PROCEEDINGS OF SCIENCE

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

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

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

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)1389

1. Introduction

Strong CP problem is that a CP violating term in Lagrangian of quantum chromodynamics which can induce a neutron dipole moment, however, is found to be highly suppressed[1, 2] at $\lesssim 10^{-10}$ level in 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] 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 interacting ^{57}Fe nucleus

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 nucleus on the earth and emit monochromatic 14.4 keV γ by the deexcitation. 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,

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

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

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

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

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

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

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].

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 and the readout system composed of two X-ray detector modules, a position sensitive cosmic-ray veto counter in the climate chamber.

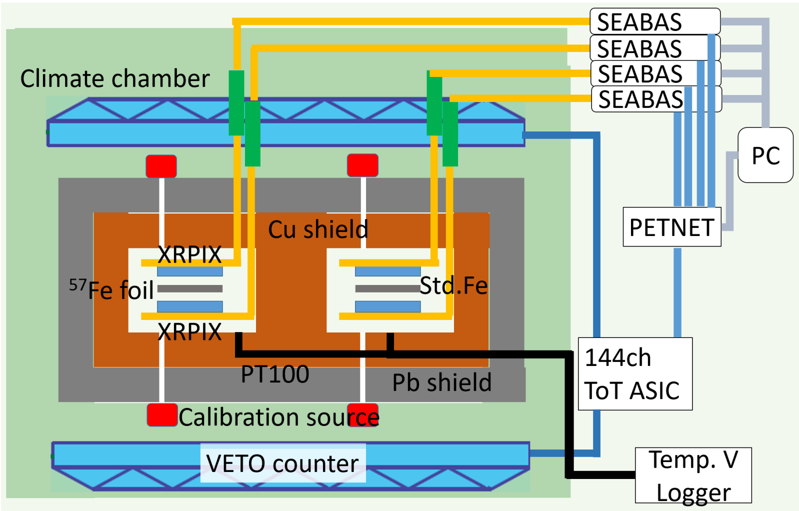

Figure 1: Schematic drawing of ISAI detector.

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 silicon on insulator 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 in the event-driven mode which enables XRPIX to cope with external detectors for background rejection by an anti-coincidence technique. Analog signal from XRPIX is readout through the flexible printed circuit board (flex) cable and digitized by SEABAS board[24, 25] in Fig. 2 a). The data is acquired by PC through the Ethernet.

In the previous study[26], 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 b), composed of 2 layers of G10 rigid circuit board on top and bottom of 2 layers of polyimide flex which contains the least radioactive isotopes background, internally connecting electrically. It realizes physical separation and electrical connection between the 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. 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 detector inside of the copper shield has a $\sim 10^{-3}$ radioactivity compared with the G10 board. The major background source of current detector is multi-layer ceramic capacitors. Fig. 4 shows energy resolution measured by the XRPIX7 on the FLEX using ^{241}Am source. We obtained the energy resolution of 2.8 keV (FWHM) at 13.9 keV.

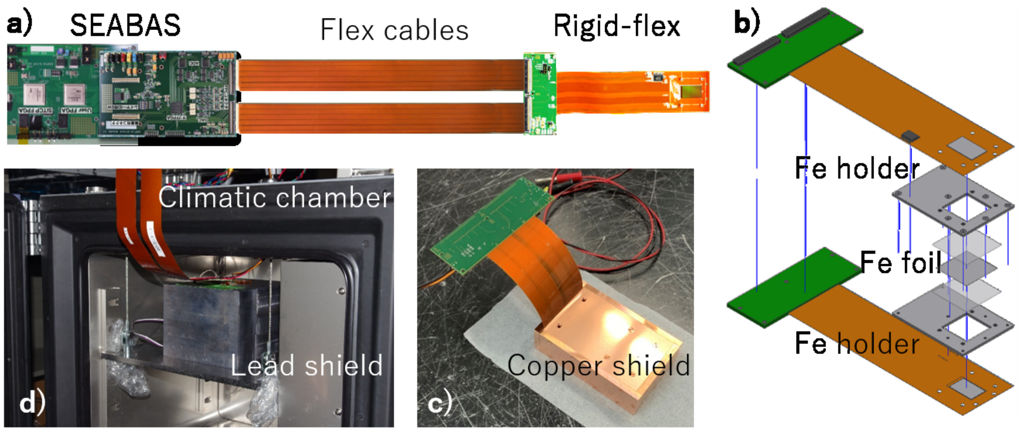

Figure 2: Readout of XRPIX using rigid-flexible circuit board. a) shows a readout unit of a XRPIX7. b) represents schematic drawing of a module composed of two XRPIXs. c) and d) are pictures of copper and lead shield, respectively.

