ISAI: Investigating Solar Axion by Iron-57

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Abstract

The existence of the axion is a unique solution for the strong CP problem, and the axion is one of the most promising candidates of the dark matter. Investigating Solar Axion by Iron-57 (ISAI) is being prepared as a complemented table-top experiment to confirm the solar axion scenario. Probing an X-ray emission from the nuclear transitions associated with the axion-nucleon coupling is a leading approach. ISAI searches for the monochromatic 14.4 keV X-ray from the first excited state of ^{57}Fe using a state-of-the-art pixelized silicon detector, dubbed XRPIX, under an extremely low-background environment. We highlight scientific objectives, experimental design and the latest status of ISAI.

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1 Introduction

Quantum chromodynamics requires extremely fine-tuning to explain the observed electric dipole moment of the neutron [1, 2]. This problem is generally known as the strong CP problem. Peccei and Quinn proposed a global $U(1)$ symmetry whose breaking gives a rise to a new pseudoscalar boson called axion [3–5]. Moreover, the axion could be a part of the dark matter [6]. Therefore, the axion search is one of the most important topics in the fields of astrophysics and particle physics. The axion mass (m_a) and the coupling strength are proportional to the inverse of the breaking scale (f_a). The axion mass can be written with the following relation:

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

where $z = m_u/m_d$ is the mass ratio of the up and down quark. Since the higher breaking scale than the electroweak scale makes the weakly interacting, axions become invisible. One of the invisible axion models is the Kim-Shifman-Vainstein-Zakharov (KSVZ) axion, or called as the hadronic axion, which does not have tree-level couplings to leptons and ordinary quarks. The brightest source of such axion is the Sun, and the solar axion flux on Earth is calculated in Ref [7]. Some experiments have been performed as the axion helioscope and searched for the axion-photon and axion-electron coupling using the Primakoff effect or Compton interaction [8, 9]. The other novel method to independently verify the axion-nucleon coupling of the hadronic axion was proposed by Moriyama [10]. ^{57}Fe nuclei are thermally excited in the Sun and can decay by emitting monochromatic axions corresponding to 14.4 keV. Emitted monochromatic axions can resonantly excite ^{57}Fe nuclei thanks to the doppler broadening of the axion energy due to the thermal motion of the ^{57}Fe nuclei in the Sun. The expected excitation rate per unit mass of ^{57}Fe is written as,

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

where C depends on the nuclear structure. The most stringent upper limit on the mass of the axion was reported in 2007 to be $m_a < 216$ eV using the Si PIN photodiodes [11]. In this paper, we propose to search for the monochromatic 14.4 keV axion with a pixelized silicon detector called XRPIX. Furthermore, we describe the detector design, its performance, and the predicted sensitivity to the mass of the axion.

2 Detector design and instruments

2.1 Investigating Solar Axion by Iron-57 (ISAI)

The detector design of the Investigating Solar Axion by Iron-57 (ISAI) is shown in Fig. 1. ISAI consists of two detector modules. In one module, a 95.85% enriched ^{57}Fe foil, whose size is 3.2 cm × 3.2 cm × 40 μm, is set and used as the axion absorber. In the other module, a natural Fe foil is set instead and used as a reference for the background study. The escape probability of 14.4 keV X-rays from such foil is 24.8%. Foils are covered by two XRPIX detectors, whose detection area and the depletion thickness are 21.9 mm × 13.8 mm and 300 μm, respectively. The distance between the XRPIXs and the foil is 3 mm and its detection efficiency of the 14.4 keV X-rays is 14.5%. Oxygen-free copper plates with a thickness of 5 mm are arranged around the XRPIXs as passive shieldings to protect from X- and beta-rays emitted from the lead shieldings outside. The lead shieldings, whose thickness is 50 mm are specified to reduce the penetration of environment gamma rays. Anti-counters made by plastic scintillators are used to measure the trajectory of cosmic-ray particles to reduce these backgrounds. These instruments are located inside a thermostatic chamber to keep the XRPIXs at a low temperature.

