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Solar axion search by annual modulation with XMASS-I detector

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Abstract. Kaluza-Klein (KK) axions produced in the Sun have been proposed to explain several astrophysical anomalies. We searched for the decay of such solar KK axions using $832 \times 359 \text{ kg} \cdot \text{days}$ XMASS-I data. No significant event rate modulation is found, and we set the first experimental constraint on KK axion photon-coupling of $4.8 \times 10^{-12} \text{ GeV}^{-1}$ for a KK axion number density of $\bar{n}_a = 4.07 \times 10^{13} \text{ m}^{-3}$ at 90% C.L.

1. Introduction

Axions arise from the Peccei-Quinn solution to the strong CP problem in QCD [1]. Large extra dimensions on the other hand are proposed to solve the gauge hierarchy problem [2, 3]. Such extra dimensions are thought to be compactified in a certain radius R . In theories with n extra dimensions, axions may propagate in these extra dimensions, and thus acquire Kaluza-Klein (KK) excitations [4], which have an almost equidistant mass-spectrum with the distance related to the compactification radius R . KK axions produced in the Sun have been proposed in particular to account for unexplained heating of the solar corona [5]. In this scenario, a small fraction of the solar KK axions are gravitationally trapped in orbits around the Sun and accumulated over the age of the Sun. KK axions decay into two photons, typically X-rays. Considering production, trapping and decay rate as a function of KK axion mass, the extra coronal heating can be explained by the decay X-rays from KK axion decay. In this paper, we present the result from a search for solar KK axions by annual modulation with the assumption of a fundamental scale $M_F = 100 \text{ TeV}$, a number $n = 2$ of extra dimensions, and a number $\delta = 2$ of extra dimensions that axions can propagate in, which corresponds to the compactification radius $R \sim 10^3 \text{ keV}^{-1}$.

2. The XMASS-I detector

The XMASS project is designed to observe rare events such as dark matter recoils, neutrino-less double beta decay, and ${}^7\text{Be}/pp$ solar neutrinos with a single phase liquid xenon (LXe) scintillator. The XMASS-I detector is located in the Kamioka mine under an overburden of 2700 m.w.e. Its sensitive volume contains about 832 kg of LXe inside a 80 cm diameter pentakis-dodecahedral OFHC copper structure. Scintillation light from the LXe is detected by 642 low background 2 inch PMTs. The total photocathode coverage is larger than 62 %. In order to reduce external

gamma rays, neutrons, and muon-induced backgrounds, the detector is placed at the center of a 10 m diameter, 10.5 m high water tank filled with pure water. More details are given in Ref. [6]. The salient feature of the XMASS experiment is a large scintillation light yield (~ 15 photoelectron (p.e.)/keV_{ee}). The energy threshold is enough low to search for solar KK axions.

3. Expected signal from gravitationally trapped KK axions

In the Ref. [5], the expected number density of trapped KK axions against the distance from the Sun is simulated up to 200 solar radii. For this simulation, KK axion-photon coupling of $g_{a\gamma\gamma} = 9.2 \times 10^{-14} \text{ GeV}^{-1}$ is chosen so that the axion decays can explain the X-ray surface brightness of the quiet Sun. The distribution is well fit by a function proportional to r^{-4} , and we use that fit to evaluate the number density of trapped KK axion at the Earth's orbit. Here r denotes the distance from the Sun. Gravitationally trapped KK axion could be observed decaying to two X-ray photons inside the terrestrial detector. The expected decay rate R is given by [7]:

$$R = \left(2.5 \times 10^{11} \text{ m}^{-3} \text{ day}^{-1}\right) \left(\frac{g_{a\gamma\gamma}}{\text{GeV}^{-1}}\right)^2 \left(\frac{n_a}{\text{m}^{-3}}\right) \quad (1)$$

where n_a denotes the number density of trapped KK axion. Since the distance between the Earth and the Sun changes with the season and n_a is proportional to r^{-4} , the expected decay rate has annual modulation.

