The Tokyo Axion Helioscope Experiment

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A preliminary result of the solar axion search experiment at the University of Tokyo is presented. We searched for axions which could be produced in the solar core by exploiting the axion helioscope. The helioscope consists of a superconducting magnet with field strength of 4 Tesla over 2.3 meters. From the absence of the axion signal we set a 95\% confidence level upper limit on the axion coupling to two photons $g_{a\gamma\gamma} \times 6.0 \times 10^{-10} \text{GeV}^{-1}$ for the axion mass $m_a < 0.03 \text{eV}$. This is the first solar axion search experiment whose sensitivity to $g_{a\gamma\gamma}$ exceeds the limit inferred from the solar age consideration.

1. INTRODUCTION

The axion is a light pseudoscalar particle introduced to solve the strong CP problem\textsuperscript{[1–5]}. However, the theory of axion does not predict its mass. The axion would be produced in the solar core through the Primakoff effect if its mass is a few electronvolts.

Sikivie\textsuperscript{[6]} proposed an experiment to detect the axions emitted by the sun using a system of a strong magnetic field and an x-ray detector, called the axion helioscope. In the magnetic field, solar axions convert back to x-rays of black body radiation spectrum with an average energy of about 4 keV by the inverse process. The conversion can be coherently enhanced by filling the conversion region with dense gas\textsuperscript{[7]}. The principle of detection is illustrated in Fig. 1.

We constructed a dedicated superconducting magnet to search for the solar axions. We are going to adopt cold helium gas as conversion medium with a temperature just above 4K, the boiling point at one atmosphere. With electron density of this medium, conversion of axions with mass of 2.65 eV gets enhanced coherently. However, we tried without any conversion medium at first because we need some time to develop the gas container. We report on the results of this first helioscope run without conversion gas.

2. AXION HELIOSCOPE

The axion helioscope consists of a superconducting magnet\textsuperscript{[8]}, x-ray detectors, and an altaz-
imuth to direct the helioscope toward the sun. A schematic illustration of the axion helioscope is shown in Fig. 2.

The superconducting magnet has a field strength of 4 Tesla over effective length of 2300 mm. With a help of two Gifford-McMahon refrigerators attached on its top, it is cooled down to 5.2 K without any liquid helium. The magnet consists of two split racetrack superconducting coils, which are connected to the refrigerators by conduction rods. These coils are installed in a cylindrical vacuum chamber.

![Figure 2. Schematic view of the axion helioscope](image)

It takes 14 days to achieve the temperature needed to operate the magnet if we start from the room temperature. Excitation of the magnet takes one hour to reach the field strength of 4 Tesla. The field is then maintained by a persistent current of 268 amperes. Main parameters of the magnet are summarized in the Table 1.

The magnet is supported on the altazimuth, with which it can be turned by 360 degrees around the vertical axis, and ±28 degrees above and below the horizontal plane. Averaging over one year in Tokyo, the sun is within ±28 degrees of altitude for about 50% of the time. When the sun is out of this region, we take background data. The mounting is controlled by a computer to track the sun. The horizontal and elevational origin was determined by a precision theodolite. We determined the north direction by observing the star called β-Ori. The horizontal level was determined by a spirit level.

The errors of the tracking were found to be smaller than ±0.50 mrad in the azimuthal direction and ±0.45 mrad in the elevational direction. Since the aperture of the helioscope is ±5 mrad, these errors are small enough.

For the axion-converted x-ray detection, we use 16 pieces of PIN photodiodes, Hamamatsu S3590-06. 9 pieces out of 16 were actually used for the first measurement because of unexpected damages during the cooling. These are windowless photodiodes with active area of 9 mm × 9 mm each and thickness of 500 µm. The typical capacitance of the diode is 30 pF with a reverse bias voltage of 100 V. It is originally supplied on a ceramic substrate. However, we ordered special diodes with substrates of Kapton and Teflon because we observed that the ceramic had detectable radioactive contaminations in it. The temperature of the diodes is kept around 50K by the first stage of the refrigerators.

Energy calibration was done by irradiating x or γ rays of checking sources before the detector installation. The energy resolution of the PIN photodiodes was 0.34 keV in the energy region of the present interest as determined by test pulses. The detection efficiency was estimated with 5.9 keV x-rays from 55Fe of known activity. It was found that the absolute detection efficiency was at least 0.5 at 4 keV, and more than 0.9 at 10 keV.

