

# Searches for axioelectric effect of solar axions with BGO-scintillator and BGO-bolometer detectors

V.N. Muratova<sup>1</sup>, A.V. Derbin<sup>1</sup>, L. Giorni<sup>2,3</sup>, S.S Nagorny<sup>4,5</sup>, L. Pattavina<sup>4</sup>, S.V. Bakhlanov<sup>1</sup>, J.W. Beeman<sup>6</sup>, F.Bellini<sup>7,8</sup>, M. Biassoni<sup>2,3</sup>, S. Capelli<sup>2,3</sup>, M. Clemenza<sup>2,3</sup>, I.S. Dratchnev<sup>1,5</sup>, E. Ferri<sup>2,3</sup>, A. Giachero<sup>2,3</sup>, C. Gotti<sup>2,3</sup>, A.S. Kayunov<sup>1</sup>, C. Maiano<sup>2,3</sup>, M. Maino<sup>2,3</sup>, M. Pavan<sup>2,3</sup>, S. Pirro<sup>4</sup>, D.A. Semenov<sup>1</sup>, M. Sisti<sup>2,3</sup>, E.V. Unzhakov<sup>1</sup>

<sup>1</sup>St.Petersburg Nuclear Physics Institute, Gatchina 188350 - Russia

<sup>2</sup>INFN - Sezione di Milano Bicocca, Milano I-20126 - Italy

<sup>3</sup>Dipartimento di Fisica, Università di Milano-Bicocca, Milano I-20126 - Italy

<sup>4</sup>INFN - Laboratorio Nazionale del Gran Sasso, Assergi (L'Aquila) I-67100 - Italy

<sup>5</sup>Gran Sasso Science Institute, INFN, L'Aquila (AQ) I-67100 - Italy

<sup>6</sup>Lawrence Berkeley National Laboratory, Berkeley, California 94720 - USA

<sup>7</sup>INFN -Sezione di Roma, Roma I-00185 - Italy

<sup>8</sup>Dipartimento di Fisica - Università di Roma La Sapienza, Roma I-00185 - Italy

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A search for axioelectric absorption of 5.5 MeV solar axions produced in the  $p+d \rightarrow {}^3\text{He} + \gamma$  (5.5 MeV) reaction has been performed with a BGO detectors. A model-independent limit on the product of axion-nucleon  $g_{AN}^3$  and axion-electron  $g_e$  coupling constants has been obtained:  $|g_{Ae} \times g_{AN}^3| < 1.9 \times 10^{-10}$  for 90% C.L..

## 1 Introduction

There are new possibilities for strong CP problem solution, which allow the existence of axions with a large mass ( 1 MeV), while their interaction with ordinary particles remain at the level of the invisible axions. The models rely on the hypothesis of mirror particles [1] and SUSY at the TeV scale [2]. The existence of these heavy axions is not forbidden by the laboratory experiments or astrophysical data.

This article describes the experimental search for 5.5 MeV solar axions, which can be produced by  $p + d \rightarrow {}^3\text{He} + A$  reaction. Axion flux should be proportional to the  $pp$ -neutrino flux, which has been estimated with high accuracy [3]. The searches have been performed with the use of bismuth orthogermanate  $\text{Bi}_4\text{Ge}_3\text{O}_{12}$  (BGO) scintillation and bolometric detectors. The solar axions are supposed to interact with atoms via the reaction of axioelectric effect  $A + e + Z \rightarrow e + Z$ . This kind of interaction is governed by  $g_{Ae}$ -constant and the cross section depends on the charge as  $Z^5$ . From this point of view the BGO detector is a very suitable target, because of the high  $Z_{Bi} = 83$  of bismuth nucleus.

The high energy solar axions and axions from a nuclear reactor have been looked by the Borexino [4, 5], the CAST [6] and the Texono [7] collaborations. This paper is based on the results of obtained with BGO scintillation [8] and BGO bolometer detectors [9].

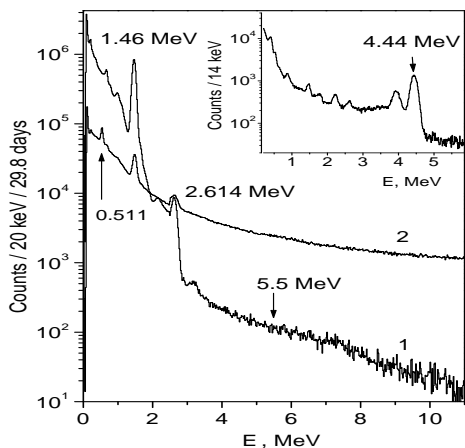


Figure 1: The energy spectrum of the BGO detector measured (1) in anticoincidence and (2) in coincidence with the muon veto signal.

