A Search for the Resonant Absorption of Solar Axions by Atomic Nuclei

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2011-04/unzhakov_evgeniy

A search for resonant absorption of solar axions by ^{57}Fe and ^{169}Tm targets was performed. The Si(Li) detector placed inside a low-background setup was used to detect the γ-quanta appearing from the de-excitation of the low-lying nuclear levels of ^{57}Fe and ^{169}Tm (14.4 keV and 8.41 keV correspondingly): $A+N_{target} \rightarrow N^{*}_{target}+\gamma$. The obtained data allowed us to set the new upper limits on the axion mass value: $m_A \leq 145$ eV at 95% c.l.

1 Introduction

A natural solution of the strong CP-problem is based on the introduction of the global chiral symmetry $U(1)_{PQ}$ that was proposed by Peccei and Quinn in 1997. The spontaneous breaking of this new symmetry at the energy scale f_a should lead to the generation of a new neutral zero-spin pseudoscalar particle - axion. Theory describes the interaction of axions with ordinary matter (nucleons, leptons and photons) in terms of effective coupling constants: g_{AN}, g_{Ae}, $g_{A\gamma}$ correspondingly. The axion mass m_A and the values of these constants appear to be inversely proportional to the $U(1)_{PQ}$ symmetry breaking scale f_A. After the first hypothesis of $f_A \approx 250$ GeV (electro-weak scale) was experimentally excluded, two types of new theoretical models were introduced. They removed the restrictions on the f_A value, allowing it to go up to the Planck mass, therefore significantly suppressing the interaction of axions with ordinary matter and shifting the expected axion mass to the lighter region.

2 Solar axion flux

If axions do exist, then stars (including the Sun) should be intense sources of these particles. There are several possible mechanisms that could stand behind the production of solar axions.

Firstly, the Primakoff conversion of photons in the electromagnetic field of plasma can efficiently produce axions ($\gamma + \overrightarrow{B} \rightarrow A$). The resulting axoin flux has an average energy of 4 keV and can be detected by inverse Primakoff conversion in laboratory magnetic fields or by the coherent conversion to photons in crystal detectors. These experiments are sensitive to $g_{A\gamma}$ constant. The flux of Primakoff axions is parameterized by the following expression [1]:

$$\frac{d\Phi_A}{dE_A} = (g_{A\gamma})^2 \cdot 3.82 \cdot 10^{30} \frac{E_A^3}{\exp(E_A/1.103) - 1}$$

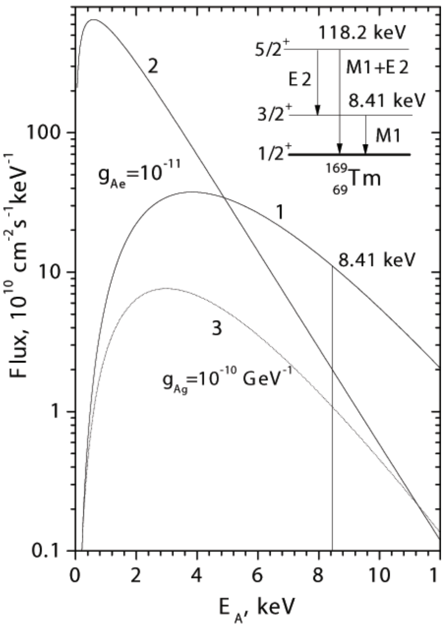

Figure 1: **1**, **2** - Compton process and the bremsstrahlung axion spectra, correspondingly. **3** - Primakoff axion spectrum. The level scheme of ^{169}Tm nucleus is shown in the inset.

