Results of a search for monochromatic solar axions using $^{57}$Fe

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Abstract

We have searched for 14.4 keV monochromatic axions which could be emitted from $^{57}$Fe nuclei in the solar core. Using the resonant absorption of $^{57}$Fe nuclei, no evidence related to the axions is observed, and upper limit on axion mass of $m_a < 216$ eV is obtained at 95% C.L. This limit is factor 3.4 more stringent than the previous similar experiment, and, except for the SN1987A arguments, the most stringent experimental limit purely obtained from axion–nucleon couplings.

Key words: Solar axions, PIN photodiodes, Nuclear M1 transitions, Resonance scattering

1 Introduction

Quantum ChromoDynamics (QCD) is the theory to describe the strong interactions. Although QCD has proven remarkably successful, there is a blemish called the strong CP problem. The most attractive solution to solve the strong CP problem is the Peccei-Quinn mechanism [1] in which a global chiral symmetry breaks down spontaneously at an energy scale $f_a$. The CP breaking term of the QCD is canceled to be zero, and a new pseudo Nambu-Goldstone boson, an axion, is predicted [2].

It was originally thought that the breaking scale ($f_a$) is at the weak interaction scale ($\sim 250$ GeV), and the coupling strength of the axion is relatively large. Although this original axion model has been experimentally excluded, some variant axion models in which $f_a$ is much higher than the electroweak scale are still viable. Because the axion mass ($m_a$) and the strength of its couplings
are proportional to the inverse of $f_a$, axions with large $f_a$ becomes weakly interacting. One of such weak-interactive axion models is KSVZ (Kim, Shifman, Vainshtein, and Zakharov) axion, or called as hadronic axion [3].

Many laboratory experiments have been performed to search for the axion, but they excluded only $m_a \geq 10$ keV region [5,6]. Some cosmological or astrophysical arguments constrain $m_a$ to the well-known allowed window, $10^{-6}$ eV $< m_a < 10^{-2}$ eV, however, many of them depend on cosmological models or stellar models [4]. Furthermore, another uncertainty also comes from the axion model itself. Although many astrophysical arguments are based on the stellar energy loss arguments which depends on the axion-photon coupling, this coupling has a model-dependent parameter $E/N$, which is the ratio of the electromagnetic and color anomaly [7]. In some worst cases like KSVZ model ($E/N \simeq 2$), the axion-photon coupling almost vanishes, and the constraints based on this coupling become weak. In this case, only the axion-nucleon coupling can be reliable, and only the arguments from SN1987A constrain the heavier side of the window. Another allowed window opens at around $m_a \simeq$ a few tens of eV [8].

In this paper, we assumed the best known astrophysical object, the sun, as an axion source, and searched for solar axions at the laboratory. For the axion emission and observation, we assumed only the axion-nucleon coupling, which does not suffer from the $E/N$ uncertainty.

\section{Experimental principle}

The method to detect the axion using $^{57}$Fe isotope has been proposed in [9]. 14.4keV monochromatic axions are emitted from the sun. $^{57}$Fe nuclei are thermally excited to the 14.4 keV first excited state in the solar core whose temperature is about 1.3 keV. The excited $^{57}$Fe nucleus soon de-excites and emits a 14.4 keV photon or a conversion electron. Since this transition is $M1$ transition, an axion also could be emitted from the nucleus. Because of the weak couplings between the axion and matters, the emitted axion could easily escape from the solar core. The expected flux of the monochromatic axion on the earth surface is

$$A = 2.0 \times 10^{13} \text{ cm}^{-2}\text{s}^{-1}\text{keV}^{-1} \left( \frac{10^6 \text{ GeV}}{f_a} \right)^2 C^2, \quad (1)$$

Here, $C$ contains parameters of the nuclear structure as follows [9].

$$C(D, F, S, z) = -1.19 \left( \frac{3F - D + 2S}{3} \right) + (D + F) \frac{1 - z}{1 + z}, \quad (2)$$
where $D$ and $F$ denote the reduced matrix elements for the $SU(3)$ octet axial vector currents, $S$ characterizes the flavor singlet coupling, and $z = m_u/m_d$ is the up- and down-quark mass ratio. As for $D$ and $F$, they can be measured by nucleon and hyperon $\beta$ decays, and we use their values of $D = 0.798$ and $F = 0.459$. For $S$ and $z$, we assumed $S = 0.5$ and $z = 0.56$ as in [10].

