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Constraining axion couplings with the JUNO detector

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The forthcoming Jiangmen Underground Neutrino Observatory (JUNO) is planned to resolve the neutrino mass ordering. However, given its energy resolution capability and detector volume, the JUNO detector can be used to test various new physics predictions. Among numerous new physics, this work is dedicated to scrutinizing the 5.49 MeV solar axions flux, which would be produced, in the $p(d,^3\mathrm{He})a$ nuclear reaction. For axion detection, we adopt various processes such as Compton and inverse Primakoff conversion, along with their decay into two photons or electron-positron pairs inside the detector. We perform a likelihood analysis in order to forecast the JUNO's sensitivity. To make a comprehensive study, the sensitivity limit arising from various other experiments has also been conferred.

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1. Introduction

The QCD axion [1–3] is one of the best motivated fundamental particles beyond the Standard Model (BSM). It provides the most simple solution to the "strong CP problem" of QCD, where the spontaneous breaking of a global $U(1)$ symmetry, called the Peccei-Quinn (PQ) symmetry $U(1)_{PQ}$, gives rise to a pseudo-Nambu-Goldstone (pNG) boson. The model-dependent axion couplings to SM fields provide various opportunities for their detection. The most widely studied experimental detection channels are through the couplings with photons ($g_{a\gamma}$), electrons (g_{ae}), and nucleons (isosinglet g_{0aN} and isotriplet g_{3aN}). The effective low-energy axion Lagrangian for these interactions are represented by

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)^2 - m_a^2 a^2 - \frac{1}{4}\, g_{a\gamma}\, a F_{\mu\nu}\widetilde{F}^{\mu\nu} - i g_{ae} a\, \bar{e}\gamma_5 e - i a \bar{N}\gamma_5\, \left(g_{0aN} + \tau_3 g_{3aN}\right) N\,, \quad (1)$$

where the first two terms depict the kinetic and mass terms of the axion field a, the electromagnetic field strength tensor and its dual are represented by $F_{\mu\nu}$ and $\widetilde{F}^{\mu\nu}$, and N refers to the proton-neutron isospin doublet.

A noteworthy experimental effort has been assigned to axion searches in recent years. Solar axions produced from the nuclear $p + d \to {}^3$He + a(5.49 MeV) reaction have been probed by the Borexino collaboration, constraining the coupling combinations $(g_{3aN}\,,\ g_{ae})$ and $(g_{3aN}\,,\ g_{a\gamma})$ [4]. In this work, we make an attempt to improve the limits set by Borexino using other neutrino experiments. In doing so, we consider the proposed Jiangmen Underground Neutrino Observatory (JUNO) represents a step forward, since it combines a large fiducial mass ($\sim$ 20 kton) and an exquisite energy resolution ($3\%/\sqrt{E(\mathrm{MeV})}$) [5]. For this reason, we focus on the JUNO detector, showing that it can improve by about an order of magnitude bounds set by the Borexino experiment.

While performing our analysis, we consider the JUNO events spectrum provided in Ref. [6]. Particularly, we focus on the axion flux from the $p + d \to {}^3$He + a(5.49 MeV) reaction, as in Ref. [4]. This axion flux can be detected through various channels. Here, the Compton conversion of axions to photons, a + $e \to e + \gamma$, inverse Primakoff conversion on nuclei, a + $Z \to \gamma + Z$, axion electron-pair production, and axions decay into two photons as well as two electrons have been investigated.

2. Solar axion flux

Axions can be non-thermally produced in the Sun through nuclear reaction processes induced by the last term in Eq. (1). It is well studied that a monochromatic flux of axions is produced in magnetic dipole transitions from the de-excitation of excited levels of nuclei in the Sun, e.g. ${}^{57}\mathrm{Fe}^* \to {}^{57}\mathrm{Fe} + a(14.4\,\mathrm{keV})$ and ${}^{83}\mathrm{Kr}^* \to {}^{83}\mathrm{Kr} + a(9.4\,\mathrm{keV})$, or from nuclear reactions such as $p + d \to {}^3\mathrm{He} + a\,(5.49\,\mathrm{MeV})$.

