

# Search for axioelectric effect of 5.5 MeV solar axions using BGO detectors

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A search for axioelectric absorption of solar axions produced in  $p + d \rightarrow {}^3\text{He} + \gamma$  (5.5 MeV) reactions has been performed with a BGO detector placed in a low-background setup. A model-independent limit on an axion-nucleon and axion-electron coupling constant has been obtained:  $|g_{Ae} \times g_{AN}^3| < 2.9 \times 10^{-9}$  for 90% confidence level. The constraints of the axion-electron coupling have been obtained for hadronic axion with masses in (0.1 - 1) MeV range:  $|g_{Ae}| \leq (1.4 - 9.7) \times 10^{-7}$ .

## 1 Introduction

New possibilities for solving a strong CP problem are based on the concept of the existence of the mirror particles [1] and supersymmetry [2]. These models suppose the existence of axions with the mass of about 1 MeV, and this existence is forbidden by neither laboratory experiments nor astrophysical data.

Recently, the high energy solar axions and axions from a nuclear reactor have been sought by the Borexino [3, 4], the CAST [5] and the Texono [6] collaborations. We have previously published a search for 5.5 MeV axions with BGO detectors [7, 8].

## 2 Axion production in nuclear magnetic transitions and the axioelectric effect

The reactions of the main solar chain and *CNO* cycle can produce axions with higher energies. The most intensive flux is expected as a result of the reaction:  $p + d \rightarrow {}^3\text{He} + \gamma$  when 5.5 MeV axion is emitted instead  $\gamma$ -quantum. The expected solar axion flux can thus be expressed in terms of the  $pp$ -neutrino flux, which is  $\Phi_{\nu pp} = 6.0 \times 10^{10} \text{cm}^{-2}\text{s}^{-1}$  [9].

In the  $p(d, {}^3\text{He})\gamma$  reaction, the M1-type transition corresponds to the capture of a proton with a zero orbital momentum. The probability of proton capture from the *S* state at proton energies below 80 keV has been measured in [10]; at the proton energy of  $\sim 1$  keV, M1 fraction of the total  $p(d, {}^3\text{He})\gamma$  cross section is  $\chi = 0.55$ . The proton capture from the *S* state corresponds to the isovector transition, and the ratio of the probability of a nuclear transition with the axion

production ( $\omega_A$ ) to the probability of a magnetic transition ( $\omega_\gamma$ ) depends only on  $g_{AN}^3$  [8, 11]:

$$\frac{\omega_A}{\omega_\gamma} = \frac{\chi}{2\pi\alpha} \left[ \frac{g_{AN}^3}{\mu_3} \right]^2 \left( \frac{p_A}{p_\gamma} \right)^3 = 0.54(g_{AN}^3)^2 \left( \frac{p_A}{p_\gamma} \right)^3. \quad (1)$$

where  $p_\gamma$  and  $p_A$  are, respectively, the photon and axion momenta;  $\alpha$  is the fine-structure constant; and  $\mu_3$  is isovector nuclear magnetic momenta.

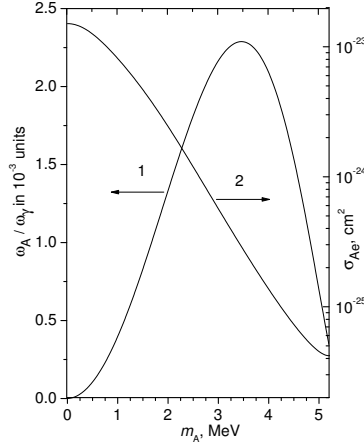


Figure 1: The ratio of the emission probabilities for axions and  $\gamma$  quanta ( $\omega_A/\omega_\gamma$ ) in the  $p + d \rightarrow {}^3\text{He} + \gamma$  reaction (curve 1, left-hand scale); the cross section of the axioelectric effect for 5.5-MeV axions on bismuth atoms for  $g_{Ae} = 1$  (curve 2, right-hand scale).