The second mechanism is based on the possibility of thermal excitation of low-lying nuclear energy levels ($N^* \to N + A$). The most intense monochromatic axion flux is connected with $M1$-transition of ^{57}Fe nucleus. The energy of the first excited nuclear level $3/2^-$ is equal to 14.413 keV, and the admixture of $E2$-transition is $\delta^2 = 0.22\%$. The axion flux depends on the level energy $E_\gamma =$ 14.413 keV, temperature T, nuclear level lifetime $\tau_\gamma = 1.34\ \mu s$, the abundance of the ^{57}Fe isotope on the Sun N and the axion/photon emission branching ratio ω_A/ω_γ [2]:

$$\Phi_A \sim \frac{N}{\tau_\gamma} \frac{2\exp(-E_\gamma/kT)}{(1 + 2\exp(-E_\gamma/kT))} \frac{\omega_A}{\omega_\gamma}$$

Monochromatic 14.4 keV axions produced by the $M1$-type nuclear transition of ^{57}Fe nucleus can be observed in the inverse reaction of the resonant absorption and registration of the following γ-rays emitted by the de-excitation of ^{57}Fe target nuclei. The probability of emission and subsequent absorption of the axion in a $M1$-type transition is determined only by the axion-nucleon coupling g_{AN}.

Nuclear reactions of the solar cycle could be another source of axions. An attempt to detect heavy 5.5 MeV monochromatic solar axions produced by p(d,^{3}He)A reaction was made in [3].

Also, axions could be produced as a result of the Compton process ($\gamma + e^- \to e^- + A$) and bremsstrahlung ($e^- + Z \to Z + e^- + A$) in the hot solar plasma. The cross sections of these reactions depend on the axion-electron coupling constant g_Ae. The expected spectrum of such axions is calculated using the theoretical predictions for the Compton cross section and the axion bremsstrahlung produced by the electron-nucleus collisions. The axion flux is determined by radial temperature distribution $T(r)$ and densities of electrons $N_e(r)$ and nuclei $N_{Z,A}(r)$. The resulting corresponding parameterizations of Compton and bremsstrahlung axions are [4]:

$$\frac{d\Phi_A}{dE_A} = g_{Ae}^2 \cdot 1.33 \cdot 10^{33} E_A^{2.98} e^{-0.774 E_A}$$

$$\frac{d\Phi_A}{dE_A} = g_{Ae}^2 \cdot 4.14 \cdot 10^{35} E_A^{0.89} e^{-0.7E_A - 1.26\sqrt{E_A}}$$

The total flux of solar axions produced by various processes is shown in Fig. 1. In our work we used ^{169}Tm target for resonant absorption of bremsstrahlung, Compton and Primakoff axions and ^{57}Fe for the absorption of 14.4 keV monochromatic axions. Therefore, these experiments were sensitive to g_{Ae}, $g_{A\gamma}$ and g_{AN} values correspondingly.

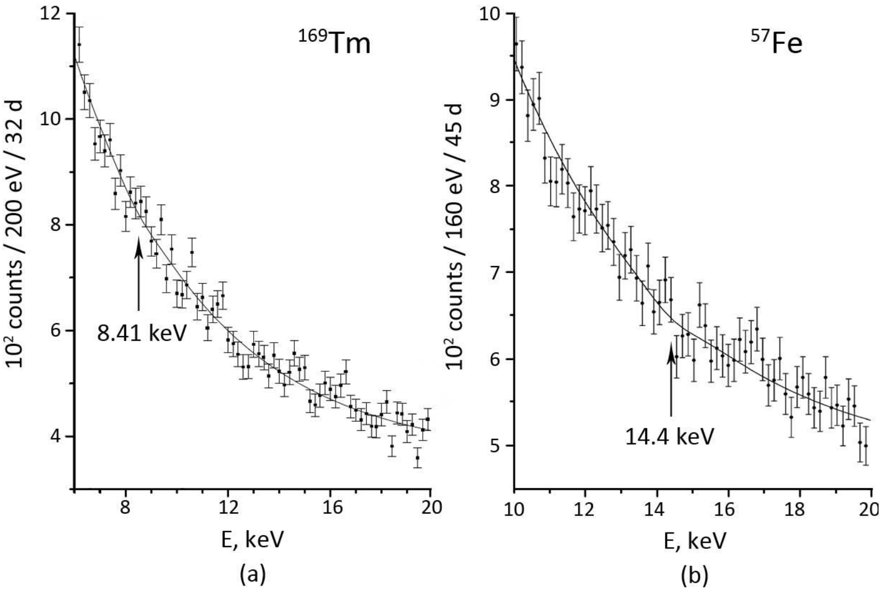

Figure 2: The Si(Li) detector energy spectra of ^{169}Tm **(a)** and ^{57}Fe **(b)** targets, measured in the anticoincidence with the veto signal. Solid line shows the fitting results for corresponding regions.