4. Modulation analysis

The data set for the solar KK axion analysis spans the time from November 2013 to March 2015. After removing periods of operation with excessive PMT noise or data acquisition problems, the total livetime is 359 days. The following 4 event selection steps are applied to both data and signal simulation:

- Trigger is ID only with a threshold of four PMTs hit within 200 ns
- To remove unphysical events, the timing difference from the previous ID event should be longer than 10 ms and the root mean square of the hit timings in the event should be less than 100 ns
- To remove Cherenkov events, events which have less than 200 p.e. should have less than 60% of their hits in the first 20 ns.
- To remove backgrounds occurring in front of a PMT window, the ratio of the largest number of p.e. detected by a single PMT to the total p.e. should be less than a certain value. The actual value applied in this cut depends on the total p.e. in the event [8].

Fig. 1 shows the energy spectra of data and simulation after each selection step. The horizontal axis keV_{ee} represents the electron equivalent energy. The energy range between 3 and 22 keV_{ee}, excluding the range between 14 and 17 keV_{ee}, is used for this analysis. This exclusion avoids systematic effects associated with the discrete Cherenkov cut applied only below 200 p.e.

To monitor the detector stability, frequent ^{57}Co source calibration data were taken. From the calibration data, up to 10% change in the p.e. yield was observed over the measurement period. Parameters such as the absorption length and the intrinsic light yield of the LXe are extracted from the comparison between calibration data and simulation. We found that the time variation of the observed p.e. yield can be reproduced with a change of the absorption length of LXe from 4 m to 11 m [8]. This variation of the observed p.e. affects the cut efficiencies, especially the Cherenkov cut and the p.e. ratio cut. We simulate the change of cut efficiency against background events. The dominant background events in this study are found to come from the aluminum seals used at the PMT windows (^{238}U – ^{230}Th and ^{210}Pb) and the copper plates on the surface of the inner detector (^{210}Pb). These background simulations with different

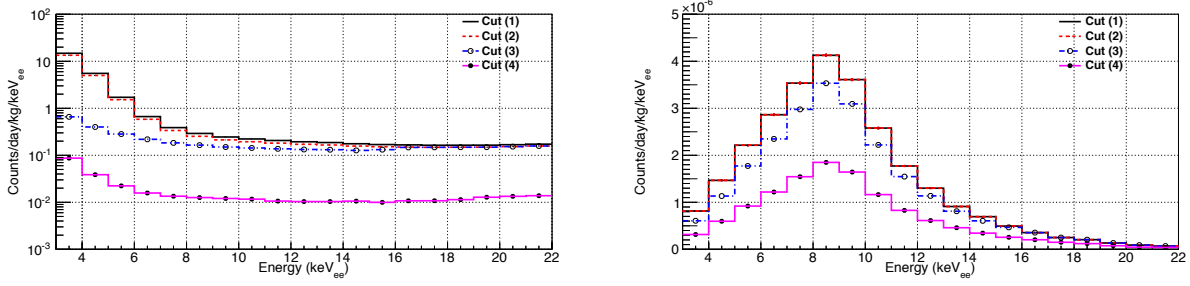


Figure 1. Taken from Ref [10]. Energy spectra of the observed data (left) and simulated KK axion events (right) after each reduction step mentioned in Section 4. Here $g_{a\gamma\gamma} = 9.2 \times 10^{-14} \text{ GeV}^{-1}$ and $n_a = 4.07 \times 10^{13} \text{ m}^{-3}$ are assumed in the signal simulation.

absorption lengths of the LXe are generated and used to evaluate the cut efficiency relative to the MC with an absorption length of 8m.

The systematic uncertainties due to these relative cut efficiencies, the non-linearity of the scintillation yield, and a temporary applied different way of calibrating electronics gains between April and September 2014 are carefully considered in this analysis. Other systematic uncertainties are found to be negligible.

