An x-ray detector using PIN photodiodes for the axion helioscope

T. Namba c Y. Inoue b S. Moriyama c M. Minowa a,*

a Department of Physics and Research Center for the Early Universe (RESCEU), School of Science, University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033

b International Center for Elementary Particle Physics, University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033, and RESCEU

c Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan

Abstract

An x-ray detector for a solar axion search was developed. The detector is operated at 60K in a cryostat of a superconducting magnet. Special care was paid to microphonic noise immunity and mechanical structure against thermal contraction. The detector consists of an array of PIN photodiodes and tailor made preamplifiers. The size of each PIN photodiode is $11 \times 11 \times 0.5 \text{ mm}^3$ and 16 pieces are used for the detector. The detector consists of two parts, the front-end part being operated at a temperature of 60K and the main part in room temperature. Under these circumstances, the detector achieved 1.0 keV resolution in FWHM, 2.5 keV threshold and $6 \times 10^{-5} \text{ counts sec}^{-1} \text{ keV}^{-1} \text{ cm}^{-2}$ background level.

Key words: axion, helioscope, x-ray, superconducting, PIN, photodiode

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1 Axion helioscope

The axion is a light neutral pseudoscalar particle yet to be discovered. It was introduced to solve the strong CP problem [1]. The axion would be produced in the solar core through the Primakoff effect if it has enough coupling to photons [2]. It has an energy spectrum very similar to that of black body radiation photons with an average energy of about 4 keV. It can be converted

* Corresponding author

Email address: minowa@phys.s.u-tokyo.ac.jp (M. Minowa).
back to an x-ray in a strong magnetic field in the laboratory by the inverse process. We search for such x-rays coming from the direction of the sun with a newly developed instrument called axion helioscope.

A schematic view of the helioscope is shown in Fig. 1. It consists of three parts, a tracking system, superconducting coils and x-ray detectors. The tracking system supports and drives a 3-m long cylinder of the helioscope to track the sun. The superconducting coils and the x-ray detector are mounted in the cylinder. The coils are cooled by Gifford McMahon refrigerators directly by conduction. The aperture volume between the coils is 2300(L) × 92(H) × 20(W) mm$^3$ and the magnetic field strength in the aperture is 4 T. The details of this cryogen-free superconducting magnet is described elsewhere[3].

By using the helioscope, we performed a series of axion search experiments[4] and obtained a limit to the coupling constant of the axion to photons, $g_{a\gamma\gamma} < 6.0 - 9.6 \times 10^{-10}$ GeV$^{-1}$ for $m_a < 0.26$ eV.

We report in this paper on the development of the x-ray detector made of PIN photodiode operated in a low temperature environment.

2 PIN photodiode

The x-ray detector for the axion helioscope is required to have following features.

- large area
  Rare event search needs large sensitive area.
- tolerance to magnetic field
  The detector is operated near the superconducting coils, and operated under $10^{-2}$ T magnetic field.
- low energy threshold and moderately good resolution
  Since the energy spectrum extends to zero energy, the threshold needs be low enough. The higher resolution also helps but needs not be excellent because the spectrum has no sharp structures.
- low-temperature operation
  No thermal insulation is possible between the detector and the superconducting magnet while keeping good x-ray transmission.
- high efficiency for low energy x-rays
  A thick window would stop low energy x-rays and lose low energy portion of the spectrum.
- low background
  In a rare event search, the remaining background rate limits the sensitivity.
We found silicon PIN photodiodes with thick depletion layers satisfy the above requirements [5]. The PIN photodiode we use is Hamamatsu S3590-06-SPL, $11 \times 11 \text{ mm}^2$ in size and 500 $\mu\text{m}$ in thickness. It is originally a windowless silicon PIN photodiode but it has also high efficiency to x-rays of energy less than 10 keV. To cover the full aperture of the superconducting magnet, an array of 16 PIN photodiodes was used.

As measured with the calibration source, the energy resolution of the PIN-photodiode detector is 0.9 to 1.0 keV in FWHM at 5.9 keV. The measured spectrum is shown in Fig. 3 The energy threshold is 2.5 keV.

Although the PIN photodiode is of windowless type, it has an aluminum electrode along four sides of the surface and they block the x-rays. To get rid of this inefficient section, the PIN photodiodes were arranged to overlap on their electrodes each other (Fig. 2).

Besides the electrode, there exists a slight thickness of inefficient silicon dioxide in front of the depletion layer of the PIN photodiode. The thickness of the insensitive layer was estimated by measuring the inefficiency of 5.9 keV x-rays from $^{55}\text{Fe}$ source, and was found to be less than 6.1 $\mu\text{m}$ at the 95% confidence level. This means that the efficiency is more than 0.2 for 3 keV x-ray and 0.92 for 10 keV.

A surface-scan measurement guaranteed that the efficiency is uniform in $9 \times 9 \text{ mm}^2$ region inside the electrode.

