Tm-Containing Bolometers for Resonant Absorption of Solar Axions

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2015-02/derbin_alexander

A search for resonant absorption of solar axions by ^{169}Tm nuclei will be performed using the Tm-containing bolometers installed inside a low-background setup at the LNGS. The thulium crystals - $NaTm(WO_4)_2$ and $NaTm(MoO_4)_2$ have been grown and tested for the first time as bolometric detectors. The expected sensitivity of 1 kg Tm-bolometer to axion-photon $g_{A\gamma}$ and axion-electron g_{Ae} coupling constants for axions with mass in the range 10 eV to 8 keV is stronger than the present astrophysical limits.

1 Introduction

As a pseudoscalar particle, the axion should be subject to resonant absorption and emission in nuclear transitions of a magnetic type. In our experiments we chose the ^{169}Tm nucleus as a target [1, 2]. The energy of the first nuclear level ($3/2^+$) is equal to 8.41 keV. The resonant absorption should lead to the excitation of low-lying nuclear energy level: $A+^{169}\mathrm{Tm} \rightarrow ^{169}\mathrm{Tm}^*$ $\rightarrow ^{169}\mathrm{Tm} + \gamma, e$ (8.41 keV). The level discharges through $M1$-type transition with $E2$-transition admixture value of δ^2=0.11% and internal conversion ratio $\eta = \gamma/e = 3.79 \times 10^{-3}$.

The cross-section of the resonant absorption for the axions with energy E_A is given by an expression similar to the one for γ-ray resonant absorption, but the ratio of the nuclear transition probability with the emission of an axion (ω_A) to the probability of magnetic type transition (ω_γ) has to be taken into account. The rate of solar axion absorption by ^{169}Tm nucleus will be

$$R_A = \pi\sigma_{0\gamma}\Gamma\frac{d\Phi_A}{dE_A}(E_A = 8.4)\left(\frac{\omega_A}{\omega_\gamma}\right), \quad (1)$$

where $\sigma_{0\gamma}$ is a maximum cross-section of γ-ray absorption ($\sigma_{0\gamma} = 2.56 \times 10^{-19}$ cm^2), Γ is a width of energy level (1.13×10^{-10} keV), and $d\Phi_A/dE_A$ is the axion flux at the energy 8.41 keV.

The ω_A/ω_γ ratio was calculated in the long-wave approximation in [3, 4]. In case of the

^{169}Tm nucleus the branching ratio can be rewritten as [1,2],

$$\frac{\omega_A}{\omega_\gamma} = 1.03(g^0_{AN} + g^3_{AN})^2(p_A/p_\gamma)^3. \quad (2)$$

Here, g^0_{AN} and g^3_{AN} are dimensionless isoscalar and isovector coupling constants and p_γ and p_A are the photon and axion momenta. For ^{169}Tm nucleus, in contrast with ^{57}Fe (14.4 keV) [5] and ^{83}Kr (9.4 keV) [6] nuclei, the uncertainty of the flavor-singlet axial-vector matrix element S and light quark-mass ratio $z = m_u/m_d$ do not significantly change the value of (2).

Axions can be efficiently produced in the Sun by the Primakoff conversion of photons in the electromagnetic field of plasma. The resulting axion flux, $d\Phi_A/dE_A$, depends on $g^2_{A\gamma}$ and can be detected by the inverse Primakoff conversion of axions to photons in the laboratory magnetic fields [7]. The rate of Primakoff axion absorption by ^{169}Tm nucleus depends on $g_{A\gamma}$ and g_{AN} coupling constants [1],

$$R_A = 104 \times g^2_{A\gamma}(g^0_{AN} + g^3_{AN})^2(p_A/p_\gamma)^3 \mathrm{s}^{-1}, \quad (3)$$

where $g_{A\gamma}$ is in GeV^{-1} units.

Additional axions can be emitted by Compton $\gamma + e^- \to e^- + A$ and bremsstrahlung $e^- + Z \to e^- + Z + A$ processes in the hot solar plasma. The cross sections of both reactions depend on the axion-electron coupling constant g^2_{Ae}. The rate of Compton and bremsstrahlung axion absorption by ^{169}Tm nucleus can be written in a model-independent view [2],

$$R_A = 1.55 \times 10^5 g^2_{Ae}(g^0_{AN} + g^3_{AN})^2(p_A/p_\gamma)^3 \mathrm{s}^{-1}. \quad (4)$$

The amount of observed γ-rays that follow the axion absorption depends on the number of target nuclei N_{T_m}, measurement time T and detector efficiency ϵ, while the probability of 8.4 keV peak observation is determined by the background level B of the experimental setup.

