PROCEEDINGS OF SCIENCE

"ISAI" Investigating Solar Axion by Iron-57 : the commissioning and the first run

Yoshiyuki Onuki,[a,*] **Yoshizumi Inoue,**[a] **Akimichi Taketa,**[b] **Toshihiro Fujii,**[c] **Takeshi Tsuru,**[d] **Tomonori Ikeda,**[d] **Masamune Matsuda,**[d] **Kazuho Kayama,**[d] **Hiromu Iwasaki,**[d] **Hiroki Namba,**[d] **Mei Anazawa,**[d] **Mizuki Uenomachi,**[d] **Kentaro Miuchi**[e] **and Ayaki Takeda**[f]

[a] *University of Tokyo, ICEPP,*
Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan
[b] *University of Tokyo, ERI,*
1-1-1 Yayoi, Bunkyo-ku, Tokyo, 113-0032, Japan
[c] *Osaka Metropolitan University,*
Sugimoto 3-3-138, Sumiyoshi-ku, Osaka 558-8585, Japan
[d] *Kyoto University,*
Kitashirakawa-Oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan
[e] *Kobe University,*
1-1, Rokkodai-cho, Nada-ku, Kobe, 657-8501, Japan
[f] *Miyazaki University,*
1-1 Gakuen Kibanadai-nishi, Miyazaki 889-2192, Japan

E-mail: yoshiyuki-onuki@g.ecc.u-tokyo.ac.jp

ISAI, Investigating Solar Axion by Iron-57 is an experiment dedicated measurement of an interaction between the Axion and nucleus without introducing the other interactions. An event-triggered monolitic SOI X-ray pixel detector XRPIX, originally developing for the X-ray imaging spectroscopy for space observation satellite project, is applied for the Axion experiment with position sensitive timing veto counters. We developed the readout using a rigid-flex circuit board which enables us to separate the XRPIX and the most of peripheral electrical components that would have non-negligible radioactivity without introducing any connectors. We surveyed radioactivity of the detector inside of the shield using HPGe detector and confirmed a $\sim 10^{-3}$ reduction with respect to the previous our detector composed of a rigid circuit board. Two timing triggers of the XRPIX and the veto counter can be recorded by a high time resolution DAQ system so that we will reject backgrounds induced by cosmic-ray or environmental radiation at the offline analysis. We constructed the detector with oxygen-free copper and lead shields inside of the climatic chamber. We will present the experimental apparatus, the performance, the commissioning.

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*Speaker

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1. Introduction

Strong CP problem is that a CP violating term in quantum chromodynamics Lagrangian which can induce a neutron dipole moment, however, is found to be highly suppressed[1, 2] and reached at $\lesssim 10^{-10}$ level implied by the latest measurement [3]. The most promising solution is to introduce a global chiral $U(1)$ symmetry known as Peccei-Quinn symmetry[4, 5]. It breaks spontaneously and a Nambu-Goldstone boson, axion, appears. Though original Peccei-Quinn symmetry assumed to break in an energy scale f_a coincided with electroweak energy scale but it was ruled out by experiment, so far invisible axions have a much larger energy scale, so called KSVZ[6, 7] axion and DFSZ axion[8, 9] regards with reference models, have been studied theoretically and searched experimentally, observationally. Axion can interact with standard model particles as following, interactions axion-photon coupling $g_{a\gamma}$, axion-electron coupling g_{ae} and axion-nucleon coupling g_{an}. Many laboratory experiments, astrophysical and cosmological observations gave upper limits on the couplings with respect to the axion mass.