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. 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 triangular 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 digitalization by a dual 32 channel 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. 3 shows a hit map distribution of XRPIX7. In this region we can monitor the detection efficiency and the gain, respectively. Also, independent PT100 temperature sensors inside the lead shield and supplied voltages are monitored by the Grafana based system.

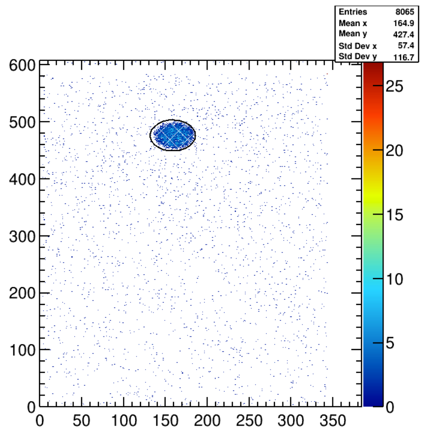

Figure 3: Demonstrated hit map distribution irradiated by ^{241}Am source through pin hole in the shield.

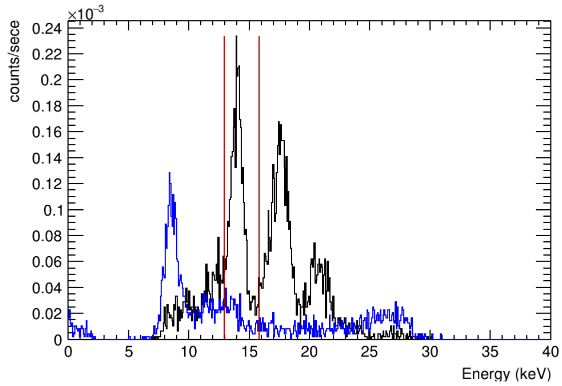

Figure 4: Demonstrated energy distribution irradiated by ^{241}Am source in Fig.3. The black line and blue line show the energy distribution of pixels inside and outside of pin-hole, respectively. The red lines show signal boundary defined by the FWHM 2.8 keV at 13.9 keV around 14.4 keV.

4. 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, $\eta = 0.105$, $\epsilon = 14.9$ %, $z = 0.56$, nuclear structure parameters $C = -0.27$, $D = 0.77$, $F = 0.48$, $S = 0.45$ and assuming internal background 0.004 counts/day.

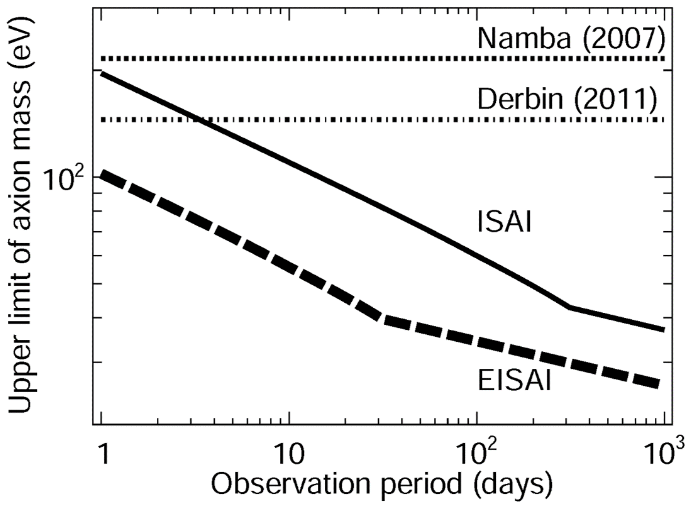

Figure 5: Expected sensitivity of ISAI experiment. The solid and dashed lines show the sensitivity of ISAI, the sensitivity of $10\times$ larger ^{57}Fe mass of future experiment EISAI, respectively. The dotted and dash-dotted lines represent the constraint from Namba [14] and Derbin[15].

5. Commissioning

There is a known problem in XRPIX7 cannot operate with full depletion but it is solved by the latest XRPIX. Though reason of the issue in XRPIX7 is not fully understood, we confirmed the chip works under the moderate bias voltage of 10 V. The detection efficiency is estimated to be a several % by a ratio of collimated radiation fluxes of XRPIX and the Amptek XR100SDD whose efficiency provided in the specification sheet. The first module comprises of a standard Fe foil sandwiched two XRPIXs was assembled and shielded by copper and lead of same thickness of ISAI experiment for the background measurement without timing veto from the plastic scintillator detector. The first preliminary result of raw background distribution in the commissioning without gain correction is shown in Fig. 6. The coarse binning is adjusted to be sufficiently larger than the typical gain correction range.