3 Experimental setup

In order to observe 8.41 keV and 14.4 keV γ-rays we used the planar Si(Li) detector with a sensitive area diameter $d = 66$ mm and thickness of 5 mm. The detector was mounted on 5 cm thick copper plate that protected the detector from the external radiation. The detector and the holder were placed in a vacuum cryostat and cooled to the temperature of the liquid nitrogen. The corresponding target was uniformly deposited on a Plexiglas substrate 70 mm in diameter at the distance of 1.5 mm from the detector surface. External passive shielding composed of copper, iron and lead layers was adjusted to the cryostat and suppressed the external radioactivity background by a factor of about 500.

The experimental setup was located on the ground surface. The events produced by cosmic rays and fast neutrons were registered by the active shielding consisting of five plastic scintillators $50 \times 50 \times 12$ cm in size. The rate of 50 μs veto signals was 600 counts/s that lead to $\approx 3\%$ of the dead time. The Si(Li) detector was sectionalized into nine separate subregions in order to reduce the capacities of individual sections and, therefore, increase the overall energy resolution. Every section was equipped with a charge-sensitive preamplifier with resistive feedback, a shaping amplifier and a 12-step ADC. Eighteen 4096-channel spectra (in coincidence and anticoincidence with the veto signal) were collected.

Though the detector amplifications were actually the same, the energy calibrations were performed for each section individually. Standard ^{57}Co and ^{241}Am calibration sources were used. The total energy resolution for a 14.4 keV γ-ray line was equal to $\sigma = 0.63$ keV. The high energy resolution and accurate knowledge of energy scale are of great importance for our experiment, because the energies of thulium characteristic x-rays are close to 8.41 keV.

The sensitive volume and area of the (Si)Li detector were measured via the x-ray and γ-lines of a standard ^{241}Am source. The detection efficiency was estimated by the MC simulation that included the self-absorption of γ-rays by the target. Total detection efficiency for the 8.41 γ-rays tured out to be $\epsilon \approx 6\%$.

4 Results

The measurements were carried out during 45 days of live time with ^{57}Fe target and during 32 days of live time with ^{169}Tm target. The detailed energy spectra of the regions where axion peak was expected are presented in Fig. 2. There were no statistically significant peaks in the given regions, therefore, we used the standard method of χ^2 profiling in order to determine the upper limits on the number of events inside the axion peak. The result of the fit corresponding to the minimum of χ^2 is shown by a solid line in Fig. 2. The value of χ^2 was determined for different fixed values of axion peak intensity S_A while the other parameter were left unrestricted. The obtained probability function $P(\chi^2(S))$ was normalized to unity for $S \geq 0$.

Ulitmately, the expected number of the axion peak γ-quanta would be proportional to the number of target nuclei N_{target}, time of measurement T, γ-ray detection efficiency ϵ and the internal converion ratio of the corresponding nuclear transition η.

The obtained results allowed us to set the following upper limits on the values of coupling constants and axion mass: $|g^0_{AN} + g^3_{AN}| \leq 3.0 \times 10^{-6}$ and $m_A \leq 145$ eV for ^{57}Fe meaurements; $g_{Ae} \times |g^0_{AN} + g^3_{AN}| \leq 2.1 \times 10^{-14}$ and $g_{Ae} \times m_A \leq 3.2 \times 10^{-7}$ eV in case of Compton and bremsstrahlung axion absorption by ^{169}Tm; $g_{A\gamma} \times m_A \leq 1.36 \times 10^{-5}$ and $m_A \leq 169$ eV in case of Primakoff axion absorption by ^{169}Tm. All the limits are given at 95 % c.l.

For more details on the calculation of the axion absorption rates, model parameter dependencies and result comparison see [1], [2] and [4].

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