists of a superconducting magnet, X-ray detectors, a gas container, and an altazimuth mounting.

The superconducting magnet [12] consists of two 2.3-m long race-track shaped coils running parallel with a 20-mm wide gap between them. The magnetic field in the gap is 4 T perpendicular to the helioscope axis. The coils are kept at 5–6 K during operation. The magnet was made cryogen-free by making two Gifford-McMahon refrigerators to cool it directly by conduction, and is equipped with a persistent current switch. Thanks to these features, the magnet can be freed from thick current leads after excitation, and the magnetic field is very stable for a long period of time without supplying current.

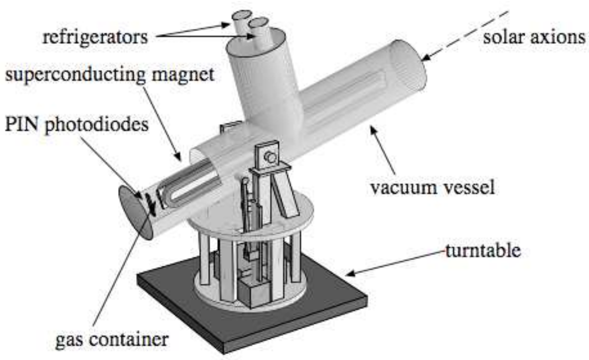

Figure 1: The schematic view of the axion helioscope.

The container to hold dispersion-matching gas is inserted in the $20 \times 92\,\mathrm{mm}^2$ aperture of the magnet. Its body is made of four 2.3-m long 0.8-mm thick stainless-steel square pipes welded side by side to each other.

Sixteen PIN photodiodes, Hamamatsu Photonics S3590-06-SPL, are used as the X-ray detectors [13], whose chip sizes are $11 \times 11 \times 0.5\,\mathrm{mm}^3$ each. In the present measurement, however, twelve of them are used for the analysis because four went defective through thermal stresses since the measurement of the previous phase. The effective area of a photodiode was measured formerly using a pencil-beam X-ray source, and found to be larger than $9 \times 9\,\mathrm{mm}^2$. It has an inactive surface layer of $0.35\,\mu$m [14].

The entire axion detector is constructed in a vacuum vessel and the vessel is mounted on an altazimuth mount. Its trackable altitude ranges from -28° to $+28^\circ$ and its azimuthal direction is designed to be limited only by a limiter which prevents the helioscope from endless rotation.

However, in the present measurement, the azimuthal range is restricted to about 60° because a cable handling system for its unmanned operation is not completed yet.

3 Measurement and Analysis

From December 2007 through April 2008, a measurement employing dispersion-matching gas was performed for 34 photon mass settings with about three days of running time per setting to scan around 1 eV.

Event reduction process is applied in the same way as the second phase measurement [11]. As a result, no significant excess was seen for any m_a, and thus an upper limit on $g_{a\gamma\gamma}$ at 95% confidence level was given. Fig. 2 shows the limit plotted as a function of m_a. Our previous limits from the first [10] and the second [11] phase measurements and some other bounds are also plotted in the same figure. The shown previous limits have been updated using newly measured inactive surface layer thickness of the PIN photodiode [14]; the difference is, however, marginal. The SOLAX [16], COSME [17] and DAMA [18] are solar axion experiments which exploit the coherent conversion on the crystalline planes [19] in a germanium and a NaI detector. The experiment by Lazarus et al. [15] and CAST [21] are the same kind of experiments as ours. The latter utilizes large decommissioned magnets of the LHC at CERN. Its limit is better than our previous limits by a factor of seven in low m_a region due to its larger B and L in Eq. (2). In the region $m_a > 0.14\,\text{eV}$, however, our previous and present limits surpass the limit of CAST[1]. The limit $g_{a\gamma\gamma} < 2.3 \times 10^{-9}\text{GeV}^{-1}$ is the solar limit inferred from the solar age consideration and the limit $g_{a\gamma\gamma} < 1 \times 10^{-9}\text{GeV}^{-1}$ is a more stringent limit reported by Schlattl et al. [20] based on comparison between the helioseismological sound-speed profile and the standard solar evolution models with energy losses by solar axions.

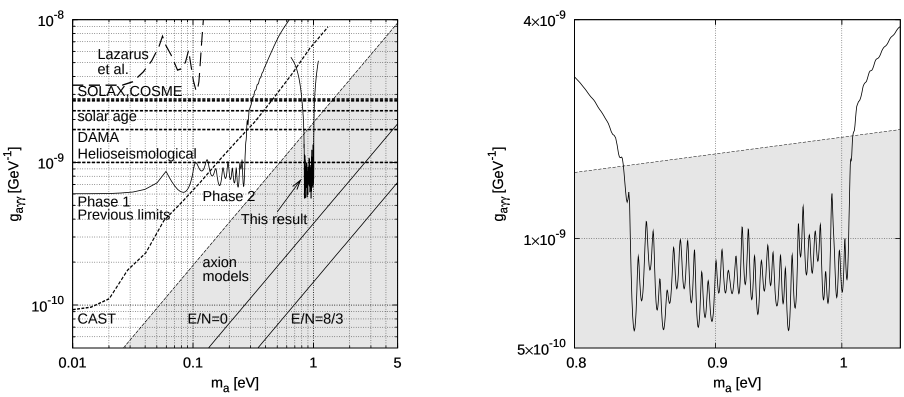

Figure 2: The left figure is the exclusion plot on $g_{a\gamma\gamma}$ to m_a. The new limit and the previous ones[10, 11] are plotted in solid lines. Dashed lines are explained in the text. The hatched area corresponds to the preferred axion models [22]. The right figure shows the magnified view of the new limit.

[1] CAST collaboration showed a preliminary limit in the region $m_a < 0.39\,\text{eV}$ in the present workshop.

4 Conclusion

The axion mass around 1 eV has been scanned with an axion helioscope with cold helium gas as the dispersion-matching medium in the $4\,\mathrm{T} \times 2.3\,\mathrm{m}$ magnetic field, but no evidence for solar axions was seen. A new limit on $g_{a\gamma\gamma}$ shown in Fig. 2 was set for $0.84 < m_a < 1.00\,\mathrm{eV}$. It is the first result to search for the axion in the $g_{a\gamma\gamma}$-m_a parameter region of the preferred axion models [22] with a magnetic helioscope. Full description of the present result is published in Ref. [23].

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