2. Solar axion from ^{57}Fe

The Sun would be a powerful axion source. An experimental scheme of solar axion search using an isolated axion-nucleon interaction was proposed[10]; ^{57}Fe nucleus in core of the Sun could be thermally excited and emit axion of monochromatic 14.4 keV via axion-nuclepn coupling, and the axion could excite ^{57}Fe on the earth and emit monochromatic 14.4 keV γ by the deexcitation; $^{57}\mathrm{Fe}^* \rightarrow {}^{57}\mathrm{Fe} + a(\text{in solar core}) \rightarrow {}^{57}\mathrm{Fe} + a(\text{in laboratory}) \rightarrow {}^{57}\mathrm{Fe}^* \rightarrow {}^{57}\mathrm{Fe} + 14.4\mathrm{keV}\gamma$. The axion-nucleon coupling which consists of isoscalar and isovector parts; $g_{an} = -1.19 g^0_{an} + g^3_{an}$. These couplings and axion mass are related as f_a below,

$$g^0_{an} = -7.8 \times 10^{-8} \left(\frac{6.2 \times 10^6}{f_a/\mathrm{GeV}} \right) \left(\frac{3F - D + 2S}{3} \right), \tag{1}$$

$$g^3_{an} = -7.8 \times 10^{-8} \left(\frac{6.2 \times 10^6}{f_a/\mathrm{GeV}} \right) \left((D + F) \frac{1 - z}{1 + z} \right), \tag{2}$$

$$m_a = 1\mathrm{eV} \frac{\sqrt{z}}{1 + z} \frac{1.3 \times 10^7}{f_a/\mathrm{GeV}}, \tag{3}$$

where both D and F are the reduced matrix elements for the SU(3) octet axial vector currents can be obtained from hyperon semileptonic decays[11], S characterizes the flavor singlet coupling[12] and $z = m_u/m_d \sim 0.56$ in the first order calculation.

The expected rate of absorption can be

$$R = 3.0 \times 10^2 \ \mathrm{day}^{-1} \ \mathrm{kg}^{-1} \left(\frac{10^6 \ \mathrm{GeV}}{f_a} \right)^4 C^4, \tag{4}$$

$$C = -1.19 \left(\frac{3F - D + 2S}{3} \right) + (D + F) \frac{1 - z}{1 + z}. \tag{5}$$

Several observations were conducted and got null results[13–15]. Current upper limit, $g_{an} \leq 3.0 \times 10^{-6}$ which is respected to the constraint of axion mass $m_a < 145$ eV at 95% C.L. by [15].

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3. ISAI experiment

Investigating Solar Axion by Iron-57(ISAI) is an experiment dedicated measurement of an interaction between the axion and nucleus without introducing the other interactions. Fig. 1 shows a schematic view of the ISAI detector composed of two X-ray detector modules, a position sensitive cosmic-ray veto counter in the climate chamber and the readout system.

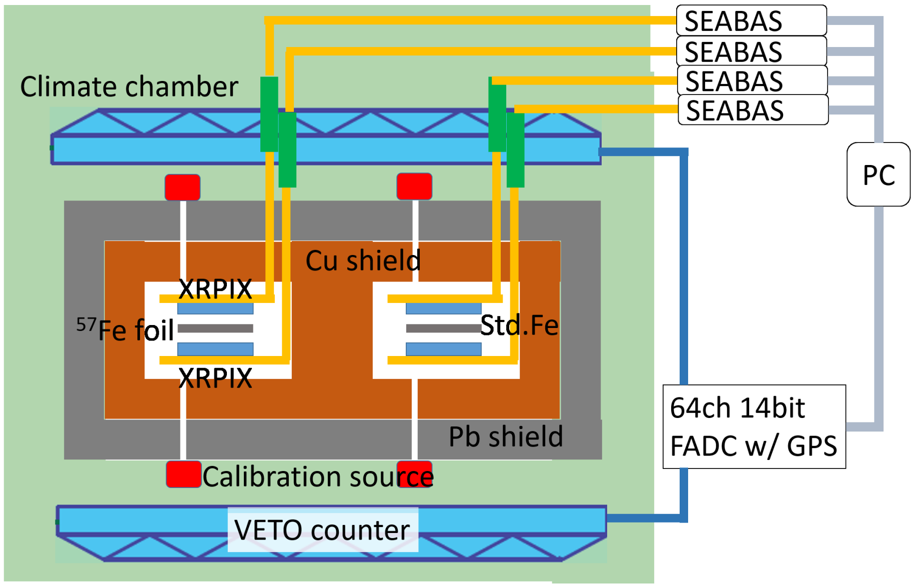

Figure 1: ISAI detector.

