A new limit on the resonant absorption of solar axions obtained via ^{169}Tm-containing bolometer

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Abstract. A newly developed experimental technique based on ^{169}Tm-containing cryogenic bolometer detector was employed in order to perform the search for solar axions. The inclusion of target material into the active detector volume allowed for significant increase in sensitivity to axion parameters. A short 6.6 days measurement campaign with 8.18 g detector crystal yielded the following limits on axion couplings: $|g_{A\gamma}(g_{AN}^0 + g_{AN}^3)| \leq 1.44 \times 10^{-14} \mathrm{GeV}^{-1}$ and $|g_{Ae}(g_{AN}^0 + g_{AN}^3)| \leq 2.81 \times 10^{-16}$. The achieved results demonstrate high scalability potential of presented experimental approach.

1. Introduction

Experimental searches for an axion, hypothetical pseudoscalar particle, have been The initial axion hypothesis emerged as a consequence of suggested solution to the long-standing strong CP problem of QCD. The solution proposed by Peccei and Quinn assumes the existence of additional global chiral symmetry [1]. Spontaneous braking of this symmetry at some energy scale f_A dynamically compensates the CP-violating term in QCD Lagrangian, thus solving the strong CP problem by means of QCD itself. Soon, Weinberg [2] and Wilczeck [3] independently of each other came to the conclusion that due to the Nambu-Goldstone mechanism such spontaneous symmetry breaking should lead to existence of a new pseudoscalar particle — *an axion*.

The model independent axion-gluon interaction enables axion mixing with η'-mesons and, consequently, with pions and the rest of mesons. This enables further derivative couplings with photons, leptons and nucleons, which are described in terms of effective coupling constants ($g_{A\gamma}$, g_{Ae} and g_{AN}, correspondingly). The initial theoretical model expected spontaneous breaking

of Peccei-Quinn symmetry at electroweak scale ($f_A \approx 250$ GeV), giving concrete predictions on axion coupling strength and expecting the axion mass to be $m_A \approx 160$ KeV. Several experimental searches soon followed and disproved this initial hypothesis, so the theoretical models were forced to adapt, effectively removing the upper limits on the symmetry breaking scale f_A. As the axion mass m_A and effective coupling constants are inversely proportional to f_A value, its increase leads to a light and weakly interacting axion, which was hence dubbed "invisible". These updated invisible axions naturally became a very fitting dark matter candidates, increasing the motivation for experimental axion discovery. Mainly, new theoretical models can be divided into two large subcategories: hadronic axion (introduces two additional Higgs doublets) [4, 5] or GUT axion (introduces additional quark, carrying the PQ-charge) [6, 7]. Due to wide variety of axion models, the axion mass m_A appears to be strongly model-dependent, so in order to simplify comparison between experiments results are usually presented in form of limits on model independent effective coupling constants.

Stellar interiors could provide the necessary conditions for axion production by several couplings: $g_{A\gamma}$ — Primakoff conversion of photons, g_{Ae} — axion bremsstrahlung, Compton-like scattering, atomic de-excitation, g_{AN} — thermal excitation of nuclei with sufficiently low energy levels.

In the laboratory, the resonant absorption of an axion (g_{AN}) could bring the target nucleus into excited state, which then relaxes emitting the X-ray quanta that can be detected by conventional means. The resonant nature of the reaction means that its cross-section is relatively high, thus allowing for competitive parameter sensitivity while using small-scale experimental setup. The number of M1-type nuclear transitions with X-ray energy scale (~ 10 keV) required for axion absorption is quite limited. Nevertheless, several experiments based on resonant axion absorption by various target nuclei have been proposed over the history of axion searches, including ^{57}Fe [8], ^{7}Li [9], ^{83}Kr [10] and ^{169}Tm [11].