The calculated values of the  $\omega_A/\omega_\gamma$  ratio as a function of the axion mass are shown in Fig.1. The axion flux on the Earth's surface is  $\Phi_A = \Phi_{\nu pp}(\omega_A/\omega_\gamma)$ .

To detect 5.5 MeV axions, we chose the reaction of axioelectric effect  $A + Z + e \rightarrow Z + e$  which is caused by the axion-electron interaction. The cross section of the axioelectric effect depends on the nuclear charge according to the  $Z^5$  law, and therefore, it is reasonable to search for this process using detectors with a large  $Z$ . The detection efficiency for the produced electron is close to 1 and the background level at 5.5 MeV is much lower than in the range of natural radioactivity. As a result, the sensitivity to constants  $g_{Ae}$  and  $g_{AN}$  can be high even in an experiment using a relatively small target mass.

The axioelectric effect cross section for K-shell electrons has been calculated (on the assumption that  $E_A \gg E_b$  and  $Z \ll 137$ ) in [12]. The dependence of the cross section on the axion mass for the coupling constant  $g_{Ae} = 1$  is shown in Fig.1.

### 3 Experimental setup

We used a 2.46 kg BGO crystal, manufactured from bismuth orthogermanate  $\text{Bi}_4\text{Ge}_3\text{O}_{12}$  (1.65 kg of Bi), to search for the 5.5 MeV axions. The BGO crystal was grown at the Nikolaev Institute of Inorganic Chemistry and it was shaped as a cylinder, 76 mm in diameter and 76 mm in height. The detector signal was measured by an R2887 photoelectron multiplier, which had an optical contact with a crystal end surface.

The external  $\gamma$  activity was suppressed using a passive shield that consisted of successive layers of lead (90 mm) and bismuth (15 mm  $\text{Bi}_2\text{O}_3$ ). The total thickness of the passive shield was  $\approx 110 \text{ g cm}^{-2}$ . The setup was located on the Earth's surface. In order to suppress the cosmic-ray background we used an active veto, which consisted of five  $50 \times 50 \times 12 \text{ cm}$  plastic scintillators.

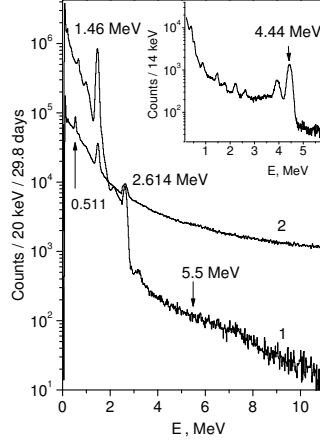


Figure 2: The energy spectrum of the BGO detector measured (1) in anticoincidence and (2) in coincidence with the active shielding signal. The location of the expected 5.5 MeV axion peak is denoted by an arrow. In inset the spectrum measured with Pu-Be neutron source is shown.

## 4 Results

The measurements were performed over 29.8 days in live time. The energy spectrum of the BGO detector in the range of (0–11) MeV is shown in Fig.2. The spectrum of the BGO signals that were not accompanied by the active shielding signal is designated as 1.

The positions and dispersion of the 1.46 MeV and 2.614 MeV peaks determined during the measurements were used to find the energy scale and resolution of the BGO detector. For higher energies the energy calibration was checked with a  $^{239}\text{Am}$ - $^9\text{Be}$  neutron source. (Fig.2, inset).

Figure 3 shows the energy range of (4.5 – 6.5) MeV, in which the axion peak was expected. The spectrum measured was fitted by a sum of exponential and two Gaussian functions. The intensity of the 5.49 MeV peak was found to be  $S_1 = -18 \pm 58$ , this corresponds to the upper limit on the number of counts in the peak,  $S_{lim} = 85$  at a 90% confidence level.

