Search for 5.5 MeV Solar Axions Produced in a $p(d, ^3\text{He})\text{A}$ Reaction with Borexino Detector

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A search for 5.5-MeV solar axions produced in the $p + d \rightarrow {}^3\text{He} + \gamma(5.5\text{MeV})$ reaction was performed using the Borexino detector. Model independent limits on axion-electron (g_{Ae}), axion-photon ($g_{A\gamma}$), and isovector axion-nucleon (g_{3AN}) couplings are obtained: $|g_{Ae} \times g_{3AN}| \le 5.5 \times 10^{-13}$ and $|g_{A\gamma} \times g_{3AN}| \le 4.6 \times 10^{-11}\text{GeV}^{-1}$ at $m_A < 1$ MeV (90% c.l.). These limits are 2-4 orders of magnitude stronger than those obtained in previous laboratory-based experiments using nuclear reactors and accelerators.

The Sun potentially represents an efficient and intense source of axions. The most intense flux of high energy axions is expected from the formation of the ^{3}He nucleus[1] -[3]:

$$p + d \rightarrow {}^3\text{He} + \gamma(5.49\ \text{MeV}). \tag{1}$$

According to the Standard Solar Model (SSM), 99.7% of all deuterium is produced from the fusion of two protons, $p+p \rightarrow d+e^+ + \nu_e$, while the remaining 0.3% is due to the $p+p+e^- \rightarrow d+\nu_e$ reaction. The expected solar axion flux can thus be expressed in terms of the pp-neutrino flux. The proton capture from the S state corresponds is an isovector transition, and the ratio between the probability of a nuclear transition with axion production (ω_A), and the probability of a magnetic transition (ω_γ) depends only on g_{3AN}: [4]-[6]:

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

The expected solar axion flux on the Earth's surface is then

$$\Phi_{A0} = \Phi_{\nu pp}(\omega_A/\omega_\gamma) = 3.23 \times 10^{10}(g_{3AN})^2(p_A/p_\gamma)^3 = 2.44 \times 10^{-5} m_A^2 (p_A/p_\gamma)^3,$$

where $\Phi_{\nu pp} = 6.0 \times 10^{10}\text{cm}^{-2}\text{s}^{-1}$ is the *pp* solar neutrino flux and m_A is the axion mass in eV units.

An axion can scatter an electron to produce a photon in the Compton-like process $A + e \to \gamma + e$. For axions with fixed g_{Ae} the phase space contribution to the cross section is approximately independent of m_A for $m_A < 2$ MeV and the integral cross section is $\sigma_{CC} \approx g_{Ae}^2 \times 4.3 \times 10^{-25}\text{cm}^2$. The dimensionless coupling constant g_{Ae} is associated with the electron mass m, so that $g_{Ae} = C_e m/f_A$, where C_e is a model dependent factor of the order of unity. The hadronic axion has no tree-level couplings to the electron, but there is an induced axion-electron coupling at one-loop level [7].

The other process associated with axion-electron coupling is the axio-electric effect $A + e + Z \to e + Z$ (the analogue of the photo-electric effect). In this process the axion disappears and an electron is emitted from an atom with an energy equal to the energy of the absorbed axion minus the electron binding energy [8]. The cross section has a Z^5 dependence and for carbon atoms the cross section is low $\sigma_{ae} \approx g_{Ae}^2 \cdot 1.3 \cdot 10^{-29}$ cm^2/electron for $m_A < 1$ MeV. However, the axio-electric effect is a potential signature for axions with detectors having high Z active mass [3].

For axions with a mass above $2m_e$, the main decay mode is the decay into an electron-positron pair: $A \to e^+ + e^-$. The condition that time of flight is less than lifetime - $\tau_f < 0.1\tau_{e^+e^-}$ (in this case, 90% of all axions reach the Earth) limits the sensitivity of solar axion experiments to $g_{Ae} < (10^{-12} - 10^{-11})$ [3].

If the axion mass is less than $2m_e$, $A \to e^+ + e^-$ decay is forbidden, but the axion can decay into two γ quanta. The probability of the decay, which depends on the axion-photon coupling constant $g_{A\gamma}$ and the axion mass, is given by the expression: $\tau_{2\gamma} = 64\pi/g_{A\gamma}^2 m_A^3$. The flux of axions reaching the detector is given by $\Phi_A = exp\,(-\tau_f/\tau_{2\gamma})\,\Phi_{A0}$.