This monochromatic axion would resonantly excite $^{57}$Fe nuclei similar to the Mössbauer effect. The difference from the Mössbauer experiments is that there is no need to move the axion absorber, since the emitted energy width is extremely broadened (FWHM $\sim 5$ eV) due to the thermal motion of the source nuclei in the solar core. The expected excitation rate of $^{57}$Fe is also calculated as follows [9].

$$R = 3.0 \times 10^2 \text{ day}^{-1} \text{ kg}^{-1} \left( \frac{10^6 \text{ GeV}}{f_a} \right)^4 C^4. \quad (3)$$

Krčmar et al. reported a pioneering result [10] by searching 14.4 keV $\gamma$ rays from an iron foil with a standard Si(Li) detector and obtain limit of $m_a < 745$ eV.

### 3 Detector setup

Figure 1 shows a schematic view of our detector. The detector consists of an iron foil, two silicon PIN photodiodes, a cryostat, and lead shielding. Because the attenuation length of 14.4 keV $\gamma$ rays in iron is 20 $\mu$m, a 95.85% enriched $^{57}$Fe foil whose size is 40 $\mu$m $\times$ 32 mm $\times$ 32 mm is used as the axion absorber.

Two silicon PIN photodiodes, Hamamatsu S3584–06 SPLPKG 4175, are used for the detection of 14.4 keV $\gamma$ rays. The chip size of these PIN photodiodes is 500 $\mu$m $\times$ 30 mm $\times$ 30 mm, and the active area of them is 28 mm $\times$ 28 mm. These chips are mounted on special low background ceramic bases. The standard ceramic base of S3584–06 contains radioactive impurities (U-chain: $\sim$ 0.3 Bq and Th-chain: $\sim$ 0.1 Bq), and fluorescence X rays from these impurities make peaks around 14.4 keV. U/Th-chain contaminations are reduced by about two orders of magnitude, and no peak structures are observed around 14.4 keV with this low background base.

These two PIN photodiodes are placed in two brass holders, and these holders sandwich the iron foil. No materials are placed between the foil and silicon chips, and the distance between the foil and the each chips are 2 mm.

Amplifiers for these photodiodes are almost same circuits described in [12]. The first stage circuits which include JFETs (HITACHI 2SK291) and 5 GΩ
feed back resistors are placed on the back sides of the each brass holders. The other parts of the preamplifiers are attached at the outside of the cryostat.

The photodiodes and the first stage circuits are set at the bottom of the cryostat and cooled down by dry ice (195 K) to suppress thermal noise. During measurements, the cryostat was evacuated by a TMP at around $10^{-4}$ Pa, and the temperatures of the brass holders and the first stage JFETs are kept at (198 ± 1) K and (212 ± 1) K, respectively.

The output signals of the preamplifiers are amplified by another linear amplifiers and taken by flash ADC’s (REPIC RPC-081). The outputs of linear amplifiers are also fed into shaping amplifiers (ORTEC 572) and used to make triggers by discriminators (LeCroy CL620). The flash ADC’s take the waveform of the linear amplifiers over ±100 µs with a sampling period of 0.2 µs for triggered events.

4 Detection efficiency

The detection efficiency for 14.4 keV $\gamma$ rays emitted from the $^{57}$Fe enriched foil is important to estimate the detection power of such solar axions. This efficiency is estimated with a GEANT4 based simulation which includes the iron foil, the photodiodes, and their supporting structures.