In this work we used ^{169}Tm nucleus with first excited state at 8.41 keV as a target in order to probe "tail" of continuous solar axion spectra generated by $g_A\gamma$, and g_{Ae} related processes (see Fig. 1). The detailed description of calculations of expected axion energy spectra and axion absorption rate can be found in [12] and references therein. Here, we shall only note that axion fluxes, as well as probability of resonant axion absorption by ^{169}Tm nucleus, are all proportional
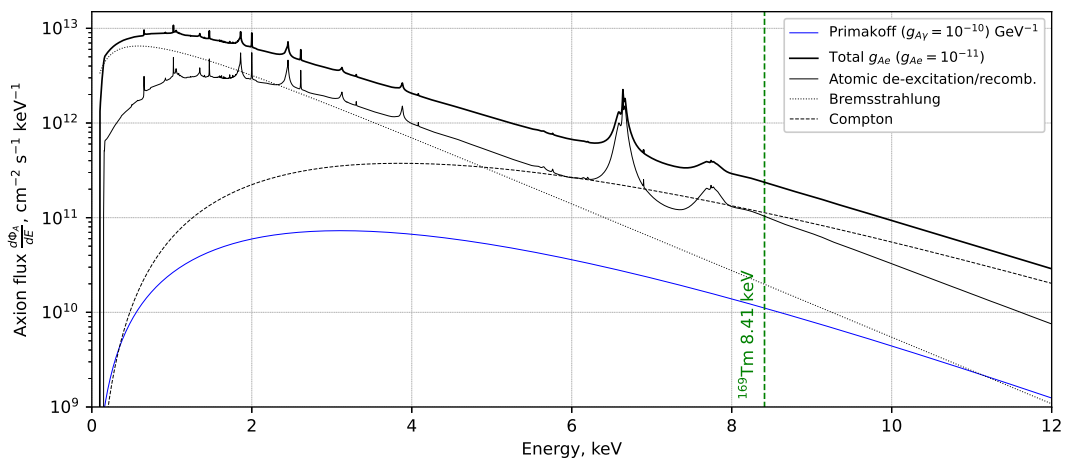
Figure 1. Energy spectrum of solar axions produced by $g_{A\gamma}$ and g_{Ae} related processes in assumption of $m_A = 0$. Spectra are calculated for nominal values of coupling constants, relevant to contemporary experimental limits.

to the square of relevant coupling constants, so the expression for axion absorption rate can be given as:

$$R_A = C_{Ax}\, g_{Ax}^2\, g_{AN}^2\, (p_A/p_\gamma)^3 \tag{1}$$

where rate R_A is expressed in atom$^{-1} \times$ s^{-1} units. The value of constant C_{Ax} is determined by properties of the chosen target nucleus and axion model parameters. In our case for ^{169}Tm nuclide $C_{A\gamma} = 104$ and $C_{Ae} = 2.76 \times 10^5$.

2. Experimental setup

The main idea behind our experiment is to use bolometric detector created from crystal of a garnet family containing the ^{169}Tm target nuclei in its lattice. Several Tm$_3$Al$_5$O$_{12}$ crystal samples were grown at Prokhorov General Physics Institute in Moscow, Russia, specifically for this task.

Our recent study [13] has confirmed that thulium-containing garnet crystal can be used in bolometric setup with neutron transmutation doped sensor (NTD), although the achieved energy threshold has proven to be too high to perform physical axion searches via ^{169}Tm target (first excited state at $E = 8.41$ keV). In order to reduce the energy threshold and improve the energy resolution, it was decided to replace the NTD with a transition edge sensor (TES). Since the same crystal sample from [13] was used, it was thoroughly processed with dichloromethane to remove previous NTD-sensor and glue residuals.