3. MEASUREMENT and ANALYSIS

The first measurement was done from 26th till 31st December 1997. We tracked the sun with the axion helioscope so far as its altitude is within 28 degrees above and below the horizon. The earth can be practically considered to be transparent to the axion. A total time of 1.9 × 10^5 sec was dedicated to the tracking run. We measured the background data during the rest of the time,
Coil

| Shape         | racetrack               |
|---------------|-------------------------|
| Quantity      | 2                       |
| Winding thickness | 64 mm               |
| Winding width  | 50 mm                   |
| Winding cross section area | $3.2 \times 10^3 \text{mm}^3$ |
| Inner/outer radius of both ends of coil | 50/100 mm     |
| Liner length  | 2100 mm                 |
| distance between coils | 20 mm               |
| volume        | $14.95 \times 10^4 \text{mm}^3$/coil |
| weight        | 133.5 kg/coil           |

Winding coil

| layer       | 54/coil |
| turn        | 33.5/coil |
| number of turns | 1809/coil |
| Operation current | 268 A (336 A) |
| Central magnetic field | 4.0 T (5.0 T) |
| Max magnetic field  | 5.74 T (7.18 T) |
| Inductance        | 15.5 H   |
| Stored energy     | 560 kJ (875 kJ) |
| Weight (4 K part) | 670 kg   |

GM-refrigerator

| Quantity      | 2                       |
| capacity      | 1st: 20 W @ 40 K       |
|               | 2nd: 0.5 W @ 4.2 K     |

Table 1
Main parameters of the magnet. Designed parameters are shown in parentheses.

which amounted to $2.0 \times 10^5$ sec.

The output signals from the preamplifiers are fed into shaping amplifiers for the trigger. On the other hand, the waveform of the preamplifier outputs are digitized over 50 $\mu$sec before and after a trigger and recorded with a sampling period of 0.1 $\mu$sec. The stored waveforms are then shaped digitally in a computer.

After event selection cuts to eliminate cosmic muon events, we got energy spectra of source runs and background runs, each of which is the sum of the data from nine PIN photodiodes. They are shown in Fig. 3.

Since the axion signal can be observed only in the source spectrum, we subtracted the background contribution from it. We then fit the theoretical spectrum to it. The fitting region is restricted to the energy region between 4 and 14 keV, where most events are concentrated and the trigger efficiency is almost 100%.

The conversion probability, $p_{a\to\gamma}$, is written by a Fourier transformation of the magnetic field\[7\],

$$p_{a\to\gamma} = \left| \int_0^L \frac{g_{a\gamma\gamma}}{2} B(x, y, z) \exp(iqz)dz \right|^2.$$  \hspace{1cm} (1)

where $g_{a\gamma\gamma}$ is the axion coupling constant to two photons, $B$ and $L$ are the magnetic field and its length, $q = n_z^2 / 2E$ is the momentum transfer, $z$ is a coordinate along the magnet axis, and $x$ and $y$ are coordinates perpendicular to the $z$ axis. In the fitting, the coupling constant $g_{a\gamma\gamma}$ is left free. Thus obtained $p_{a\to\gamma}$ is multiplied by the axion differential flux, the detection efficiency and
the trigger efficiency. We then get the theoretical spectrum after convolution with the detector response function with the energy resolution.

The fitting was done assuming a certain value for $m_a$. Fig. 4 shows an example for $m_a = 0.001$ eV. The solid line corresponds to the best fit and the dashed line the 95% confidence level upper limit. Then the fitting is repeated with various values for $m_a$. We thus obtain 95% CL upper limits as a function of $m_a$ in the range from 0.001 to 1 eV as shown in Fig. 5. In the same figure, upper limits from earlier experiments by other groups as well as the limit inferred from the solar age consideration are also shown. This is the first solar axion search experiment which has sufficient sensitivity to $g_{a\gamma\gamma}$ below the solar limit. The present experiment gives factor of 4.5 more stringent limit than the recent limit by Avignone et al.[10] in the region $m_a < 0.03$ eV.

4. CONCLUSION

We searched for axions which could be produced in the solar core using the axion helioscope, which consists of a super conducting magnet with field strength of 4 Tesla over 2.3 meters. From the absence of the axion signal we set a 95% confidence level upper limit on the axion coupling to two photons $g_{a\gamma\gamma} < 6.0 \times 10^{-10}$ GeV$^{-1}$ for the axion mass $m_a < 0.03$ eV. This is the first solar axion search experiment whose sensitivity to $g_{a\gamma\gamma}$ exceeds the limit inferred from the solar age consideration. The present limit gives a factor of 4.5 improvement over the formerly best limit in the region $m_a < 0.03$ eV.

5. PROSPECTS

After completion of the development of the gas container, in which the cold conversion gas is to be filled, we will start the next measurement. In
this new measurement we should have sensitivity in $m_a$ range between 0.03 and 2.6 eV, especially we can reach the sensitivity predicted by the hadronic axion models around $m_a = 2.6$ eV.

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