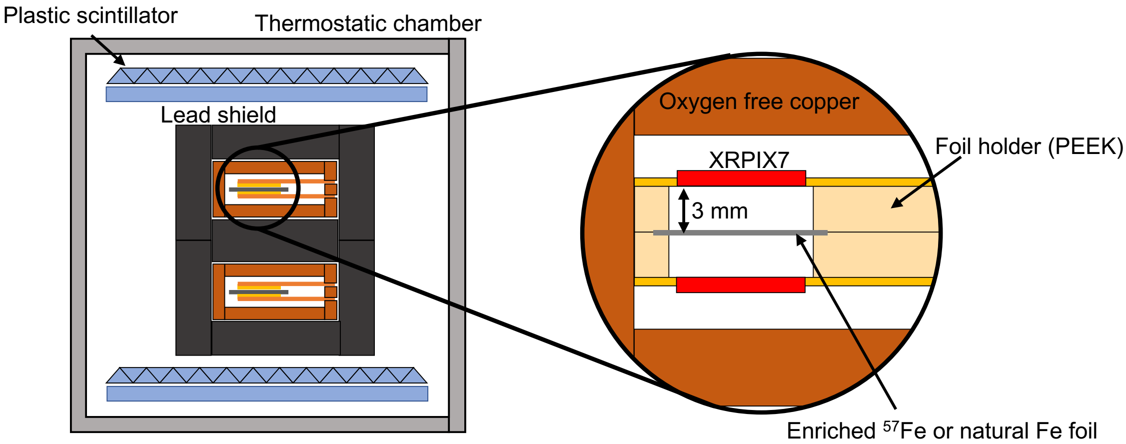

Figure 1: Schematic drawing of the detector design of ISAI. The left picture shows the overall detector, which consists of two sets of main detector modules surrounded by plastic scintillators as the anti-counter and a thermostatic chamber. The right picture shows the details around the enriched ^{57}Fe or natural Fe foil.

2.2 XRPIX

XRPIX [12–18], which is one of the monolithic active pixel detectors based on the silicon-on-insulator (SOI) pixel technology, has been developed for a future X-ray astronomy mission, so-called FORCE [19], since 2011. We are planning to employ series number seven (XRPIX7) which has the largest detection area. The XRPIX7 has 608 × 384 pixels and the pixel size is 36 μm × 36 μm. Therefore, the XRPIX7 covers a detection area of 21.9 mm × 13.8 mm. The picture of XRPIX7 is shown in Fig. 2(a). Each pixel is equipped with a CMOS circuit for the signal processing, including comparators. The comparator gives the hit trigger, timing, and position. Furthermore, the XRPIX7 outputs the pulse heights around the hit pixels as the event-driven readout mode. Therefore, the XRPIX7 offers a time resolution better than 10 μs, $\sim 10^{3-5}$ faster than scientific CCDs, and enables the use of an anti-coincidence technique to reduce backgrounds. Fig. 2(b) shows the observed spectrum of an ^{241}Am source with the event-driven readout mode. The obtained energy resolution was 478 eV (FWHM) at 13.9 keV on the whole detection area. An X-ray image taken with a metal mask is shown in Fig. 2(c).

The conventional circuit board made of G10 glass epoxy included many background sources of ^{238}U, ^{232}Th, and ^{40}K [20]. Hence, we developed a rigid flexible print circuit board as a low-background readout system (Fig. 2(a)). The XRPIX7 bare chip is mounted on the flexible print circuit part without G10 glass epoxy and the rigid print circuit is part from the sensor. Only ceramic capacitors are implemented near the XRPIX7. Compared to the conventional circuit board, the background rate in the energy region of 14.4 keV is a factor of about 10^{-3}.

2.3 Plastic scintillator as anti-counter

An anti-counter system comprised of plastic scintillators is installed on the top and bottom of the main detector as shown in Fig. 1. The cross-section of each scintillator is not a square, but an isosceles triangle with a width of 5 cm and a height of 1 cm to enhance the position accuracy by a signal ratio of two adjacent scintillators. There are 11 scintillators with a length of 30 cm in each layer. Two sets of two layers of X and Y directions are capable of measuring the trajectory of an individual cosmic ray particle as a position-sensitive anti-counter. The