The 5.5 MeV axion production probability ratio ( $\omega_A/\omega_\gamma$ ) depends only on the isovector axion-nucleon coupling constant  $g_{AN}^3$  (see [9] and refs therein):

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

where  $p_\gamma$  and  $p_A$  are, respectively, the photon and axion momenta and  $\mu_3$  is isovector nuclear magnetic momenta. At the Earth's surface the axion flux is:

$$\Phi_A = \Phi_{\nu pp}(\omega_A/\omega_\gamma) \quad (2)$$

where  $\Phi_{\nu pp}$  is the  $pp$ -neutrino flux. The cross section for the a.e. effect was calculated in [10].

## 2 BGO scintillation detector

BGO crystal with mass 2.46 kg contains 1.65 kg of Bi. The crystal was shaped as a cylinder, 76 mm in diameter and 76 mm in height. The detector signal was measured by an R1307 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 layers of lead and bismuth ( $\text{Bi}_2\text{O}_3$ ) with the total thickness  $\approx 110 \text{ g cm}^{-2}$ . 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. The measurements were performed over 29.8 days. The energy spectrum of the BGO detector in the range of (0–11) MeV is shown in Fig. 1. In inset the calibration spectrum measured with Pu-Be neutron source is shown.

In the spectrum, one can identify two pronounced peaks at 1.460 MeV and 2.614 MeV; these are due to the natural radioactivity of the  $^{40}\text{K}$  and of  $^{208}\text{Tl}$  from the  $^{232}\text{Th}$  family. The positions and intensities of these peaks were used for monitoring of time stability of the detector.

## 3 BGO bolometers

Four cubic ( $5 \times 5 \times 5 \text{ cm}^3$ ) BGO bolometers, containing 1.65 kg of Bi, were arranged in a four-plex module, one single plane set-up. The scintillation light was monitored with an auxiliary bolometer made of high-purity germanium [12]. The detector was installed in the  $^3\text{He}/^4\text{He}$  dilution refrigerator in the underground laboratory of L.N.G.S. and operated at a temperature of few mK. The four crystals were housed in a highly pure copper structure, the same described in [13]. Neutron Transmutation Doped (NTD) germanium thermistor was coupled to each bolometer, NTD acts as a thermometer: recording the temperature rises produced by particle interaction and producing voltage pulses proportional to the energy deposition. Details on electronics and on the cryogenic set-up can be found in [14, 15]. The detector was operated for a total live time of 151.7 days.

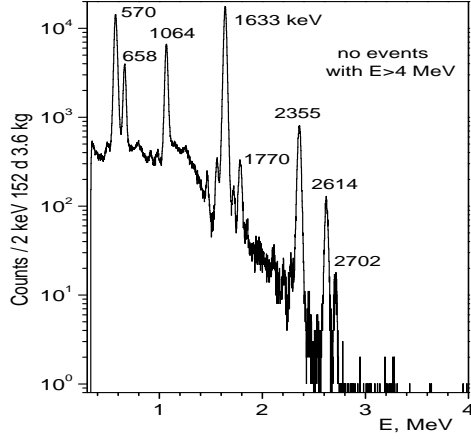


Figure 2: The energy spectrum of the four BGO detectors ( $\beta$  – and  $\gamma$ – events) measured for a 151.7 days.

The different light yield of interacting particles was used to discriminate  $\alpha$ –events from  $\beta/\gamma$  ones. This allowed to strongly increase the sensitivity, due to rejection of all  $\alpha$ –events in the region of interest. The total statistics in the range of (0.3–4) MeV for  $\beta/\gamma$  events are in shown in Fig.2. The most intense gamma lines are produced by  $^{207}\text{Bi}$  decays. In first approximation, the energy resolution of large mass bolometric detector is independent of the energy - the FWHM is  $33.7 \pm 0.6$  keV at 2614 keV ( $^{208}\text{Tl}$ ) and  $33.2 \pm 0.1$  keV at 570 keV ( $^{207}\text{Bi}$ ).

## 4 Results

The expected number of axioelectric absorption events are:

$$S_{abs} = \varepsilon N_{Bi} T \Phi_A \sigma_{Ae} \quad (3)$$

where  $\sigma_{Ae}$  is the axioelectric effect cross section;  $\Phi_A$  is the axion flux (2);  $N_{Bi}$  is the number of Bi atoms;  $T$  is the measurement time; and  $\varepsilon$  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  $(g_{Ae})^2 \times (g_{AN}^3)^2$ . 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. 3, at  $m_A \rightarrow 0$  the limits

$$|g_{Ae} \times g_{AN}^3| \leq 2.9 \times 10^{-9} \quad \text{and} \quad (4)$$

$$|g_{Ae} \times g_{AN}^3| \leq 1.9 \times 10^{-10} \quad \text{at 90\% c.l.} \quad (5)$$

were obtained for BGO scintillating and BGO bolometer detectors, correspondingly. These constraints are completely model-independent and valid for any pseudoscalar particle with coupling  $|g_{Ae}|$  less than  $10^{-6(4)}$ .