If axions exist (and are coupled to nucleons), the number of axions produced can be related to the number of photons and thus (assuming the axions are not reabsorbed in the solar medium) to the neutrino flux. Specifically, $\Phi_{a0} = (\Gamma_a/\Gamma_\gamma)\Phi_{\nu pp}$, further details are described in [7], where the coefficient

$$\frac{\Gamma_a}{\Gamma_\gamma} = \left(\frac{k_a}{k_\gamma}\right)^3 \frac{1}{2\pi\alpha}\frac{1}{1+\delta^2}\left[\frac{\beta\, g_{0aN} + g_{3aN}}{\left(\mu_0 - \frac{1}{2}\right)\beta + \mu_3 - \eta}\right]^2 , \tag{2}$$

measures the probability for a given nuclear transition to result in an axion rather than a photon emission. Here, the axion and photon momenta are denoted by k_a and k_γ, α is the electromagnetic fine structure constant, $\mu_0 = \mu_p + \mu_n \approx 0.88$ and $\mu_3 = \mu_p - \mu_n \approx 4.77$ are the isoscalar and isovector nuclear magnetic moments (expressed in nuclear magnetons). Various parameters δ, β and η are constants dependent on the nuclear structure. The ^{3}He formation process is identified by $\beta = \delta = 0$, and $\eta = 1$ which, in particular, implies that only the isotriplet axion-nucleon coupling g_{3aN} is relevant in this process, that can be expressed numerically as

$$\frac{\Gamma_a}{\Gamma_\gamma} \simeq 0.54\, g_{3aN}^2 \left(\frac{k_a}{k_\gamma}\right)^3 . \tag{3}$$

Furthermore, if axions interact sufficiently weakly, they will escape the Sun without being reabsorbed, just like the neutrinos, and produce an axion flux on Earth. Thus, one can find the expected axion flux on Earth by inserting the known pp solar neutrino flux, $\Phi_{\nu pp} = 6.0 \times 10^{10}\,\mathrm{cm^{-2}s^{-1}}$ [4], and accounting for a possible axion decay as

$$\Phi_a = \Phi_{a0}\, e^{-d_\odot/l_{\rm tot}} \simeq 3.23 \times 10^{10}\, e^{-d_\odot/l_{\rm tot}}\, g_{3aN}^2 \,(k_a/k_\gamma)^3\,\mathrm{cm^{-2}s^{-1}} , \tag{4}$$

where $l_{\rm tot} = (1/l_\gamma + 1/l_e)^{-1}$ is the total axion decay length, with l_γ and l_e the decay length in photons and electron pairs respectively, and $d_\odot = 1.5 \times 10^{13}$ cm is the Earth-Sun distance.

3. Axion detection channels

Axion-electron coupling: Axions interacting with electrons can be detected at the JUNO through Compton-like scattering $a + e^- \longrightarrow \gamma + e^-$, the axio-electric effect $a + e^- + Ze \longrightarrow e^- + Ze$, pair production in the electric field of nuclei and electrons $a + Ze \longrightarrow Ze + e^- + e^+$ and the decay into electron-positron pairs $a \longrightarrow e^+ + e^-$. For the Compton-like scattering, the phase space contribution to the cross section σ_C is approximately independent of the axion mass for $m_a \lesssim 2$ MeV, (for more details, see [7]) and the integral cross section reduces to

$$\sigma_C \approx g_{ae}^2 \times 4.3 \times 10^{-25}\,\mathrm{cm}^2 . \tag{5}$$

Moreover, for axions mass $m_a > 2\,m_e$, axions can decay into electron-positron pairs, with decay length

$$l_e = \frac{\gamma v}{\Gamma_{a\to e^+e^-}} \simeq 0.33\,\frac{E_a}{m_a}\frac{\sqrt{1-\frac{m_a^2}{E_a^2}}}{\sqrt{1-\frac{4m_e^2}{m_a^2}}}\left(\frac{g_{ae}}{10^{-11}}\right)^{-2}\left(\frac{m_a}{\mathrm{MeV}}\right)^{-1} d_\odot . \tag{6}$$

Therefore, the axion flux, as shown in Eq. (4), arriving on Earth is reduced by a factor $\exp(-d_\odot/l_e)$.