3 Assembly

The x-ray detector is divided into two parts, the cold head part and the main part in room temperature. The head part of the x-ray detector is mounted on a 60 K copper plate and surrounded by shields to reduce the radioactive background from the environment (Fig. 1). In the head part, PIN photodiodes and front-end circuits are assembled.

Just beside the array of the PIN photodiodes, there are front-end circuits of charge-sensitive preamplifiers. The schematic diagram of the amplifier is shown in Fig. 4. In the front-end circuits are junction field-effect transistors (JFETs, HITACHI 2SK291), feedback resisters (5 G$\Omega$), 130 V inverse bias voltage buffers and pulser inputs. The residual parts of the preamplifiers are mounted outside of the cylinder at the room temperature. Also in the room temperature part are high-pass filters and booster amplifiers, which we will mention later.
The head part of the x-ray detector is mounted on 60 K plate in order not to radiate much thermal energy onto the 4 K superconducting coils. The low temperature is also useful to reduce the thermal noise in the front-end circuits, because the electric noises of the PIN photodiodes and circuits decrease as the temperature drops. However, the JFET does not function at such a low temperature. Therefore, the JFET was warmed up to a temperature around 130 K by a small electric heater attached on it. Between the front-end circuit and the 60 K plate, 6 mm thick acrylic plastic sheets are inserted for the thermal insulation, whose impedance saves necessary heat to warm the JFET up to the working temperature.

For the calibration of assembled PIN photodiodes, an x-ray source of $^{55}$Fe is installed in front of them. The source can be retracted behind the shield during the run so that the storage of the check source inside the cryostat does not increase the background level.

4 Background and noise

Since the PIN photodiode is made of silicon whose atomic number is small, it has relatively low photoelectric efficiency for high energy photons. Therefore the detector should be properly shielded lest the Compton scattering of photons form continuous backgroung at the low energy region.

The radioactive background consists of two parts, external and internal. The external component is reduced by the shield shown in Fig. 1. The PIN photodiodes are surrounded by 10 cm thick lead, (partly mounted on room temperature part and partly on 60 K), 1 cm oxygen free copper and 0.3–1 cm acrylic plastic sheets. The copper is also used as 60 K thermal radiation shield and as a cold finger to cool the x-ray detectors.

On the other hand, one of the possible internal radioactive source is the ceramic commonly used for the base of the PIN photodiode. The ceramic has usually $^{238}$U and $^{232}$Th chain contaminations which amount to about $10^{-2}$–$10^{-3}$ Bq per PIN photodiode. To get rid of these radioactivities, the base material was changed. The new bases are made of flexible polyimide sheets. Their size is $11 \times 16$ mm$^3$ which just fits to our PIN photodiode array. With this new bases the background rate is reduced to $6 \times 10^{-5}$ counts sec$^{-1}$ keV$^{-1}$ cm$^{-2}$.

The superconducting coils of the helioscope is directly cooled by Gifford-McMahon refrigerators, and its continuous back-and-forth movement causes microphonic noises of the detector. To reduce the microphonic noises, connections between the PIN photodiodes and the front-end circuits are kept as short and rigid as possible. As is shown in Fig. 5 the bases of the PIN photodiodes
are fixed on Super Invar steel sheets by epoxy resin. The Super Invar sheets are then screwed on the acrylic sheets. Invar steel has as small thermal contraction coefficient as the silicon and prevents the silicon from cracking due to the thermal contraction of the acrylic sheet. All parts of the front-end circuit were molded with Stycast-1266 epoxy resin which is mixed with #250-mesh SiO₂ powder with a weight fraction of 55% to make its overall contraction coefficient comparable to the parts in the mold.

Signals from the preamplifiers are amplified by the booster with a gain of 0–1000 and then the waveform is digitized at a sampling rate of 10 MHz with a length of 1024 words per event. The high-pass filters are inserted in front of the boosters to reduce microphonic noises whose major components reside below several 100 Hz. The cut-off frequencies are set to be 3 kHz, since signal below this frequency has less meaning considering the sampling duration of 102.4 µs.

Shaping of the signal is done off-line and still remaining microphonic events can be removed digitally.

5 Conclusion

We developed an x-ray detector for the axion helioscope using a PIN photodiodes array. It works at a low temperature of 60 K, with low background, low microphonics and high sensitivity for low energy x-rays.

With this system we performed a series of axion search experiments[4] . We are now preparing more massive axion search experiment with our helioscope by filling buffer gas into the magnetic field region.

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References
Fig. 1. Schematic view of the axion helioscope and the tail part of the cylinder.
Fig. 2. The array of the PIN photodiodes as seen from the incident direction. The figures marked on the scale are in millimeters.

Fig. 3. Spectrum of 5.9 keV Mn-x rays measured by 16 PIN photodiodes.
Fig. 4. Schematic diagram of the amplifier.

Fig. 5. PIN photodiode mounted on an Invar steel sheet.