Search for 5.5 MeV solar axions with the Borexino detector

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The sensitivity of the Borexino large scintillation detector was determined for search for axions with an energy of 5.5 MeV produced in the nuclear reaction $p + d \to {}^3\mathrm{He} + A$ in the Sun through the Compton process and the conversion of an axion into a photon in the solar core field. Basing on the measured Borexino spectrum, new upper limits have been established for the product of the coupling constants of the axion with electrons and nucleons $|g_{Ae}g^3_{AN}| \leqslant 4.6 \cdot 10^{13}$ and with a photon and nucleons $|g_{A\gamma}g^3_{AN}| \leqslant 3.6 \cdot 10^{-11}\,\mathrm{GeV}^{-1}$, both limits are given for 90% confidence level.

Keywords: solar axions, dark matter, axion-like particles.

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An axion is a hypothetical Nambu–Goldstone field boson introduced in order to solve the problem of CP violation in strong interaction, which is manifested, among other things, in an anomalously small neutron dipole moment value [1–3]. If axions exist, the Sun should be an intense source of these particles, including those produced in magnetic-type nuclear transitions. Such a transition with an energy of 5.49 MeV is found among the reactions of the proton-proton chain that produces the bulk of solar energy; the reaction in question is fusion $p + d \to {}^3\mathrm{He} + A$. The flux of axions with an energy of 5.5 MeV turns out to be proportional to the flux of solar pp neutrinos produced in the same chain of reactions, which is known with high accuracy. The coefficient of proportionality depends on the isoscalar (g^0_{AN}) and isovector (g^3_{AN}) axion–nucleon coupling constants. In numerical form, the terrestrial flux of solar axions is written as [4]

$$\Phi_A = \Phi_{pp} \cdot 3.23 \cdot 10^{10}(g^3_{AN})^2(p_A/p_\gamma)^3, \tag{1}$$

where $\Phi_{pp} = 6 \cdot 10^{10}\,\nu \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ is the solar pp neutrino flux and p_A and p_γ are the axion and photon momenta, respectively. The axion mass to which the search for this reaction is sensitive may reach 5 MeV.

The flux of solar axions may be detected in the process of conversion of an axion into a photon in the nuclear field ($A + Z \to \gamma + Z$), in the decay of an axion into two photons ($A \to \gamma\gamma$), in the axioelectric effect reaction ($A + e^- + Z \to e^- + Z$), and in the Compton process ($A + e^- \to e^- + \gamma$). In the present study, only the conversion of an axion in the nuclear field, which is similar to the Primakoff conversion of a π^0 meson, and the Compton conversion at an electron are considered. In both cases, the final state contains two particles with a total energy of 5.5 MeV.

The integral cross section of the Compton process has a complex form and depends on axion–electron coupling constant g^2_{Ae}, axion mass m_A, and its energy E_A [5]. If axions are relatively light (have a mass below 1 MeV) and have an energy above 5 MeV, the cross section is almost independent of axion energy and is written as

$$\sigma_{CC} \cong g^2_{Ae} \cdot 4.3 \cdot 10^{-25}\,\mathrm{cm}^2. \tag{2}$$

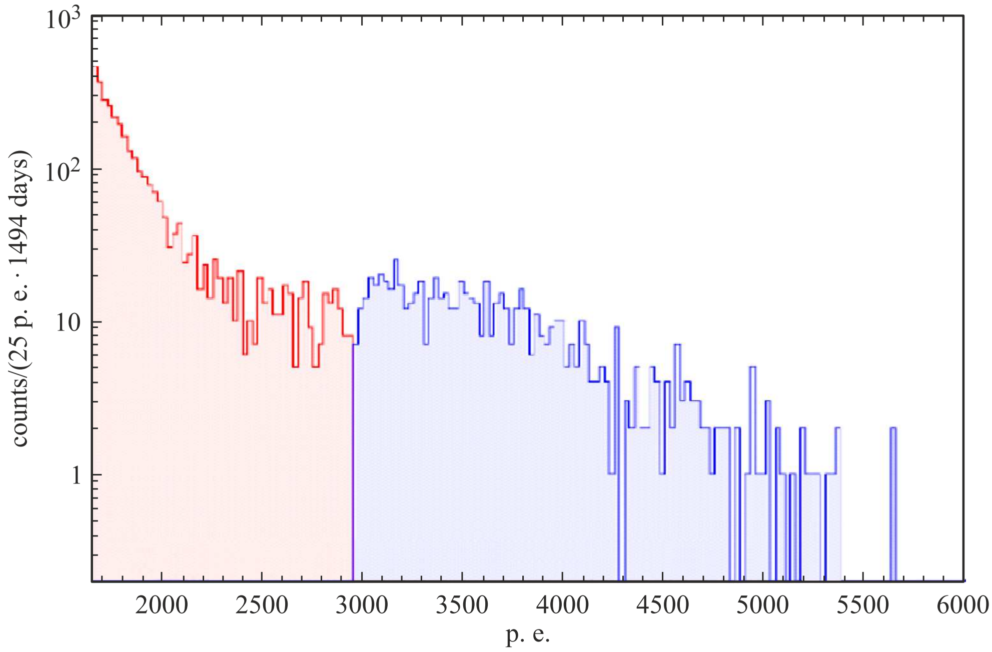
The cross section of axion conversion into a photon in the nuclear field in an organic scintillator ($A + {}^{12}\mathrm{C} \to \gamma + {}^{12}\mathrm{C}$) depends on axion–photon coupling constant $g^2_{A\gamma}$:

$$\sigma_{PC} = g^2_{A\gamma}\frac{\alpha Z^2}{2}\left[\frac{1+\beta^2}{2\beta^2}\ln\left(\frac{1+\beta^2}{1-\beta^2}\right) - \frac{1}{\beta}\right].$$

Here, Z is the nuclear charge, $\alpha = 1/137$ is the fine structure constant, and $\beta = p_A/E_A$ is the axion velocity [6]. The flux of axions coming from the Sun is weakened due to their decay into two gamma quanta, which must be taken into account in the process of detection of axions through the conversion reaction in the nuclear field.