The efficiency is estimated conservatively with the following assumptions.

- The size of the $^{57}$Fe enriched foil is $135 \, \mu\text{m} \times 28 \, \text{mm} \times 28 \, \text{mm}$.
  Although the averaged thickness of the foil is 40 µm, we assumed its thickness as 35 µm which is the worst value assured by the company. The area of the foil is also underestimated as $28 \times 28 \, \text{mm}^2$. Its corresponding mass is 211 mg. This assumption means that we define only 35 µm from the surface of the foil as $^{57}$Fe region and ignore the deeper region.
  In this setup, the escape probability of 14.4 keV $\gamma$ rays from the foil is 26.2%. Taking account of the acceptance of the photodiodes, 22.7% of emitted $\gamma$ rays can reach the effective region of them.
- The surface insensitive layer of the photodiode is 36 µm, and the depletion layer is 385 µm.
  The detection efficiency of the photodiode for the perpendicular irradiation is independently measured with collimated 14.4 keV $\gamma$ rays from a $^{57}$Co source. The absolute intensity from the collimator is calibrated with a CaF$_2$ scintillator, and the detection efficiency of the photodiode for the perpendicular irradiation is found to be (70.6 ± 5.5)% at 95% confidence level.
  We estimate the internal structure of the photodiode from this result.
Under the assumption that there are no surface insensitive layer, the deple-
tion layer should be thicker than 385 µm, and under the assumption that
the photodiodes only consists from the depletion layer and the surface in-
sensitive layer, the surface insensitive layer should be thinner than 36 µm.
Although these two assumptions are not established in the same time, we
conservatively use these two values.

The overall efficiency is estimated to be 14.8% with a detailed simulation. This
value is consistent with a simple calculation, (the escape probability including
the acceptance: 22.7%) × (the worst detection efficiency of the photodiode: 65.1%) = 14.8%.

5 Results and Discussion

We performed two types of measurements, the source measurements, and the
background measurements. The background is estimated with the same mea-
surements except for the $^{57}$Fe enriched foil. $^{57}$Fe enriched foil is replaced with
the natural iron foil which contains only 2.2% of $^{57}$Fe. The source measure-
ments were performed two times, from 27th July to 3rd August, 2005, and
from 25th August to 3rd September, 2005. No significant differences were ob-
served at around the signal region for the both runs. The total livetime of
the source measurements is 13.92 days. On the other hand, the background
measurements were performed between the both runs, and its livetime is 11.99
days. The obtained spectra are shown in Fig. 2 with the statistical errors. Solid
histogram shows the source measurements, and dashed shows the background
measurements.

$^{59.5}$ keV γ rays from $^{241}$Am source were irradiated from the outside of the
cryostat every day for the energy calibration. The gain fluctuation was less
than ±0.3% for all measurements, and the energy threshold was set around 8
keV which is much lower than the 14.4 keV signal region. The energy resolution
($\sigma$) at 59.5 keV peak is 0.83 keV. Although the energy resolution at 14.4 keV
should be better than that at 59.5 keV, even taking the gain fluctuation into
account, we conservatively regarded 14.4 ± 2.0 keV region as ±2σ (95.45%) signal region.

To extract the signals, we subtracted the background data from the source
data (Fig. 3). In the signal region, the total count rate of the axion signal
measurements was (1082 counts)/(13.92 days) = (77.7 ± 2.4) day$^{-1}$, and that
of the background measurements was (918 counts)/(11.99 days) = (76.6 ± 2.5) day$^{-1}$. Therefore, the obtained rate of the signals were consistent with
zero, (1.10 ± 3.46) day$^{-1}$. From this value, we obtain the 95% confidence limit
of the signal as $N_s < 6.79/0.9545$ day$^{-1}$ = 7.12 day$^{-1}$, and we can set the
95% confidence limit of the $^{57}$Fe de-excitation rate as follows.