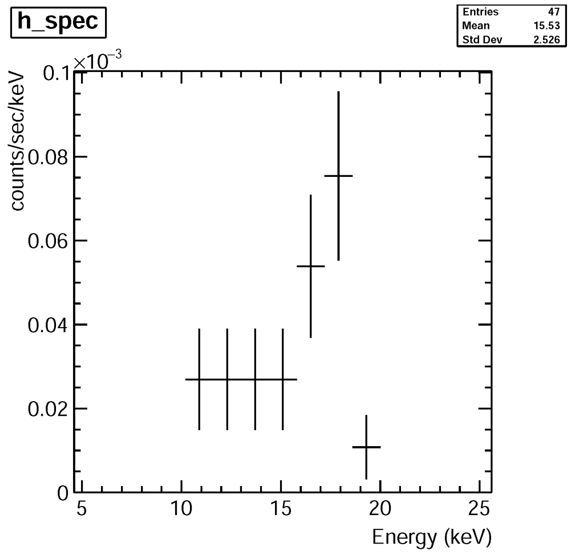

Figure 6: Raw background distribution of ISAI detector module using a standard Fe foil.

6. Summary

The ISAI is an experiment dedicated measurement of g_{an} without introducing the other interactions. The first module for the background estimation had been assembled and commissioning now. We obtained a provisional background distribution without any timing vetos. The result seems to be reasonably low rate we achieved and expects further improvement brought by timing veto in the near future. We will start full commissioning of all detector in this year and observation followed soon after.

References

[1] Baluni, V., *CP violating effects in QCD.*, *Phys. Rev. D* **19** 2227 (1979).

[2] Crewther, R.J., Di Vecchia, P., Veneziano G., Witten, E. *Chiral estimate of the electric dipole moment of the neutron in quantum chromodynamics.*, *Phys. Lett. B* **88** 123 (1979).

[3] C. Abel et al., *Measurement of the Permanent Electric Dipole Moment of the Neutron.*, *Phys. Rev. Lett.* **124** 081803 (2020).

[4] Peccei, R.D., Quinn, H.R., *CP conservation in the presence of instantons.*, *Phys. Rev. Lett.* **38** 1440 (1977).

[5] Peccei, R.D., Quinn, H.R., *Constraints imposed by CP conservation in the presence of instantons.*, *Phys. Rev. D* **16** 1791 (1977).

[6] Kim, J.E, *Weak interaction singlet and strong CP invariance.*, *Phys. Rev. Lett.* **43** 103 (1979).

[7] Shifman, M.A., Vainshtein, A.I., Zakharov, V.I., *Can confinement ensure natural CP invariance of strong interaction ?*, *Nucl. Phys. B* **166** 493 (1980).

[8] Dine, M., Fischler, W., Srendnicki, M., *A simple solution to the strong CP problem with a harmless axion.*, *Phys. Lett. B* **104** 199 (1981).

[9] Zhitnitsky A.R., *On possible suppression of the axion hadron interactions.*, *Sov. J. Nucl. Phys.* **31** 260 (1980).

[10] Shigetaka Moriyama, *Proposal to Search for a Monochromatic Component of Solar Axions Using ^{57}Fe.*, *Phys. Rev. Lett.* **75** 322 (1995).

[11] V. Mateu and A. Pich, *V_{us} Determination from Hyperon Semileptonic Decays*, *J. High Energy Phys.* **0510** 041 (2005).

[12] E143 Collaboration, K. Abe et al., *Precise Measurement of the Deuteron Spin Structure Function g_1^d*, *Phys. Rev. Lett.* **75** 25 (1995).

[13] M. Krčmar, Z. Krečak, M. Stipčević, A. Ljubičić, D. A. Bradley *Search for solar axions using ^{57}Fe*, *Phys. Lett. B* **645** 398 (2007).

[14] T. Namba, *Results of a search for monochromatic solar axions using ^{57}Fe*, *Phys. Lett. B* **645** 398 (2007).

[15] A. V. Derbin, V.N. Muratova, D.A. Semenov and E. V. Unzhakov *New Limit on the Mass of 14.4-keV Solar Axions Emitted in an M1 Transition in ^{57}Fe Nuclei*, *Phys. Atom. Nucl.* **74** 596 (2011).