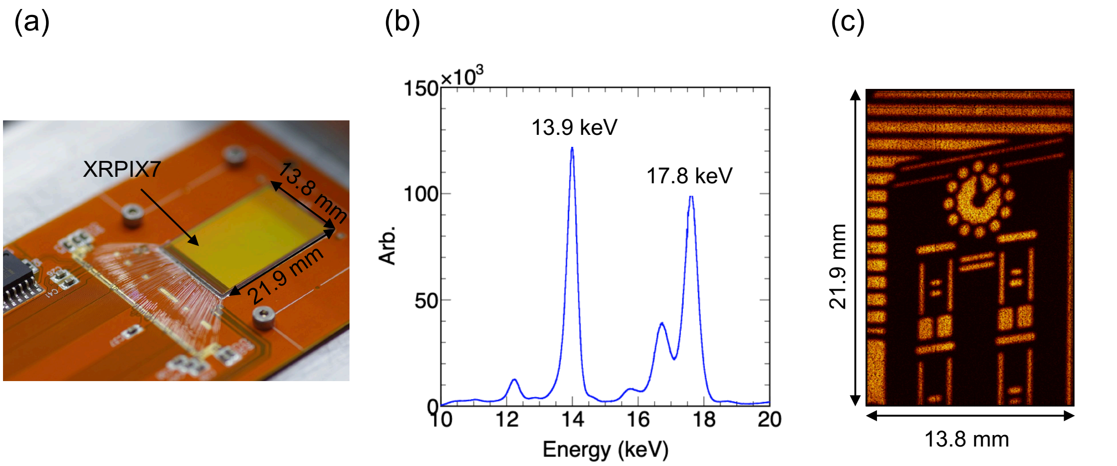

Figure 2: (a) Photograph of XRPIX7. (b) Spectrum of ^{241}Am with event-driven read-out mode. (c) X-ray image using the metal mask.

signals of scintillators are measured by SiPM (S13360-1375PE, Hamamatsu), and all of their waveforms are digitized by a dual 32ch 14-bit Flash ADC (ADS52J90, Texas Instrument).

3 Sensitivity

Using Eqs. (1) and (2), the axion mass is computed via the following equation:

$$m_a = 5.55 \times \left(\frac{R}{1\ \mathrm{day}^{-1}\mathrm{kg}^{-1}} \right)^{1/4} \mathrm{eV}\,, \tag{3}$$

where R is the ^{57}Fe de-excitation rate and rewritten as $R = N_\gamma/(M\eta\epsilon)$. We assumed the mass ratio z and the nuclear structure C as 0.56 and 0.27, respectively. Here, N_γ is the count rate, M is the ^{57}Fe mass, η is the emission probability of 14.4 keV X-rays, and ϵ is the detection efficiency. The sensitivity is calculated by replacing N_γ with the background rate N_{BG}. The black solid line in Fig. 3 shows the expected sensitivity where we assumed that $M = 127$ mg, $\eta = 0.105$, and $\epsilon = 0.145$. Furthermore, $N_{\mathrm{BG}} = 0.004$ counts/day was estimated by the internal background simulation associated with the energy resolution of 250 eV (FWHM) at 14.4 keV. A 95% confidence level upper limit on the axion mass of 145 eV corresponding to Derbin's result [21] is reachable in about four days. The dashed line indicates the expected sensitivity of the future work with ten times the target mass.

4 Future prospects

We plan to start the commissioning run without the anti-counter and the ^{57}Fe foil at the end of 2022. Then, the primary performance of XRPIX7 and the ambient gamma-ray background are verified over three months. Anti-counters are calibrated using muons of cosmic rays in parallel. In 2023, a scientific run will be carried out with the complete system of ISAI for one year. While the current energy resolution of XRPIX7 reaches less than 250 eV, we will be able to record the best upper limit in about one week. Moreover, we are developing the new XRPIX of series number ten to overcome the energy resolution. The XRPIX7 will be replaced with XRPIX10 as soon as development is complete.

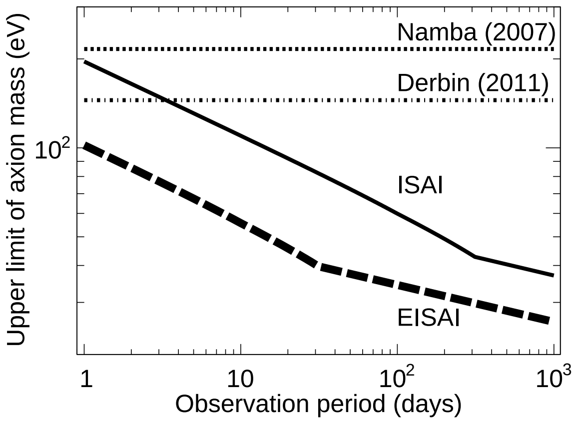

Figure 3: Expected sensitivities. The solid and dashed lines show this work and future work of 10 times ^{57}Fe, respectively. The dotted and dash-dotted lines indicate the constraints from Namba [11] and Derbin [21], respectively.

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References

[1] R. J. Crewther, P. Di Vecchia, G. Veneziano and E. Witten, *Chiral estimate of the electric dipole moment of the neutron in quantum chromodynamics*, Phys. Lett. B **88**, 123 (1979), doi:10.1016/0370-2693(79)90128-X.