$$R < \frac{N \gamma}{M_{^{57}} \cdot \gamma_E \cdot \epsilon} = \frac{7.12 \text{ day}^{-1}}{197 \text{ mg} \cdot 0.105 \cdot 0.148} = 2.33 \times 10^6 \text{ day}^{-1} \text{kg}^{-1}.$$

(4)

Here, $\gamma_E$ is the emission probability of 14.4 keV $\gamma$ rays, $\epsilon$ is the detection efficiency estimated in the previous section, $M_{^{57}}$ is the mass of $^{57}$Fe contained in the foil. Since we subtracted the background of the natural iron foil, $M_{^{57}}$ corresponds to the difference of $^{57}$Fe mass between the enriched $^{57}$Fe foil and the natural iron foil. The limit on $R$ is significantly improved by more than 2 orders of magnitude than the previous limit [11], and the best limit on $^{57}$Fe de-excitation rate.

From this result and Eq. (3), we can set the 95% limit to $f_a$,

$$f_a > 1.07 \times 10^5 \cdot |C| \text{ GeV}$$

$$> 2.89 \times 10^4 \text{ GeV (} z = 0.56, S = 0.5).$$

(5)

(6)

This limit can be rewritten in mass limit with a following relation.

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

(7)

and the obtained limit is,

$$m_a < 216 \text{ eV (95% C.L.)}.$$

(8)

This limit is about 3.4 times more stringent than the previous similar experiment [10].

In this $m_a < 10$ keV region, there are not so many reliable constraints on the axion-nucleon coupling. Only the axion burst argument of 1987A limit the axion as $m_a < 40$ eV [13]. But this argument is based on a supernova temperature and density profile which is not firmly established yet. Therefore, our constraint which is based on a reliable solar model and which is obtained under well-controlled circumstances is meaningful.

Recently, some nuclear experiments indicate smaller value on $S$, i.e., $S \simeq 0.3$ [14]. In this case, our obtained results become somewhat weaker, $f_a > 1.21 \times 10^4 \text{ GeV}$ and $m_a < 515 \text{ eV (95% C.L.)}$. However, it should be noted that this change equally affects on similar experiments like [10], and our sensitivity enhancement is not changed. It should also be noted that this uncertainty does not comes from the axion model like $E/N$ in the axion-photon coupling.
Future nuclear experiments will fix this uncertainty without the dependence of the axion model.

6 Conclusion

A monochromatic component of solar axions which could be produced in the solar core have been searched for. The signature of the axion would be an increase in the rate of $^{57}\text{Fe}$ 14.4 keV $\gamma$ rays induced by resonant absorption of the axion. From an obtained 95% limit of $^{57}\text{Fe}$ de-excitation rate, $R < 2.33 \times 10^6$ day$^{-1}$kg$^{-1}$, we set a 95% new limit for $f_a > 2.89 \times 10^4$ GeV and $m_a < 216$ eV under the assumption of $S = 0.5$ and $z = 0.56$.

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References

[11] In [10], $R$ is not explicitly shown. From our simple calculation, their limit on $R$ is $R < 3.4 \times 10^8$ day$^{-1}$kg$^{-1}$.


Fig. 1. A cross-section view of the detector. An iron foil sandwiched by two silicon PIN photodiodes are placed at the bottom of the cryostat and cooled down by dry ice. They are surrounded by 10 cm lead shield.
Fig. 2. The solid histogram shows the source measurements with the enriched $^{57}$Fe foil (95.85% of $^{57}$Fe), and the dashed shows the background measurements with the natural iron (2.2% of $^{57}$Fe). The energy region from 12.4 keV to 16.4 keV is used for the analysis.

Fig. 3. Residual spectrum after the subtraction of the background data (with natural Fe foil) from that with the enriched $^{57}$Fe foil. The dashed line shows the upper limit of a 14.4 keV solar axion signal.