For hadronic axion model with concrete relation between  $g_{AN}^3$  and  $m_A$  one can obtain a constraint on the  $g_{Ae}$  constant, depending on the axion mass (Fig. 3). For  $m_A = 1$  MeV, this limit corresponds to  $|g_{Ae}| \leq 9.6 \times 10^{-9}$  at 90% c.l..

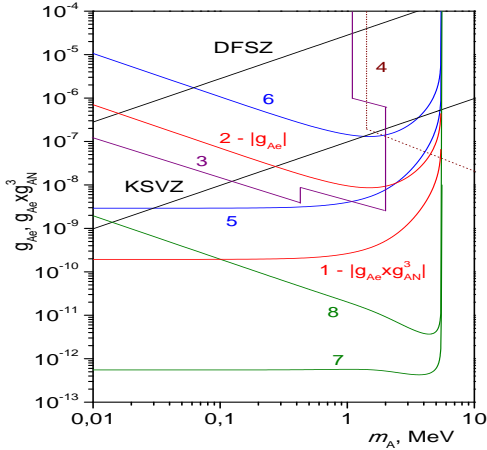


Figure 3: The limits on the  $g_{Ae}$  coupling constant obtained by 1,2 -BGO-bolometer [9] and 5,6-BGO-scintillator [8] for  $|g_{Ae}|$  and  $|g_{Ae} \times g_{AN}^3|$ , correspondingly; 3- solar and reactor experiments, 4- beam dump experiments; 7,8 - Borexino results for  $|g_{Ae} \times g_{AN}^3|$  and  $|g_{Ae}|$  [5].

Figure 3 also shows the constraints which were obtained in the Borexino experiment for 478 keV  ${}^7\text{Li}$  solar axions [4] and in the Texono reactor experiment for 2.2 MeV axions produced in the  $n + p \rightarrow d + A$  reaction [7]. Borexino coll. reported new more stringent limits on  $g_{Ae}$  coupling for 5.5 MeV solar axions [5]. Unlike our work, these limits on  $g_{Ae}$  coupling were obtained in assumption that the axion interacts with electron through the Compton conversion process.

In the model of the mirror axion [1] an allowed parameter window is found within the P-Q scale  $f_A \sim 10^4 - 10^5$  GeV and the axion mass  $m_A \sim 1$  MeV. The limit (5) may be represented as a limit on the value  $f_A$  by taking the following relations into account:  $g_{AN}^3 = 0.5(g_{Ap} - g_{An}) = 1.1/f_A$  and  $g_{Ae} = 5 \times 10^{-4}/f_A$ . For axion masses about 1 MeV, the limit is  $f_A > 1.7 \times 10^3$  GeV, which is close to the lower bound of mirror axion window.

Our results set constraints on the parameter space of the CP-odd Higgs ( $A^0$ ), which arise in the next-to-minimal supersymmetric Standard Model due to the spontaneous breaking of approximate symmetries such as PQ-symmetry. The corresponding exclusion region can be obtained from Fig.3 using the conversion  $C_{Aff} = g_{Ae}2m_W/g_2m_e$  where  $C_{Aff}$  is the coupling of the CP-odd Higgs to fermions and  $g_2 = 0.62$  is the gauge coupling. The limit (5) translates into  $C_{Aff} \times m_{A^0} \leq 3 \times 10^{-3}$  MeV for  $m_{A^0} < 1$  MeV, which is compatible with the limits obtained in reactor experiments exploring Compton conversion.

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## References

- [1] Z. Berezhiani et al., Phys. Lett. B500, 286 (2001).
- [2] L.J. Hall and T. Watari, Phys. Rev. D70, 115001 (2004).
- [3] G. Bellini et al., (Borexino coll.) Nature, 512, 7515, 383 (2014)
- [4] G. Bellini et al., (Borexino coll.) EPJ, C54, 61 (2008).
- [5] G. Bellini et al., (Borexino Coll.), Phys. Rev. D 85, 092003 (2012).
- [6] S. Andriamonje et al., (CAST coll.) JCAP 1003, 032, (2010). arXiv:0904.2103
- [7] H.M. Chang et al., (Texono Coll.) Phys. Rev. D75, 052004 (2007).
- [8] A.V. Derbin et al., Europ. Phys. J. C73, 2490 (2013). arXiv:1306.4574
- [9] A.V. Derbin et al., Europ. Phys. J. C74, 3035 (2014). arXiv:1405.3782
- [10] A.R. Zhitnitskii and Yu.I. Skovpen, Yad. Fiz., 29b, 995 (1979).
- [11] L. Cardani, S.Di Domizio, L. Gironi, JINST 7, P10022 (2012).
- [12] J.W. Beeman et al., JINST 8, P05021 (2013).
- [13] F. Alessandria et al., Astropart. Phys. 35, 839849 (2012).
- [14] S. Pirro et al., Nucl. Instrum. Methods A 444, 331 (2000).
- [15] C. Arnaboldi et al., Nucl. Instrum. Methods A 559, 826 (2006).