2 Experimental setup

The Tm-containing crystals - $NaTm(WO_4)_2$ and $NaTm(MoO_4)_2$ have been grown in Novosibirsk State University. Their dimensions are about $5 \times 5 \times 5$ mm^3 and the thulium mass in one crystal is about 200 mg. The crystals are of light green color. The transmission and absorption spectra of such crystals were measured. Except for small portions of the spectrum at 360, 475 and 690 nm, the crystals are transparent in the range from 325 to 775 nm. At the moment, growing of larger crystals has started in a new growth vessel.

The Tm-crystals were installed in the ^{3}He/^{4}He dilution refrigerator in the Hall C of the underground laboratory of L.N.G.S. ($\approx$ 3650 m w.e.) and operated at a temperature of few mK. The crystals were housed in a highly pure copper structure, the same one described in [8]. The detectors were surrounded by a passive shield made of copper, lead and polyethylene.

A neutron Transmutation Doped (NTD) germanium thermistor was coupled to each Tm-bolometer. NTD acts as a thermometer recording the temperature rises produced by particle interaction in the absorbers and producing voltage pulses proportional to the energy deposition. These pulses are then amplified and fed into an 18-bit analog-to-digital converter. Software triggers ensure that every thermistor pulse is recorded. Details on our electronics and on the cryogenic set-up can be found elsewhere [9,10].

The amplitude and the shape of the pulses are then determined by the off-line analysis. To maximize the signal-to-noise ratio, the pulse amplitude is estimated by means of the Optimum Filter (OF) technique [11, 12]. The heat channels were energy-calibrated by means of a X-ray (^{55}Fe) source. The relation between pulse amplitude and energy was parameterized with a first order polynomial fit.

3 Results

The background spectra collected during 135.2 h are presented in Fig. 1. One can see that the amplitude of the heat signal from $NaTm(MoO_4)_2$ crystals is higher than from $NaTm(WO_4)_2$ crystals.

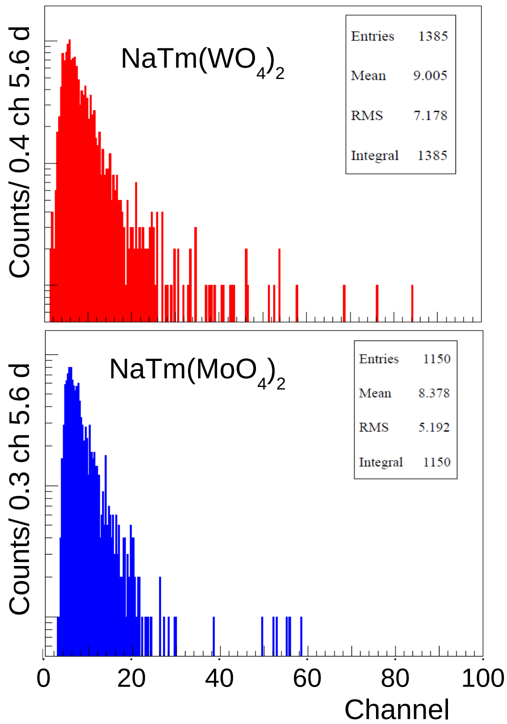

Figure 1: Energy spectra of $NaTm(WO_4)_2$ and $NaTm(MoO_4)_2$ bolometers.

There are no visible peaks in the spectra. In assumption of zero background in 8.4 keV region the upper limit on the excitation rate of ^{169}Tm by solar hadronic axions is defined as $R_{exp} = 2.44/N_{Tm}T$, where $N_{Tm} = 7.1 \times 10^{20}$ is the number of Tm nuclei in 0.2 g of thulium and $T = 4.87 \times 10^5$ s is the measurement time. The relation $R_A \leq R_{exp}$ limits the region of possible values of the coupling constants $g_{A\gamma}$, g_{Ae}, $(g^0_{AN} + g^3_{AN})$ and axion mass m_A.

