RECENT RESULTS FROM THE TOKYO AXION HELIOSCOPE EXPERIMENT

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We have searched for axions which could have been produced in the solar core using an axion helioscope which is equipped with a 2.3 m-long 4 T superconducting magnet, PIN-photodiode x-ray detectors, and a telescope mount mechanism to track the sun. A gas container to hold dispersion-matching gas has been developed and a mass region up to \( m_a = 0.26 \text{ eV} \) was newly explored. Preliminary analysis sets a limit on axion-photon coupling constant to be \( g_{a\gamma\gamma} < 6.4 \times 10^{-10} \text{ GeV}^{-1} \) for the axion mass of \( 0.05 < m_a < 0.26 \text{ eV} \) at 95% confidence level from the absence of the axion signal. This is more stringent than the limit inferred from the solar age consideration and also more stringent than the recent helioseismological bound.

1 Introduction

The axion which is renowned as a dark matter candidate is the Nambu-Goldston boson of the Peccei-Quinn symmetry introduced to solve the strong \( CP \) problem in the strong interaction theory. The expected behavior of an axion is characterized mostly by its mass, \( m_a \). If \( 10^{-5} < m_a < 10^{-3} \text{ eV} \), the axion can be copiously produced in the early universe so that they can close the universe. Another astrophysically interesting mass region is at around one to a few eV. Such axions can be allowed for some hadronic axion models by other astrophysical or cosmological constraints. In this region, the sun can be a powerful source of axions and the so-called ‘axion helioscope’ technique may enable us to detect such axions directly.

The principle of the axion helioscope is illustrated in Fig. 1. In the solar core, axions can be abundantly converted from black body radiation photons.

\textsuperscript{a}The lower bound can be even lower depending on the scenario.
In the solar core

\[ \gamma \rightarrow a \rightarrow \text{Ze, } e \]

In the magnet

\[ a \rightarrow \gamma \rightarrow B \]

Figure 1. The solar axions produced via the Primakoff process in the solar core are, then, reconverted into x rays via the reverse process.

through the Primakoff process. Then, they are coherently reconverted into x rays in a strong magnetic field in a laboratory. Their average energy is 4.2 keV reflecting the original black body radiation. The conversion rate is given by:

\[ P_{a \rightarrow \gamma} = \frac{g_{a\gamma\gamma}^2}{4} \left| \int_0^L B e^{iqz} dz \right|^2 \]  

(1)

where \( g_{a\gamma\gamma} \) is the axion-photon coupling constant, \( z \) is the coordinate along the incident solar axion, \( B \) is the strength of the magnetic field, \( L \) is the length along the \( z \)-axis, and \( q = |(m_{\gamma}^2 - m_a^2)/2E| \) is the momentum transfer by the virtual photon. Here, \( m_{\gamma} \) is the effective mass of the photon which is of course zero in vacuum.

We have constructed a helioscope with a dedicated superconducting magnet, and the first measurement \( \Phi \) was performed during from 26th to 31st December 1997. From the absence of the axion signal, an upper limit to the axion-photon coupling was set to be \( g_{a\gamma\gamma} < 6.0 \times 10^{-10}\text{GeV}^{-1} \) (95% CL) for \( m_a < 0.03 \text{eV} \). For heavier axions, momentum transfer, \( q \), becomes not negligible, thus the sensitivity of the detector is lost.

Coherence can, however, be restored by filling the conversion region with buffer gas since a photon of x-ray region has an effective mass in a medium. For light gas, such as hydrogen or helium, it is simply written as:

\[ m_{\gamma} = \sqrt{\frac{4\pi\alpha N_e}{m_e}}. \]  

(2)

We adopted cold helium gas as the dispersion-matching medium and scanned the mass region up to 0.26 eV. In this paper, we will present a preliminary result of this new measurement.
2 Experimental apparatus

The schematic figure of the helioscope is shown in Fig. 2. The detector consists of a superconducting magnet, x-ray detectors, a gas container, and an altazimuth mounting.

The superconducting magnet was so designed as to be easy to swing. It consists of two 2.3-m long race-track shaped coils run 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. They are directly cooled with two Gifford-McMahon refrigerators and no cryogen is needed. The magnet has also a persistent current switch. After excitation, it is switched into persistent current mode and the current leads are taken away.

Sixteen PIN photodiodes, Hamamatsu Photonics S3590-06, are used as the x-ray detectors. The chip size is $11 \times 11 \times 0.5 \text{ mm}^3$. Each chip is mounted on a Kapton film bonded to an Invar plate with cryogenic compatible adhesive. The x-ray detectors are mounted in a radiation shielding box made of oxygen-free high conductivity copper (OFHC Cu) which is operated at about 60 K. The copper shield is surrounded by a lead shield which is at room temperature.