[2] J. M. Pendlebury et al., *Revised experimental upper limit on the electric dipole moment of the neutron*, Phys. Rev. D **92**, 092003 (2015), doi:10.1103/PhysRevD.92.092003.

[3] R. D. Peccei and H. R. Quinn, *CP conservation in the presence of pseudoparticles*, Phys. Rev. Lett. **38**, 1440 (1977), doi:10.1103/PhysRevLett.38.1440.

[4] S. Weinberg, *A new light boson?*, Phys. Rev. Lett. **40**, 223 (1978), doi:10.1103/PhysRevLett.40.223.

[5] F. Wilczek, *Problem of strong P and T invariance in the presence of instantons*, Phys. Rev. Lett. **40**, 279 (1978), doi:10.1103/PhysRevLett.40.279.

[6] J. Ipser and P. Sikivie, *Can galactic halos be made of axions?*, Phys. Rev. Lett. **50**, 925 (1983), doi:10.1103/PhysRevLett.50.925.

[7] J. Redondo, *Solar axion flux from the axion-electron coupling*, J. Cosmol. Astropart. Phys. 008 (2013), doi:10.1088/1475-7516/2013/12/008.

[8] V. Anastassopoulos et al., *New CAST limit on the axion-photon interaction*, Nat. Phys. **13**, 584 (2017), doi:10.1038/nphys4109.

[9] E. Aprile et al., *Excess electronic recoil events in XENON1T*, Phys. Rev. D **102**, 072004 (2020), doi:10.1103/PhysRevD.102.072004.

[10] S. Moriyama, *Proposal to search for a monochromatic component of solar axions using ^{57}Fe*, Phys. Rev. Lett. **75**, 3222 (1995), doi:10.1103/PhysRevLett.75.3222.

[11] T. Namba, *Results of a search for monochromatic solar axions using ^{57}Fe*, Phys. Lett. B **645**, 398 (2007), doi:10.1016/j.physletb.2007.01.005.

[12] S. G. Ryu et al., *First performance evaluation of an X-Ray SOI pixel sensor for imaging spectroscopy and intra-pixel trigger*, IEEE Trans. Nucl. Sci. **58**, 2528 (2011), doi:10.1109/TNS.2011.2160970.

[13] S. G. Ryu et al., *Tests with soft X-rays of an improved monolithic SOI active pixel sensor*, IEEE Trans. Nucl. Sci. **60**, 465 (2013), doi:10.1109/TNS.2012.2231880.

[14] A. Takeda et al., *Design and evaluation of an SOI pixel sensor for trigger-driven X-Ray readout*, IEEE Trans. Nucl. Sci. **60**, 586 (2013), doi:10.1109/TNS.2012.2225072.

[15] A. Takeda et al., *Improvement of spectroscopic performance using a charge-sensitive amplifier circuit for an X-ray astronomical SOI pixel detector*, J. Instrum. **10**, C06005 (2015), doi:10.1088/1748-0221/10/06/c06005.

[16] S. Harada et al., *Performance of the Silicon-On-Insulator pixel sensor for X-ray astronomy, XRPIX6E, equipped with pinned depleted diode structure*, Nucl. Instrum. Methods Phys. Res. A **924**, 468 (2019), doi:10.1016/j.nima.2018.09.127.

[17] H. Hayashi et al., *Evaluation of Kyoto's event-driven X-ray astronomical SOI pixel sensor with a large imaging area*, Nucl. Instrum. Methods Phys. Res. A **924**, 400 (2019), doi:10.1016/j.nima.2018.09.042.

[18] T. G. Tsuru et al., *Kyoto's event-driven x-ray astronomy SOI pixel sensor for the FORCE mission*, Proc. SPIE **10709**, 107090H (2018), doi:10.1117/12.2312098.

[19] K. Nakazawa et al., *The FORCE mission: Science aim and instrument parameter for broadband x-ray imaging spectroscopy with good angular resolution*, Proc. SPIE **10699**, 106992D (2018), doi:10.1117/12.2309344.

[20] Y. Onuki et al., *Studies of radioactive background in SOI pixel detector for solar axion search experiment*, Nucl. Instrum. Methods Phys. Res. A **924**, 448 (2019), doi:10.1016/j.nima.2018.07.056.

[21] 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. Nuclei **74**, 596 (2011), doi:10.1134/S1063778811040041.