The data set is divided into 33 time-bins (t_{bins}) and 16 energy-bins (E_{bins}). In order to extract an annual modulation amplitude from the data, a least Chi-squares fit is performed. The following is the definition of the χ^2 with two penalty terms α and β [9]

$$\chi^2 = \sum_i^{E_{bins}} \sum_j^{t_{bins}} \frac{(R_{i,j}^{data} - R_{i,j}^{ex} - \alpha K_{i,j})^2}{\sigma_{stat;i,j}^2 + \sigma_{sys;i,j}^2} + \alpha^2 + \beta^2, \quad (2)$$

Here $R_{i,j}^{data}$, $R_{i,j}^{ex}$, $\sigma_{stat;i,j}$, $\sigma_{sys;i,j}$ are the observed event rate, the expected event rate, and the statistical and uncorrelated systematic errors for each bin, respectively. The subscripts i and j denote the respective energy and time bin. $K_{i,j}$ represents the 1σ correlated systematic error based on the relative cut efficiency for each period. α is the penalty term associated with $K_{i,j}$. From Eq. 1, the expected event rate is proportional to the KK axion number density. The number density of the KK axion is proportional to r^{-4} . Using the general equation of an ellipse and the Maclaurin expansion, the expected event rate can be written as:

$$R_{i,j}^{ex} = \int_{t_j - \frac{1}{2}\Delta t_j}^{t_j + \frac{1}{2}\Delta t_j} \left[C_i + \xi \times (A_i - \beta L_i) \left(\cos \frac{2\pi(t - t_0)}{T} + \frac{5}{2}e \cos^2 \frac{2\pi(t - t_0)}{T} \right) \right] dt, \quad (3)$$

Here $e = 0.0167$ is the eccentricity of the Earth's orbit, t is time, T represents one year, t_0 is the date when the Earth is at perihelion. Δt_j is the bin width of the j -th time bin. C_i and A_i are the constant term and the expected amplitude of the event rate in the i -th energy bin, respectively. L_i , which is associated with the penalty term β , accounts for the uncertainty stemming from the non-linearity of the scintillation efficiency on A_i . ξ is defined as $\xi = \frac{g_{a\gamma\gamma}^2}{(9.2 \times 10^{-14} \text{ GeV}^{-1})^2} \frac{\bar{n}_a}{4.07 \times 10^{13} \text{ m}^{-3}}$, and it represents the ratio of the expected amplitudes between the data and the considered model [5]. Here $\bar{n}_a$ represents the KK axion number density when the distance between the Earth and the Sun is equal to the semi-major axis, $1.496 \times 10^8 \text{ km}$. Treating C_i and ξ as free parameters in the fit, the above χ^2 is minimized.

5. Result and discussion

Fig. 2 shows the event rate modulation and the best fit result for the expected event rate from 7 keV_{ee} to 12 keV_{ee}.

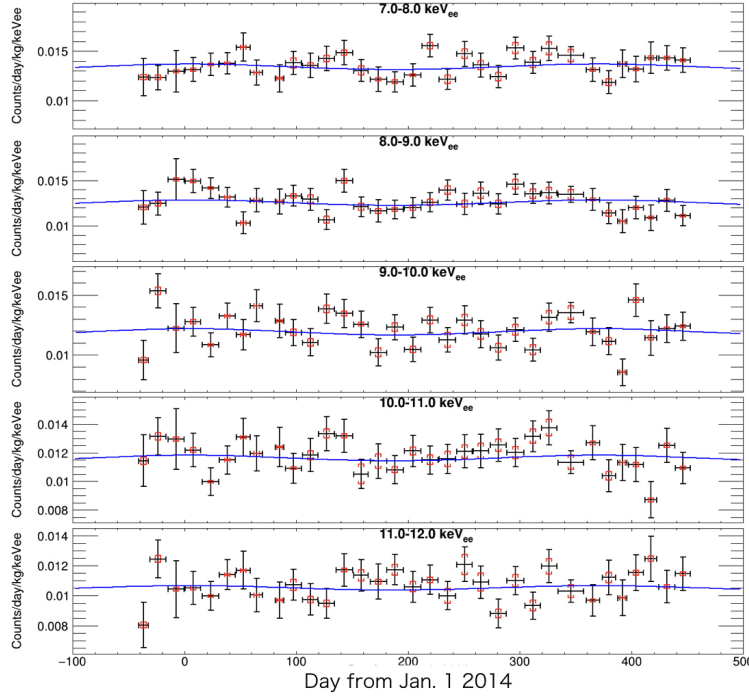


Figure 2. Time variation of the observed event rate in representative energy bin. The horizontal axis is the time in number of days from January 1st, 2014. The black points with error bars show the observed event rate for each period with statistical errors $\sigma_{\text{stat};i,j}$. The red error bars show the systematic errors ($\sigma_{\text{sys};i,j}$ and $K_{i,j}$ are added in quadrature). The blue solid curves show the 90% CL upper limit fit result of the expected event rate variation ($\xi = 2.7 \times 10^3$).