[16] S. G. Ryu, T. G. Tsuru, S. Nakashima, A. Takeda, Y. Arai, T. Miyoshi, R. Ichimiya, Y. Ikemoto, H.Matsumoto, T. Imamura, T. Ohomoto and A. Iwata, *First performance evaluation of an x-ray soi pixel sensor for imaging spectroscopy and intra-pixel trigger*, *IEEE Trans. Nucl. Sci.* **58**(5) 2528 (2011).

[17] S. G. Ryu, T. G. Tsuru, G. Prigozhin, S. Kissel, M. Bautz, B. LaMarr, S. Nakashima, R. F. Foster, A. Takeda, Y. Arai, T. Imamura, T. Ohomoto et al., *Tests with soft x-rays of an improved monolithic soi active sensor*, *IEEE Trans. Nucl. Sci.* **60**(1) 465 (2013).

[18] A. Takeda, Y. Arai, S. G. Ryu, S. Nakashima, T. G. Tsuru, T. Imamura, T. Ohomoto and A. Iwata, *Design and evaluation of an soi pixel sensor for trigger-driven x-ray readout*, *IEEE Trans. Nucl. Sci.* **60**(2) 586 (2013).

[19] A. Takeda, T. G. Tsuru, T. Tanaka, H. Uchida, H. Matsumura, Y. Arai, K. Mori, Y. Nishioka, R. Takenaka, T. Kohmura, S. Nakashima, S. Kawahito et al., *Improvement of spectroscopic performance using a charge-sensitive amplifier circuit for an x-ray astronomical SOI pixel detector*, *J. Instrum.* **10**(06) C06005 (2015).

[20] S. Harada, T. G. Tsuru, T. Tanaka, H. Uchida, H. Matsumura, K. Tachibana, H. Hayashi, A. Takeda, K. Mori, Y. Nishioka, N. Takebayashi, S. Yokoyama et al., *Performance of the silicon-on-insulator pixel sensor for x-ray astronomy, xrpix6e, equipped with pinned depleted diode structure*, *Nucl. Instrum. Methods. A* **924** 468 (2019).

[21] H. Hayashi, T. G. Tsuru, T. Tanaka, H. Uchida, H. Matsumura, K. Tachibana, S. Harada, A. Takeda, K. Mori, Y. Nishioka, N. Takebayashi, S. Yokoyama et al., *Evaluation of Kyoto's event-driven x-ray astronomical soi pixel sensor with a large imaging area*, *Nucl. Instrum. Methods. A* **924** 400 (2019).

[22] T. G. Tsuru, H. Hayashi, K. Tachibana, S. Harada, H. Uchida, T. Tanaka, Y. Arai, I. Kurachi, K. Mori, A. Takeda, Y. Nishioka, N. Takebayashi et al., *Kyoto's event-driven x-ray astronomy SOI pixel sensor for the FORCE mission*, In A. D. Holland and J. Beletic, eds., *High Energy Optical, and Infrared Detectors for Astronomy VIII*, vol. 10709, p. 107090H. International Society for Optics and Photonics, SPIE.

[23] K. Nakazawa, K. Mori, T. G. Tsuru, Y. Ueda, H. Awaki, Y. Fukuzawa, M. Ishida, H. Matsumoto, H. Murakami, T. Okajima, T. Takahashi, H. Tsunemi et al., *The FORCE mission: science aim and instrument parameter for broadband x-ray imaging spectroscopy with good angular resolution*, In J.-W. A. den Herder, S. Nikzad and K. Nakazawa, eds., *Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray*, vol. 10699, p. 106992D. International Society for Optics and Photonics, SPIE.

[24] Tomohisa Uchida and Manobu Tanaka, *Development of TCP/IP processing hardware*, *2006 IEEE Nuclear Science Symposium Conference Record* **NS33-6** 1411 (2006).

[25] Tomohisa Uchida, IEEE Nucl. Sci. Vol.56-5, pp. 2896-2904, 2009. *Hardware-Based TCP Processor for Gigabit Ethernet*, *IEEE Trans. Nucl. Sci.* **55**(3) 1631 (2008).

[26] Y. Onuki, J. A. M. Grimaldo, T. Ose, H. Aihara, Y. Inoue, Y. Kamiya, K. Shimazoe, T. G. Tsuru, T. Tanaka, K. Miuchi, A. Takeda and Y. Arai, *Studies of radioactive background in soi pixel detector for solar axion search experiment*, *Nucl. Instrum. Methods. A* **924** 448 (2019).

[27] Setsuo Sato, Uenomachi Mizuki and Kenji Shimazoe *Development of multichannel high time resolution data acquisition system for TOT-ASIC.*, *IEEE Trans. Nucl. Sci.* **68**(8) 1801 (2021).