Axion-photon coupling: Besides axion-electron couplings, axions coupled with photons can be converted into photons in the electric field of charged particles Ze via the inverse Primakoff effect $a + Ze \rightarrow \gamma + Ze$. The differential cross section can be expressed as

$$\frac{d\sigma_{\rm P}}{d\Omega_a} = \frac{g^2_{a\gamma}\,\alpha}{4\pi}\frac{k_a^4}{q^4}\,\sin^2\theta_a\,F^2(q)\,, \tag{7}$$

where $d\Omega_a = d\phi_a d\cos\theta$, θ_a is the scattering angle, and $F(q)$ is the atomic form factor, with $q^2 = m_a^2 - 2\,E_\gamma\,(E_a - k_a\,\cos\theta_a)$ and $E_\gamma \approx E_a$ is the energy of the outgoing photon.

Also, axions can decay into two photons with decay length

$$l_\gamma = \frac{\gamma v}{\Gamma_{a\to\gamma\gamma}} \simeq 2.64\,\frac{E_a}{m_a}\sqrt{1-\frac{m_a^2}{E_a^2}}\left(\frac{g_{a\gamma}}{10^{-8}\,{\rm GeV}^{-1}}\right)^{-2}\left(\frac{m_a}{\rm MeV}\right)^{-3}\,d_\odot\,. \tag{8}$$

Therefore, the axion flux arriving on Earth is reduced by a factor $\exp(-d_\odot/l_\gamma)$ as discussed in Eq. (4). As we notice that the decay rate is proportional to m_a^3, the decay becomes the dominant process for large values of $g^2_{a\gamma}\,m_a^3$.

4. Likelihood analysis and Results

We briefly describe here our fitting procedure to characterize the sensitivity of the JUNO detector [9]. In order to analyze the detector sensitivity, we define the χ^2 function as [6]

$$\begin{aligned}\chi^2 =& 2\times\sum_i\left(N_{i,{\rm pre}} - N_{i,{\rm exp}} + N_{i,{\rm exp}}\times\log\frac{N_{i,{\rm exp}}}{N_{i,{\rm pre}}}\right) + \left(\frac{\varepsilon_{\rm sb}}{\sigma_{\rm sb}}\right)^2 + \left(\frac{\varepsilon_{\rm rb}}{\sigma_{\rm rb}}\right)^2,\\ N_{i,{\rm pre}} =& (1+\varepsilon_{\rm sb})\times B_{i,{\rm sb}} + (1+\varepsilon_{\rm rb})\times B_{i,{\rm rb}} + \frac{S}{\sqrt{2\pi}\bar{\sigma}}\times e^{-\frac{(\bar{E}-E_i)^2}{2\bar{\sigma}^2}}\,,\end{aligned} \tag{9}$$

where $N_{i,{\rm exp}}$ is the number of solar neutrino events expected to be observed in the i^{th} energy bin (as given in [6]), with energy E_i, $N_{i,{\rm pre}}$ is the predicted number of events in this energy bin assuming the presence of axions, whereas $B_{i,{\rm sb}}$ and $B_{i,{\rm rb}}$ represent the solar neutrino and the radioactive background events taken from Ref. [6]. Here, ε_{sb} and ε_{rb} are the nuisance parameters and the corresponding solar and radioactive background normalization uncertainties are described by σ_{sb} and σ_{rb}, respectively.

We marginalize over the nuisance parameters and fix the normalization uncertainties for solar and radioactive background as $\sigma_{sb} = 5\%$ and $\sigma_{rb} = 15\%$, in order to perform a χ^2 test, respectively. By setting $\Delta\chi^2(S) = 2.71$, we find that the JUNO sensitivity at 90% C.L. is $S_{\rm lim} = 97$ counts in 10 years (see figure 3 of [7]). Besides this, we express the expected number of events per unit time at the JUNO detector as

$$N_{\rm ev} = N_T \otimes \Phi_a \otimes \sigma \otimes \mathcal{R} \otimes \varepsilon\,, \tag{10}$$

where N_T, Φ_a, σ, and $\mathcal{R}$ represent the number of targets, initial axion flux Φ_a, the cross section, and the detector energy resolution, respectively, while the detector efficiency ε is set to 1. Also, if axions decay into photons or electron-positron pairs inside the detector the event rate is calculated as