Another process depending on $g_{A\gamma}$ coupling is the Primakoff photo-production on carbon nuclei $A + ^{12}\text{C} \to \gamma + ^{12}\text{C}$. The integral inverse Primakoff conversion cross section is proportional Z^2: $\sigma_{PC} \approx g_{A\gamma}^2 Z^2 \alpha$ [6]. Because the cross section depends on the $g_{A\gamma}$ coupling, the decrease in the axion flux due to $A \to 2\gamma$ decays during their flight from the Sun should be taken into account.

Borexino is a real-time detector for solar neutrino spectroscopy located at the Gran Sasso Underground Laboratory. The main features of the Borexino detector and its components have been thoroughly described in ([9]-[11] and refs therein). The Monte Carlo method has been used to simulate the Borexino response $S(E)$ to electrons and γ-quanta produced by axion interactions. The MC simulations are based on the GEANT4 code, taking into account the effect of ionization quenching and non-linearity induced by the energy dependence on the event position.

Figure 1 shows the observed Borexino energy spectrum in the $(3.0 - 8.5)$ MeV range in which the axion peaks might appear. The obtained upper limits on the number of counts in the peak ($S_{CC}^{lim} \leq 0.013$ c/(100 t day) at 90% c.l.) are very low, e.g. $\sim 10^4$ times lower than expected number of events from *pp*− neutrino (135 c/(100 t day)).

The upper limits on the number of events with energy 5.5 MeV constrain the product of axion flux Φ_A and the interaction cross section $\sigma_{A-e,p,C}$ via relation: $S_{events} = \Phi_A \sigma_{A-e,p,C} N_{e,p,C} T \varepsilon \leq S^{lim}$. Yere $N_{e,p,C}$ is the number of electrons, protons and carbon nuclei in the IV, T is the

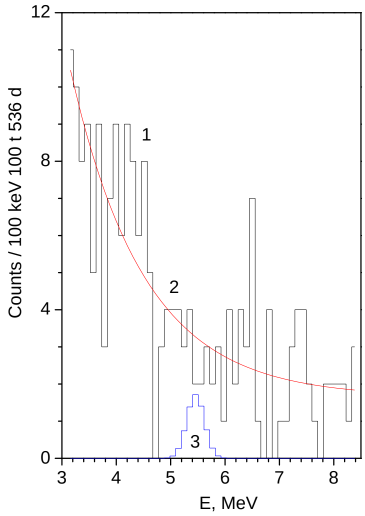

Figure 1: The fitted Borexino spectrum in the (3.2 – 8.4) MeV range. Curve 3 is the detector response function for Compton axion-photon conversion at the 90% c.l. upper limit (S=6.9 events).

measurement time and ε is the detection efficiency. The individual rate limits are:

$$\Phi_A \sigma_{A-electron} \leq 4.5 \times 10^{-39} \mathrm{s}^{-1} \quad (3)$$

$$\Phi_A \sigma_{A-proton} \leq 2.5 \times 10^{-38} \mathrm{s}^{-1} \quad (4)$$

$$\Phi_A \sigma_{A-carbon} \leq 3.3 \times 10^{-38} \mathrm{s}^{-1} \quad (5)$$

For comparison the standard solar neutrino capture rate is SNU $= 10^{-36}\mathrm{s}^{-1}\mathrm{atom}^{-1}$.

The axion flux Φ_A is proportional to the constant $(g_{3AN})^2$, and the cross section σ_{CC} is proportional to the constant g_{Ae}^2. The S_{CC} value depends, then, on the product of $g_{Ae}^2 \times (g_{3AN})^2$. The range of excluded $|g_{Ae} \times g_{3AN}|$ values is shown in Fig.2 (line 2). At $(p_A/p_\gamma)^3 \approx 1$ or $m_A < 1\mathrm{MeV}$ the limit is:

$$|g_{Ae} \times g_{3AN}| \leq 5.5 \times 10^{-13} (90\% c.l.). \quad (6)$$

These constraints are completely model-independent and valid for any pseudoscalar particle. Within the hadronic (KSVZ) axion model, one can obtain a constraint on the g_{Ae} constant, depending on the axion mass (Fig.2. line 1). For $(p_A/p_\gamma)^3 \approx 1$ the limit on g_{Ae} and m_A is:

$$|g_{Ae} \times m_A| \leq 2.0 \times 10^{-5}, \quad (7)$$

where m_A is given in eV units (90% c.l.).