The expected number of axioelectric absorption events are:

$$S_{abs} = \varepsilon N_{Bi} T \Phi_A \sigma_{Ae} \quad (2)$$

where  $\sigma_{Ae}$  is the axioelectric effect cross section;  $\Phi_A$  is the axion flux;  $N_{Bi} = 4.76 \times 10^{24}$  is the number of Bi atoms;  $T = 2.57 \times 10^6 \text{ s}$  is the measurement time; and  $\varepsilon = 0.67$  is the detection efficiency for 5.5 MeV electrons. The axion flux  $\Phi_A$  is proportional to the constant  $(g_{AN}^3)^2$ , and

the cross section  $\sigma_{Ae}$  is proportional to the constant  $g_{Ae}^2$ . As a result, the  $S_{abs}$  value depends on the product of the axion-electron and axion-nucleon coupling constants:  $(g_{Ae})^2 \times (g_{AN}^3)^2$ .

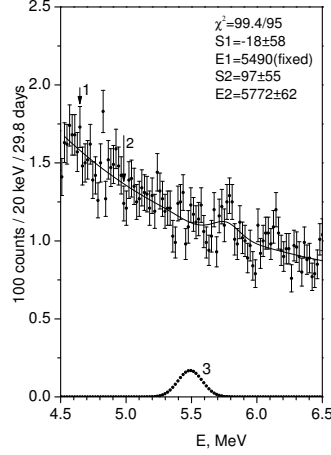


Figure 3: The fitted BGO spectrum in the (4.5 – 6.5) MeV range. Curve 3 is the detector response function for  $E_0 = 5.49$  MeV and  $\sigma = 0.093$  MeV.

The experimentally found condition  $S_{abs} \leq S_{lim}$  imposes some constraints on the range of possible  $|g_{Ae} \times g_{AN}^3|$  and  $m_A$  values. The range of excluded  $|g_{Ae} \times g_{AN}^3|$  values is shown in Fig. 4, at  $m_A \rightarrow 0$  the limit is

$$|g_{Ae} \times g_{AN}^3| \leq 2.9 \times 10^{-9}. \quad (3)$$

The dependence of  $|g_{Ae} \times g_{AN}^3|$  on  $m_A$  is related only to the kinematic factor in axio-electric cross section. These constraints are completely model-independent and valid for any pseudoscalar particle with coupling  $|g_{Ae}|$  less than  $10^{-6(4)}$  [8].

Within the hadronic axion model,  $g_{AN}^3$  and  $m_A$  quantities are related to the known relation, which can be used to obtain a constraint on the  $g_{Ae}$  constant, depending on the axion mass (Fig.4). For  $m_A = 1$  MeV, this constraint corresponds to  $|g_{Ae}| \leq 1.4 \times 10^{-7}$ .

Figure 4 also shows the constraints on the constant  $|g_{Ae}|$  that were obtained in the Borexino experiment for 478-keV  ${}^7\text{Li}$  solar axions [3] and in the Texono reactor experiment for 2.2-MeV axions produced in the  $n + p \rightarrow d + A$  reaction [6]. Recently, Borexino coll. reported new more stringent limits on  $g_{Ae}$  coupling for 5.5 MeV solar axions [4]. Unlike our work, these limits on  $g_{Ae}$  were obtained in assumption that the axion interacts with electron through the Compton conversion process.

## 5 Acknowledgments

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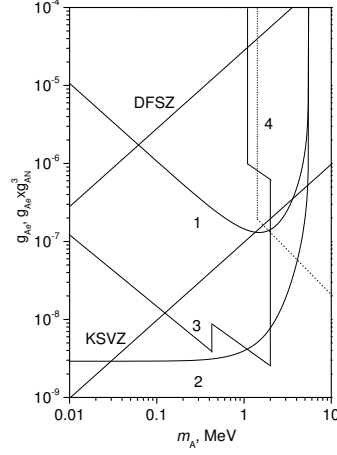


Figure 4: The limits on the  $g_{Ae}$  coupling constant obtained by 1- present work, 2 - present work for  $|g_{Ae} \times g_{AN}^3|$ , 3- solar [3] and reactor experiments [6, 13], 4- beam dump experiments [14, 15]. The allowed  $|g_{Ae}|$  and  $|g_{Ae} \times g_{AN}^3|$  values lie below the corresponding curves. The relations between  $g_{Ae}$  and  $m_A$  for DFSZ- and KSVZ-models are also shown .

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