XRPIX[16–23], a monolitic pixel sensor for X-ray imaging equipped with a 10 μsec timing resolution has been developing for a future X-ray astronomy satellite mission named FORCE using a 0.2 μm CMOS fully depleted silcon on unsulator process of the LAPIS Semiconductor Co., Ltd.. XRPIX7, in the series number of XRPIX, is used to the ISAI experiment to detect a 14.4 keV γ of the axion signal. XRPIX7 has the largest detection area of 21.9 mm $\times$ 13.8 mm with 300 μm thickness, comprised of 608 $\times$ 384 pixels which pixel size is 36 μm square. Each pixel has a correlation double sampling circuit with low readout noise for the output of signal pulse height and a comparator associated with a trigger circuit. Pixel detected signal over the trigger threshold and the neighboring pixels can be read out with a 10 μs time resolution in the event-driven mode which enables XRPIX to cope with external detectors for background rejection by an anti-coincidence technique.

In the previous study[24], background sources from internal peripherals of detector were identified by radioactive survey using HPGe detector in terms of radioactive isotopes of ^{238}U, ^{232}Th and ^{40}K. The major source is the G10 rigid circuit board on which bare XRPIX chip is implemented. To reduce the background, we had developed a rigid-flex circuit board for XRPIX7, as shown in Fig. 2 a), composed of both 4 layers of G10 rigid circuit board and 2 layers of polyimide flexible circuit board(FLEX), which contains the least radioactive isotopes background, internally connecting electricaly. It realizes both physical separation and electrical connection between the

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XRPIX chip and the G10 board by the thinnest flex part which gives enough space to put an ideal hermetic shield only around the chip. As shown Fig. 2b), both a 95% enriched ^{57}Fe foil for the axion detector and a standard Fe foil for the background detector, modularized exactly same configurations, are sandwiched by two XRPIX7, respectively. Each module except for pig-tail of rigid board is surrounding by oxygen free copper shield of 5 mm thickness and lead shield of 50 mm thickness in Fig. 2c) and d). The major background source inside of the copper shield is multi-layer ceramic capacitors which has a 10^{-3} radioactivity reduction compared with conventional G10 board. Data from XRPIX is readout by SEABAS board[25, 26].

Fig. 3 shows energy resolution measured by the XRPIX7 on the FLEX using ^{241}Am source. We obtained the energy resolution of 478 eV (FWHM) at 13.9 keV.

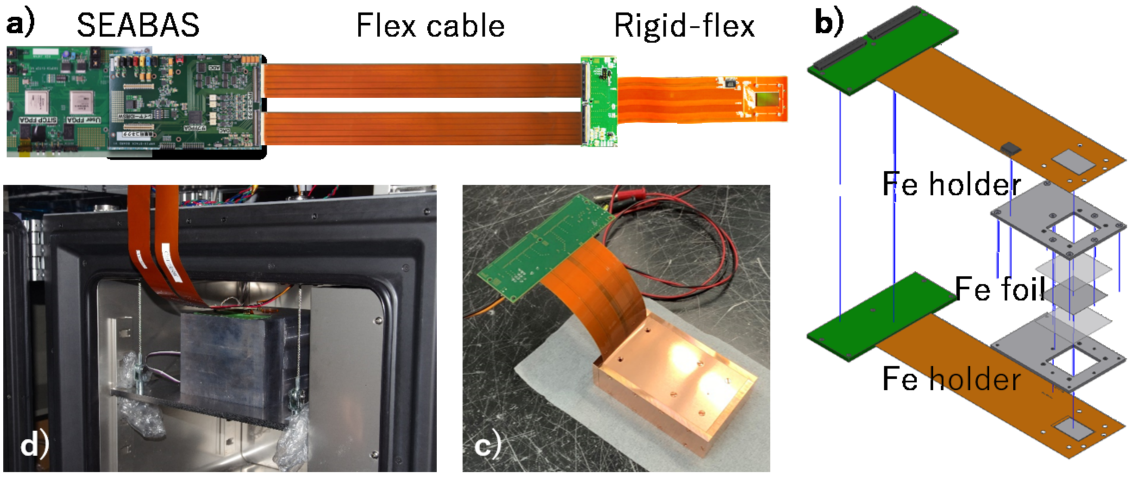

Figure 2: Rigid-flexible circuit board.