The analysis of $A \rightarrow 2\gamma$ decay and Primakoff photoproduction is more complicated because axions can decay during their flight from the Sun. The exponential dependence of the axion

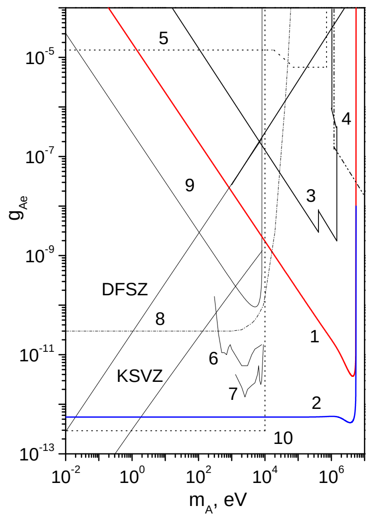

Figure 2: The limits on the g_{Ae} coupling constant obtained by 1- present work, 2 - present work for $|g_{Ae} \times g_{3AN}|$, 3- reactor and solar experiments, 4- beam dump experiments, 5- ortho-positronium decay, 6- CoGeNT, 7- CDMS, 8- solar axion luminosity, 9-resonance absorption [12], 10- read giant. The excluded values are located above the corresponding lines.

flux on $g_{a\gamma}$ and m_A must be taken into account. In the assumption that $\beta \approx 1$ the number of decays in the FV depends on g^2_{3AN}, $g^2_{A\gamma}$ and m^4_A. The limit derived at 90% C.L., is

$$|g_{A\gamma} \times g_{3AN}| \times m^2_A \leq 3.3 \times 10^{-2}. \quad (8)$$

The number of expected events due to inverse Primakoff conversion is $S_{PC} = \Phi_A \sigma_{PC} N_C T \varepsilon_{PC}$, where σ_{PC} is the Primakoff conversion cross sections. Under the assumption that $\Phi_A \approx \Phi_{A0}$ one can obtain the restriction ($g_{A\gamma}$ is in GeV^{-1} units):

$$|g_{A\gamma} \times g_{3AN}| \leq 4.6 \times 10^{-11} (90\% c.l.), \quad (9)$$

This limit is 25 times stronger than the one obtained by CAST [14], which searches for conversion of 5.5 MeV axions in a laboratory magnetic field In the KSVZ model the constraint on $g_{A\gamma}$ and m_A is given by the relation:

$$|g_{A\gamma}| \times m_A \leq 1.7 \times 10^{-3} \quad (10)$$

For m_A=1 MeV, this corresponds to $g_{A\gamma} \leq 1.2 \times 10^{-3}$. The region of excluded values of $g_{A\gamma}$ and m_A are shown in Fig.3, line 1b; under the assumption that $g_{A\gamma}$ depends on m_A as in the KSVZ model we exclude axions with masses between (1.5 - 73) keV. Our results from the inverse Primakoff process exclude a new region of $g_{A\gamma}$ values at $m_A \sim 10$ keV.

A search for 5.5 MeV solar axions emitted in the $p(d, {}^3\text{He})$A reaction has been performed with the Borexino detector. The Compton conversion of axions into photons, the decay of axions

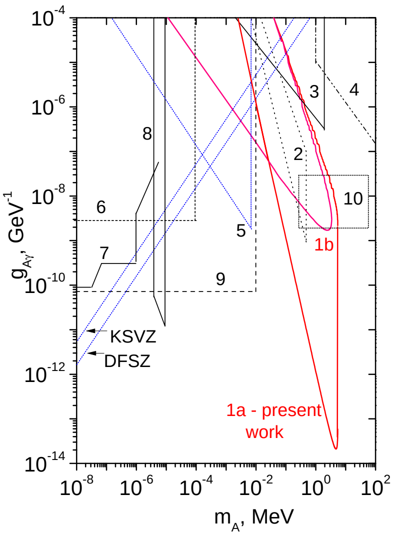

Figure 3: The limits on $g_{A\gamma}$ obtained by 1- present work (a - $A \to 2\gamma$, b - PC, areas of excluded values are located inside contour), 2 - CTF [1], 3- reactor experiments, 4- beam dump experiments, 5- resonant absorption [13], 6- solar axions conversion in crystals, 7- CAST, 8- telescopes, 9- HB Stars, 10-expectation region from heavy axion models.

into two photons, and inverse Primakoff conversion on nuclei were studied. The signature of all these reactions is a 5.5 MeV peak in the energy spectrum of Borexino. No statistically significant indications of axion interactions were found. New, model independent, upper limits on the axion coupling constants to electrons, photons and nucleons were obtained.

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