Using relation (3) and (4) one can obtain the following constrains,

$$|g_{A\gamma}(g^0_{AN} + g^3_{AN})| \leq 8.2 \times 10^{-15}, \quad (5)$$

and

$$|g_{Ae}(g^0_{AN} + g^3_{AN})| \leq 2.1 \times 10^{-16}. \quad (6)$$

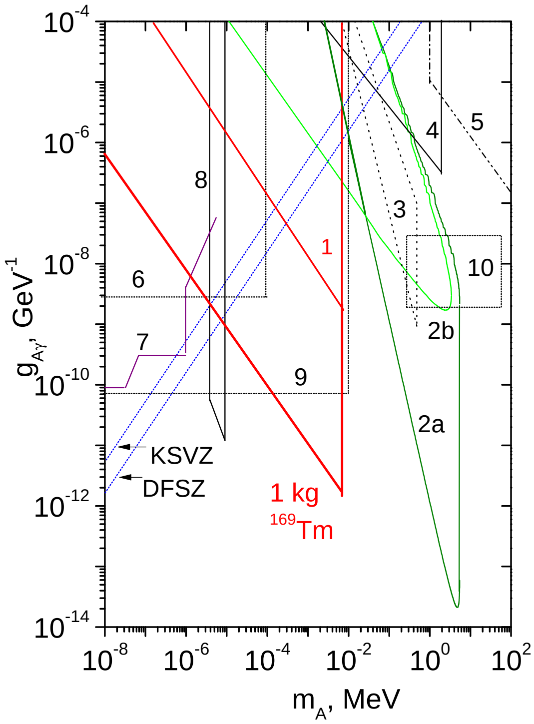

Figure 2: The sensitivity of 1 kg Tm-bolometer to $g_{A\gamma}$. 1 - ^{169}Tm resonant absorption [1], 2 - Borexino, 5.5 MeV axions, 3 - CTF, 478 keV axions, 4 - Reactor experiments, 5 - beam-dump experiments, 6 - Cosme, Solax, DAMA, 7 - CAST, 8 - Tokyo telescope, 9 - HB-stars, 10 - predictions of SUSY and mirror heavy axion models

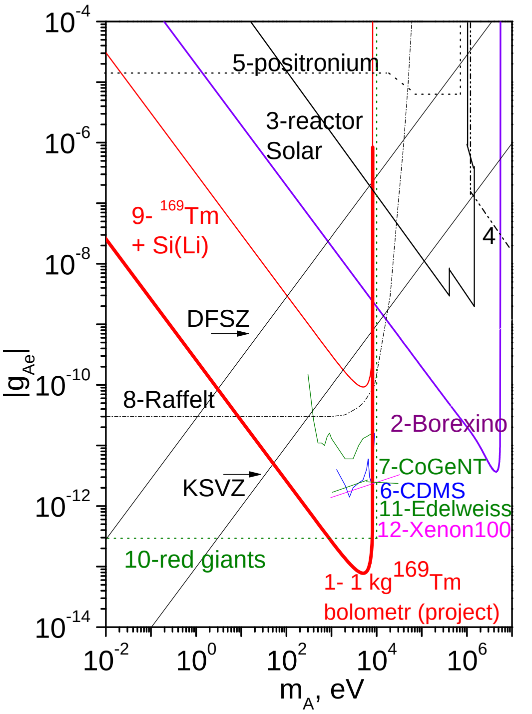

Figure 3: The sensitivity of 1 kg Tm-bolometer to g_{Ae} in comparison with the limits from others experiments

The limits (5), (6) are two orders of magnitude stronger than those obtained in our previous works [1, 2]. Since the coefficient of electron conversion for 8.4 keV transition in the nucleus ^{169}Tm is very large ($e/\gamma = 260$), the sensitivity of the experiment have been increased by $260/\epsilon = 10^4$ ($\epsilon \approx 0.02$ - detection efficiency of 8.4 keV gamma rays by Si(Li) detector [1]) for the case of registration of all particles (conversion and Auger electrons and γ- and X-rays) that follow this transition. For 1 kg detector with background level of 10 counts/day the enhancement factor can be about 2.5×10^6. The expected sensitivity of 1 kg Tm-bolometer to $g_{A\gamma}$ and g_{Ae} coupling constants are shown in Fig. 2 and Fig. 3.

Acknowledgements

The work is supported by the Russian Foundation of Basic Research (Grants No. 13-02-01199A, 13-02-12140-ofi-m and 15-02-02117A).

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