In the present study, we report the results of a search for an axion with an energy of 5.5 MeV performed with the use of experimental data from the Borexino detector (an ultrapure low-background liquid scintillation detector, which is focused on the detection of solar neutrinos [7]). This detector is a four-layer structure incorporating an external water tank 15.7 m in diameter and 16.5 m in height, which is viewed by 208 photomultiplier tubes and serves as a muon veto. A steel sphere with a diameter of 13.7 m is positioned inside the tank. A pseudocumene-based liquid scintillator with a mass of 278 t is held inside a thin nylon sphere, which is surrounded by a concentric 2.6-m-thick buffer layer of pseudocumene with a quenching additive. The sphere is viewed by 2212 photomultiplier tubes that provide an energy resolution of 5% and a spatial resolution of 13 cm at an energy of 1 MeV. The scintillator was purified to unprecedented levels (ten orders of magnitude lower than the natural radioactivity level).

The data used in the search for an axion were taken from [8] and collected within the interval from January 2008



Borexino detector spectrum measured within the 3.4–12 MeV interval in 1494 days.

to December 2016, which included 1494 days of live time. The figure presents the event spectrum after a series of selection cuts (see [8]). Number of detected photoelectrons (p.e.) N_{pe} is plotted on the abscissa axis. This number is tied to the event energy by relation $E[\mathrm{MeV}] = N_{pe}/500$ for 2000 detecting photomultiplier tubes. The spectrum corresponds to the entire active volume of the detector enclosed within the nylon sphere. At energies corresponding to N_{pe} below 2950 p.e., events shifted by more than 2.5 m vertically upward from the detector center were rejected, which explains a jump in the number of selected events at this point. The total active mass of the detector was 266 ± 5.3 t for the low-energy region, and the volume fraction was found to be equal to $\varepsilon = 0.857 \pm 0.006$.

Axions with an energy of 5.5 MeV causing axion-to-photon conversion reactions are expected to induce a detector response close to a monoenergetic peak with the corresponding energy. With the specified light yield and energy resolution, which is broadened somewhat by the non-uniformity of light signal collection, taken into account, one should expect the emergence of a Gaussian peak with position $x_0 = 2740$ p.e. and variance $\sigma = 60$ p.e., which is determined by scaling the energy resolution of the detector with account for the square-root dependence on energy. A statistically significant peak with such parameters is not observed. Since the count rate of background events within the 2500–4000 p.e. range depends only weakly on energy (see the figure), the common 3.3σ method may be used to determine the upper limit of the number of events in the Gaussian peak. Assuming conservatively that the background level at an energy of 5.5 MeV is one event per photoelectron, we may set the upper limit on the number of events in the peak to $S_{\lim} = 25$ counts at 90% CL (confidence level).

Expected number S of axions detected in the Compton conversion reaction is determined as

$$S = \sigma_{CC}\Phi_A T N_e \varepsilon. \quad (3)$$

Here, N_e is the number of electrons within the detector volume and T is the measurement time. Coupled with expressions (1) and (2), condition $(S \leqslant S_{\lim})$ allows one to impose an upper limit on the product of constants g^2_{Ae} and $(g^3_{AN})^2$:

$$|g_{Ae} g^3_{AN}| \leqslant 4.6 \cdot 10^{-13} (90\,\%\mathrm{CL}). \quad (4)$$

In the case of axion conversion into a photon in the field of ^{12}C nuclei, calculations by formula (3) with N_e replaced by number $N_{^{12}\mathrm{C}}$ of carbon nuclei and σ_{CC} substituted with cross section σ_{PC} yield the following result for constant $g_{A\gamma}$:

$$|g_{A\gamma} g^3_{AN}| \leqslant 3.6 \cdot 10^{-11}\,\mathrm{GeV}^{-1} \quad (5)$$

(also at 90% CL). Constraints (4) and (5) were both obtained under the assumption that $(p_A/p_\gamma)^{3/2} \approx 1$, which is valid for axion masses lower than 1 MeV. These constraints are on par with the best results reported in experiments at reactors and accelerators [9] and allow one to refine the earlier Borexino data [4]. In addition, the established limits exclude a significant region of possible values of constants g_{Ae} and $g_{A\gamma}$ in models with axion-like particles with masses in the region of 1 MeV [10,11].

Thus, a search for signals of reactions involving an axion was carried out in the data set provided by the Borexino detector. The measured detector spectrum turned out to be statistically consistent with known background components. As a result, new constraints on the coupling constants of an axion with an electron and nucleons and the coupling constants of an axion with photons and nucleons were obtained: $|g_{Ae}g_{AN}^3| \leqslant 4.6 \cdot 10^{-13}$ and $|g_{A\gamma}g_{AN}^3| \leqslant 3.6 \cdot 10^{-11}\,\mathrm{GeV}^{-1}$ (all at 90% CL).

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Conflict of interest

The authors declare that they have no conflict of interest.

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