The TES was manufactured via the vacuum evaporation technique, designed used in CRESST experiment [14]. The sensor consisted of a thin layer of tungsten, partially overlapped with two aluminum pads, which served as phonon collectors and bond pads (see Fig. 2). A pair of 25 μm aluminum bond wires were attached to pads to supply a bias current. The thermal link between tungsten layer of TES and $\sim$ 10 mK heat bath was provided via a long and thin gold strip attached to a small golden pad, which served as a mooring point for a 25 μm golden wire. The
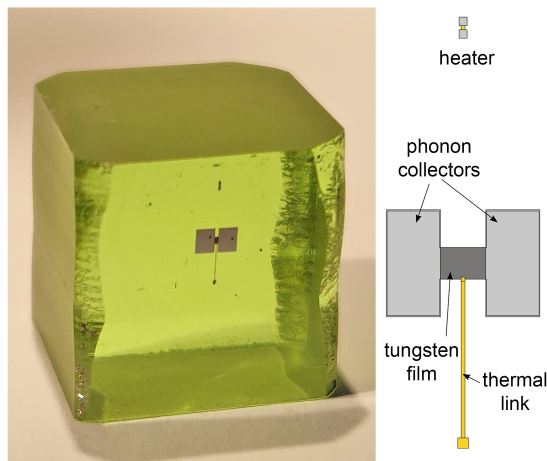
Figure 2. **Left:** View of Tm$_3$Al$_5$O$_{12}$ crystal with deposited TES and heater. **Right:** Functional scheme of TES.
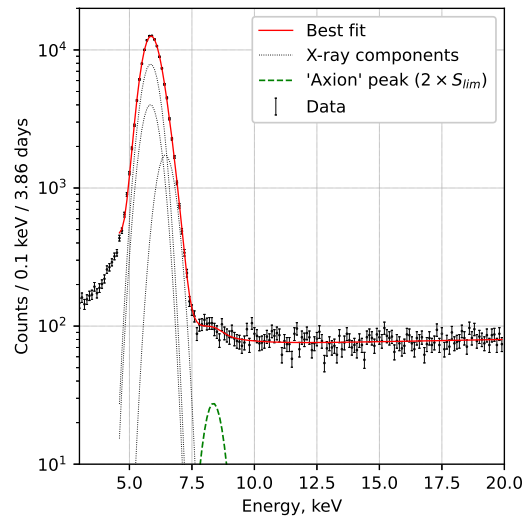
Figure 3. Spectrum of events acquired by Tm$_3$Al$_5$O$_{12}$ bolometer over 3.9 days of live time in $3-20$ keV interval. Best fit curve is shown by solid line. Dashed line represents how the "axion" peak would have looked at $2 \times S_{lim}$ intensity.

heating element was sputtered on the same crystal surface separately from TES. Two aluminum bonding pads were deposited on top of thin golden strip and were connected to two 25 μm aluminum wires, allowing to maintain TES at desired temperature via the tunable current. The heater was used to inject artificial pulses for energy calibration of the detector and to monitor system stability during the measurements.

After deposition of TES and heating element the crystal was installed via a pair of CuBe clamps into a copper holder, thermally coupled to the coldest stage of a Leiden Cryogenics dilution refrigerator. A ~ 0.4 Bq ^{55}Fe X-ray calibration source was placed inside the holder at ~ 1 mm away from the crystal surface. The whole setup was located at the Max Plank Institute for Physics (MPP) in Munich, Germany. The facility is located above ground and has no shielding against environmental and cosmic radiation.

3. Results

The data acquisition campaign lasted for 6.6 days of overall measurement time. In order to evaluate the effective measurement time simulated 8.41 keV pulses were blindly injected into a copy of the acquired data at a rate of 1.6 events $\times$ s^{-1} ($\times 10^{-3}$ in comparison to the observed environmental background). The data with injected pulses were processed in the same way as pure background data, allowing us to estimate the survival probability of expected axion signal. The effective measurement time after the trigger was significantly reduced almost by a factor of 2 and amounted to 3.89 days, although the high dead time was expected in case of above-ground experimental setup.

Further, the stability cut was applied, excluding the events registered during the time when the detector state deviated from the desired working point, reducing the effective measurement time to 3.86 days. Finally, another two quality cuts were based on pulse shape parameters. After all the cuts the overall crystal exposure amounted to 31.6 g $\times$ day, which translates into the pure ^{169}Tm target exposure of 19.2 g $\times$ day.

The acquired energy spectrum in the $3-20$ keV interval is given in Fig. 3. The single peak at 5.895 keV consists of the unresolved characteristic X-ray lines of Mn (K$_{\alpha_1}$, K$_{\alpha_2}$, K$_{\beta_{1+3}}$) from the ^{55}Fe calibration source. There is no evident event excess at the "axion" region of interest (8.41 keV), therefore we use the maximum likelihood approach to set the upper limits on the axion parameters. Fit function was chosen as sum of exponential background, three Gaussians for characteristic X-rays and a single Gaussian for expected "axion" peak:

$$N(E) = a + b \cdot E + c \cdot e^{-\frac{(E-4)}{d}} + \sum_{i=1}^{4} S_i e^{-\frac{(E_i - E)^2}{2\sigma^2}} \, , \tag{2}$$

where a, b, c, d are exponential background coefficients, σ is energy resolution, E_i are peak positions and S_i are peak intensities. The fit result with the best chi-squared criterion $\chi^2/N_{\text{DoF}} = 1.18$ is shown by solid line in (3). The χ^2-profiling yielded the upper limit on the number of "axion" events $S_{\text{lim}} = 128$ at 90 % confidence level. The sensitivity of experimental setup depends on S_{lim} as:

$$\epsilon \cdot N_{Tm} \cdot T \cdot R_A \leq S_{lim} \, , \tag{3}$$

where $\epsilon \approx 1$ is detection efficiency (since the target material is embedded into active detector volume), $N_{Tm} = 1.91 \times 10^{22}$ is the amount of Tm nuclei in 8.81 g of thulium-containing garnet, $T = 3.86$ days is the effective measurement time, and R_A is rate of axion resonant absorption by Tm nucleus, defined by expression (1).
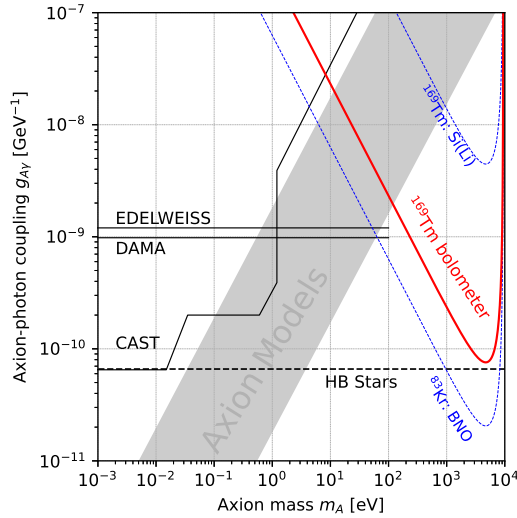
The following limits were set by performed measurements [12]:

$$\left| g_{A\gamma} \cdot (g_{AN}^0 + g_{AN}^3) \right| \leq 1.44 \times 10^{-14} \text{ GeV}^{-1} \, , \tag{4}$$

$$\left| g_{A\gamma} m_A \right| \leq 2.31 \times 10^{-7} \, ,$$

on axion-photon coupling, and:

$$\left| g_{Ae} \cdot (g_{AN}^0 + g_{AN}^3) \right| \leq 2.81 \times 10^{-16} \, , \tag{5}$$

$$\left| g_{Ae} m_A \right| \leq 4.59 \times 10^{-9} \text{ eV} \, .$$

on axion-electron coupling.

Figure 4. Limits on axion-photon coupling obtained with Tm-containing bolometer in comparison with other experiments (DAMA [15], EDELWEISS [16], CAST [17], Tm + Si(Li) [18], Kr + gas counter [19]) and astrophysical bounds [20].
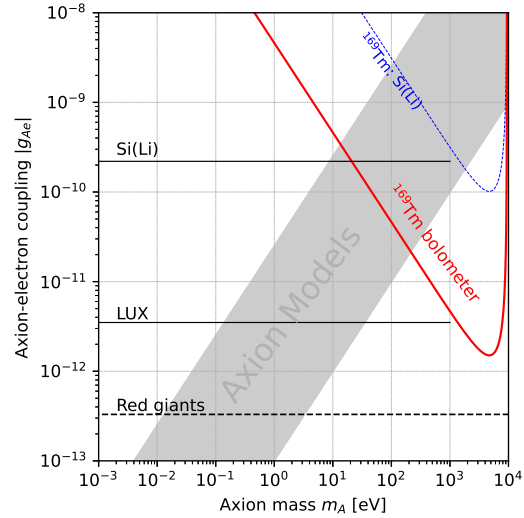
Figure 5. Limits on axion-electron coupling obtained with Tm-containing bolometer in comparison with other experiments (axio-electric effect on Si [21], LUX [22]) and astrophysical bounds [23].

4. Conclusion

A first experimental search for resonant absorption of solar axion via ^{169}Tm-containing bolometer was performed. The detector consisted of 8.18 g thulium-containing garnet ($Tm_3Al_5O_{12}$) with transition edge sensor (TES) deposited directly on the crystal surface. The data was acquired during 3.86 days of effective measurement time, yielding 19.2 g·day of pure ^{169}Tm target exposure. The obtained limits on axion-photon (4) and axion-electron (5) couplings are on competitive level in relation to modern experimental landscape.

The demonstrated approach proves the possibility of further setup scaling, increasing both detector crystal mass and measurement time. The potential reduction of background rate in the region of interest could be achieved by placing the experimental setup inside the dedicated underground facility, greatly improving the sensitivity to solar axion absorption.

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