The output from each photodiodes is fed to a charge sensitive preamplifier whose first-stage FET is at the cryogenic stage near the photodiode chip and the preamplifier outputs are digitized using flash analog-to-digital converters (FADC’s), REPIC RPC-081’s. We performed numerical pulse shaping to the raw waveform using the Wiener filter. The energy of an x ray is given by...
the peak height of a wave after shaping. Each detector was calibrated by 6-keV manganese x-ray from a $^{55}$Fe source which can be exposed and hidden freely during the measurement. The energy resolutions for 6-keV photon was 0.8–1 keV (FWHM).

The new device introduced this time is the gas container. We adopted cold helium gas as the dispersion-matching medium. Light gas is preferred since it minimizes x-ray absorption by the gas. Helium has another virtue that it remains at gas state at 5 K, the same temperature as the coil. At 5 K, the gas pressure corresponding to our ultimate goal, $m_a = 2.6 \text{ eV}$, reaches only 0.13 MPa.

The container body is made of four stainless steel square pipes welded to each other. The entire container body is wrapped with 5N high purity aluminium sheet to achieve high uniformity of temperature. At the end of the container, gas is separated from vacuum with an x-ray window which is transparent to x-ray above 2 keV and can hold gas up to 0.3 MPa at liquid helium temperature.

The whole helioscope is constructed in a vacuum vessel and is mounted on an altazimuth mount. Its trackable altitude ranges from $-28^\circ$ to $+28^\circ$ and almost any azimuthal direction is trackable. This view corresponds to about 50% of duty cycle for the sun measurement in Tokyo. The other half of a day we measure the background. This helioscope mount is driven by two AC servo motors controlled by a personal computer (PC) through CAMAC bus. The PC regularly monitors two precision rotary encoders through CAMAC bus and forms a feedback control loop. The U.S. Naval Observatory Vector Astronomy Subroutines (NOVAS) was used to calculate the sun position. The directional origin of the helioscope was measured using a theodolite. The absolute azimuth is determined from the observed direction of Polaris and the absolute altitude is determined from a spirit level.

### 3 Measurement and Analysis

During from 29th July to 1st September 2000, a new measurement with buffer gas was performed for ten photon mass settings to scan up to 0.26 eV.

In Fig. 3, one of the energy spectra of the solar observation is shown together with the background spectrum. We searched for expected axion signals which scales with $g_{a\gamma\gamma}$ for various $m_a$ in these spectra. The smooth curve in the figure represents an example for the expected axion signal for $m_a = m_\gamma = 0.26 \text{ eV}$ and $g_{a\gamma\gamma} = 7 \times 10^{-10} \text{GeV}^{-1}$.

In the analysis, the ten measurements with the ten different gas densities are combined together by using the total $\chi^2$. The energy region 4–20 keV was
used for fitting. Since no significant excess was seen for any \( m_a \), we set upper limit on \( g_{a\gamma\gamma} \) at 95% confidence level using the Bayesian method.

In Fig. 3, upper limits on \( g_{a\gamma\gamma} \) are plotted as a function of \( m_a \). The previous limit and the new preliminary limit are plotted together. There are also some other bounds plotted in the same figure. The SOLAX experiment which exploits the coherent conversion on the crystalline planes in a germanium detector. The limit \( g_{a\gamma\gamma} < 2.3 \times 10^{-9} \text{GeV}^{-1} \) is the solar limit inferred from the solar age consideration. The limit \( g_{a\gamma\gamma} < 1 \times 10^{-9} \text{GeV}^{-1} \) is a new solar limit recently reported. Above this line, standard solar models with energy losses by solar axions cannot fit to the helioseismological sound-speed profile.

4 Conclusion

We have developed a gas container and introduced cold helium gas as the dispersion-matching medium in the 4 T × 2.3 m magnetic field of our axion helioscope. The axion mass up to 0.26 eV has been newly scanned. But no evidence for solar axions was seen. New preliminary upper limit on \( g_{a\gamma\gamma} \) which ranges \( 6.4 - 9.6 \times 10^{-10} \text{GeV}^{-1} \) was set for \( 0.05 < m_a < 0.26 \text{eV} \), which is far more stringent than the solar existence limit and is also more stringent than the recent helioseismological bound. This experiment is currently the only one existing experiment which has enough sensitivity to detect such solar axion that do not violate the solar model itself.
Figure 4. The exclusion plot on $g_{a\gamma\gamma}$ to $m_a$ at 95% confidence level is plotted where some other bounds are plotted together. Our previous limit and the new limit are plotted in solid lines. Dashed lines are the limit by SOLAX experiment, the limit inferred from the solar age consideration, and the recent helioseismological bound. The hatched area is the preferred axion models. The thick line corresponds to the case when a simple GUT is assumed.

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