The fit yielded $\xi = 8.2 \times 10^2$ with $\chi^2/\text{ndf} = 522.4/492$. To evaluate the significance of the modulation amplitude related to ξ , statistical test is made by applying the same analysis to 10,000 unmodulated dummy samples which have the same statistical and systematic errors as the data [8]. This evaluation gives a p-value of 0.62, which corresponds to no significant excess. Since no significant excess in amplitude is found, a 90% confidence level (CL) upper limit is set on the KK axion-photon coupling $g_{a\gamma\gamma}$ as a function of the KK axion number density. A 90% CL upper limit on the coupling constant $g_{a\gamma\gamma} < 4.8 \times 10^{-12} \text{ GeV}^{-1}$ for $\bar{n}_a = 4.07 \times 10^{13} \text{ m}^{-3}$ is obtained. From Eq. 1, this limit can be re-calculated for different KK axion densities, which corresponds to the expected decay rate $R < 234 \text{ m}^{-3}\text{day}^{-1}$. The obtained limit line is shown in Fig. 3.

As a benchmark, the assumed solar KK axion model has $g_{a\gamma\gamma} = 9.2 \times 10^{-14}$ for $\bar{n}_a = 4.07 \times 10^{13} \text{ m}^{-3}$ [5]. The sensitivity of this study is not enough to reach the model. To reach the region of the benchmark model with the liquid xenon detector, the required background level is less than 10^{-5} events/day/kg/keV_{ee} with a mass of 3 ton and 5 year exposure.

In conclusion, no significant excess for an annual modulation signal from solar KK axions is found in XMASS-I $832 \times 359 \text{ kg}\cdot\text{days}$ exposure data. We set a 90% CL upper limit on the KK axion-photon coupling of $4.8 \times 10^{-12} \text{ GeV}^{-1}$ for $\bar{n}_a = 4.07 \times 10^{13} \text{ m}^{-3}$. This is the first experimental constraint for KK axions. This result is accepted for publishing in the journal "Progress of Theoretical and Experimental Physics" [10].

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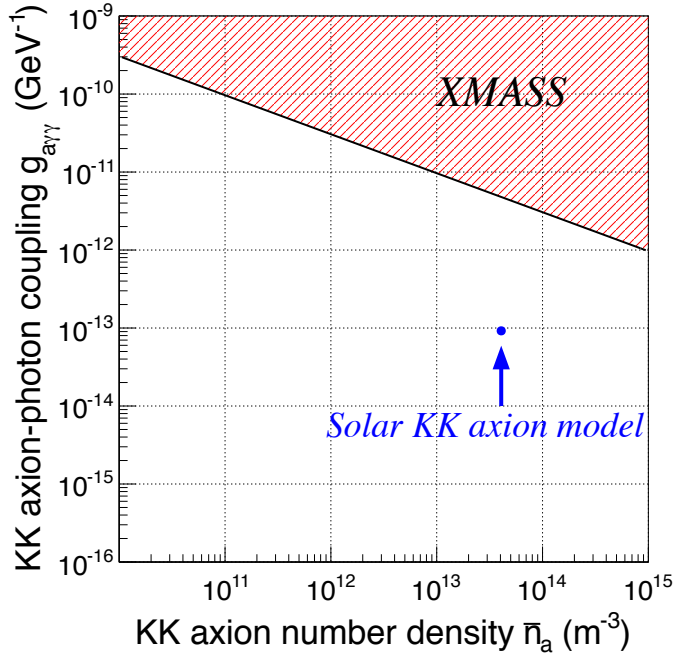


Figure 3. Taken from Ref [10]. The 90% CL excluded region from this analysis is shown by the black solid line and the red hatched area. The model assumed in this study is based on Ref.[5] and is indicated by the blue point.

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