Two plastic scintillator detectors are placed on top and bottom of the lead shield, and timing-synchronized to the XRPIX7 for anti-coincidence measurement for cosmic rays and environmental radiation as shown in Fig. 1. Size of the scintillator bar is 5 cm width, 1 cm height and 30 cm length having a wave length shifter fiber channel in the center. Each detector composed of orthogonally stacked two layers of staggered 11 triangluar prism scintillator bars and enables to reconstruct a 2 dimensional position of cosmic-ray passed through. Using the position of top and bottom, we can reconstruct track of cosmic-ray as a position sensitive anti-coincidence detector. The wave length shifter fibers in the channels are connected to the SiPM(HPK S13360-1375PE) and read by waveforms digitaization by a dual 32 channell 14-bit Flash ADC(TI ADS52J90).

Timing information including XRPIXs and scintillators are input to the PETNET board[27], originally developed for Compton-PET hybrid camera, and recorded to analyze in offline. These detectors are located inside of climatic chamber to keep XRPIXs at a low temperature.

Stabilities of the detection efficiency and the gain can be monitored by an irradiation area where the calibration source placed on top and bottom of the lead shield through the 1 mm ϕ pin-holes during the observation. The other area can be used for a fiducial area of axion measurement. Fig. 4 shows a hit map distribution of XRPIX7 for xx hours. In this region we can monitor the count rate and the peak energy position corresponding to the detection efficiency and the gain, respectively.

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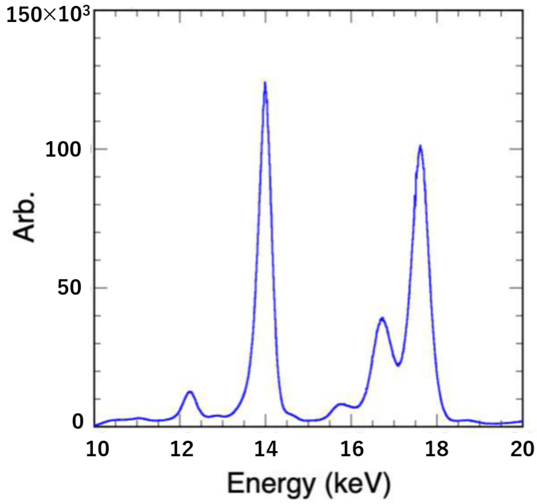

Figure 3: Energy resolution is measured by ^{241}Am source. The FWHM is 478 eV at 13.9 keV.

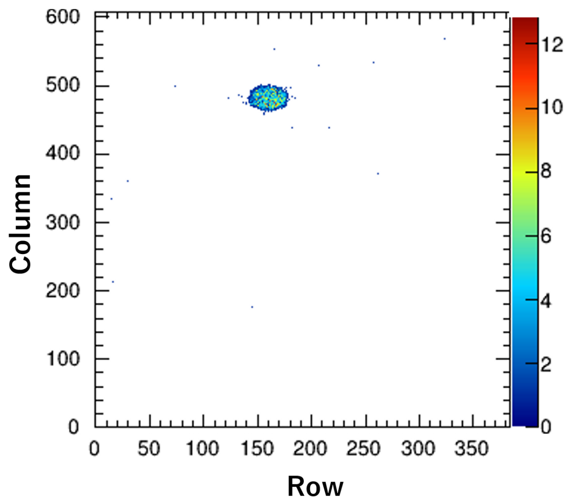

Figure 4: Hit map distribution irradiated by ^{241}Am source through pin hole in the shield.

Also, independent PT100 temperature sensors inside the lead shield and supplied voltages are monitored by the Grafana based system.

4. Commissioning

There is a known problem in XRPIX7 does not work when the full depletion voltage is applied. Though the reason is still under investigation, we comfirmed the chip works under the moderate bias voltage of XX V. To estimate the detection efficiency of XRPIX7, at first, we measured the collimated radiation flux of our ^{241}Am source by the Amptek XR100SDD using the detection efficiency in spec sheet, then we measured the efficiency as a ratio of XRPIX7 count rate to the flux under the same configuration of the first. We obtained the detection efficiency XX%.

The first module for the background subtraction which comprises of a standard Fe foil sandwiched two XRPIXs was assembled with copper and lead shields. We conducted the background measurement for X hours without any VETOs. Fig. X shows the result of background distribution of the measurement. From this, we obtained expected background rate $xx \pm yy$ dru in region of our interest of 14.4±FWHM keV. This value is comparable or lower to the rate of the measurement[XX].

5. Axion sensitivity

The de-excitation rate R is measured by the observation using $R = N_{sig}/(M\eta\epsilon)$, where N_{sig} is detected number of signal, M is the mass of ^{57}Fe, η is the probability of X-ray emission from ^{57}Fe and ϵ is detection efficiency of 14.4 keV photon.

As shown Fig. 5, we estimate an axion sensitivity of ISAI experiment using the values $M = 127$ mg, $\eta = 0.105$, ϵ =14.9 %, $z = 0.56$, nuclear structure parameters $C = -0.27$, $D = 0.77$, $F = 0.48$, $S = 0.45$ and assuming internal background 0.004 counts/day.

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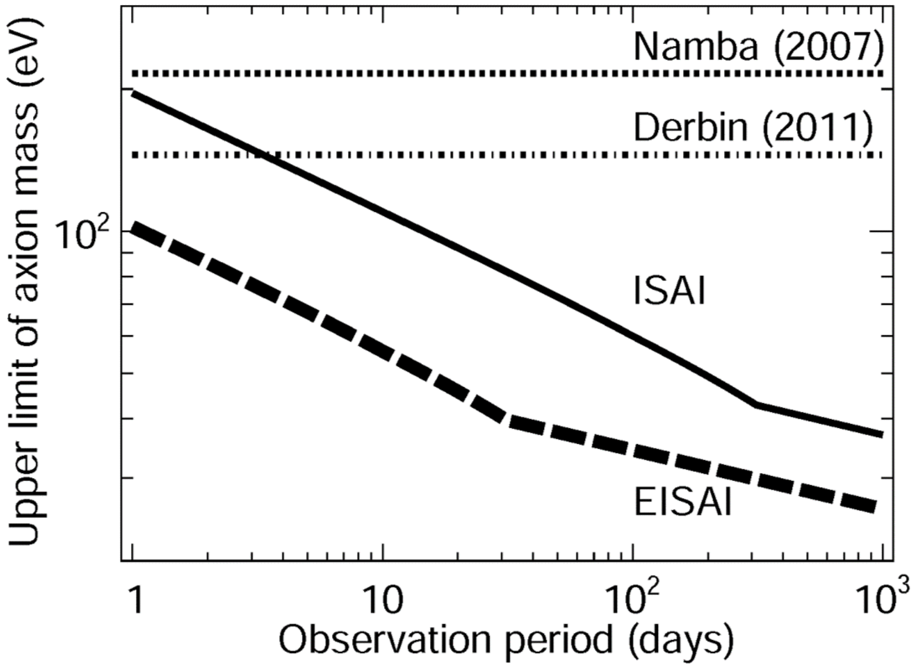

Figure 5: Expected sensitivity of ISAI experiment. The solid and dashed lines show the sensitivity of ISAI, the sensitivity of $10 \times$ larger ^{57}Fe mass of future experiment EISAI, respectively. The dotted and dash-dotted lines represent the constraint from Namba [14] and Derbin[15].

6. Summary

ISAI, Investigating Solar Axion by Iron-57 is an experiment dedicated measurement of g_{an} without introducing the other interactions. The commissioning is on-going.

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