$$N_{\rm ev} = \Phi_a\frac{V}{l_i}\varepsilon\,, \tag{11}$$

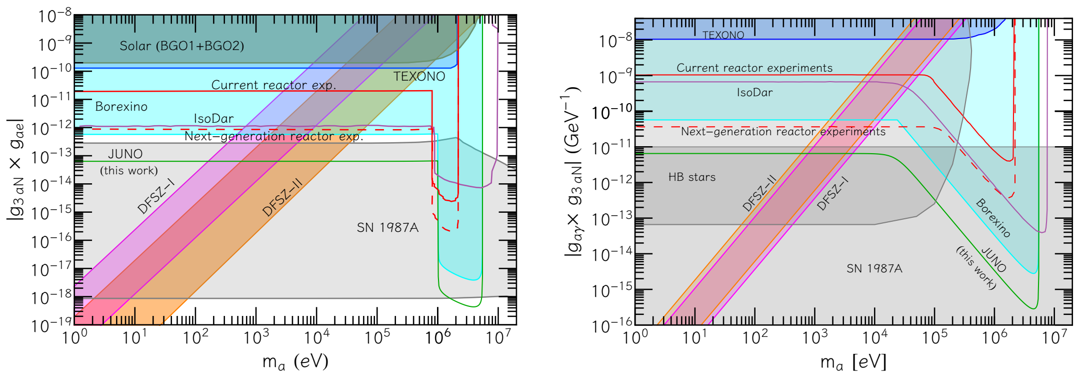

Figure 1: Exclusion region plot in the ($|g_{3aN} \times g_{ae}|, m_a$) plane (left panel) and ($|g_{3aN} \times g_{a\gamma}|, m_a$) plane (right panel) at 90% C.L. The solid green line represents the JUNO sensitivity. For a full descritpion see Ref. [7].

where V is the detector fiducial volume and l_i is the decay length in the $i-$th decay channel.

From Eq. (10), this upper limit can be used to constrain the product of the axion flux Φ_a with the cross section of processes having as targets electrons σ_{a-e} or Carbon nuclei σ_{a-C} via [4]

$$S_{\text{events}} = \Phi_a\, \sigma_{a-e,C}\, N_{e,C}\, T\, \varepsilon \leq S_{\text{lim}} \ , \tag{12}$$

where $N_e \simeq 5.5 \times 10^{33}$ and $N_C \simeq 7.1 \times 10^{32}$ are the numbers of electrons and carbon nuclei in the 16.2 kton fiducial volume (FV), respectively, $T = 10$ years is the measurement time and $\varepsilon = 1$ is the detection efficiency.

Using Eq. (12), the expected number of events due to Compton conversion can be expressed as

$$S_C = \Phi_a \sigma_C N_e T \ , \tag{13}$$

where σ_C is the Compton conversion cross section. The axion flux is proportional to g^2_{3aN} (see Eq. (4)), whereas the cross section σ_C for $m_a \lesssim 2$ MeV is given by Eq. (5). Since $(k_a/k_\gamma)^3 \simeq 1$ for $m_a \lesssim 1$ MeV in Eq. (4), Eq. (13) can be simplified to

$$S_C = g^2_{3aN} \times g^2_{ae} \times 2.42 \times 10^{28} \ . \tag{14}$$

Therefore, the JUNO sensitivity on the product of $|g_{3aN} \times g_{ae}|$ at 90 % C.L. is given by

$$|g_{3aN} \times g_{ae}| \leq 6.33 \times 10^{-14} \qquad \text{for } m_a \lesssim 1 \text{ MeV} \ . \tag{15}$$

This result is one order of magnitude stronger than the Borexino bound $|g_{3aN} \times g_{ae}| \leq 5.5 \times 10^{-13}$ [4] (cyan region) as shown by the left panel of Fig. 1. For $m_a > 1.2$ MeV, $|g_{a3N} \times g_{ae}|$ depends on m_a due to the kinematic factors. For comparison, bounds arising from various other experiments have also been incorporated (readers are guided to Ref. [7] for a detailed description).

The JUNO sensitivity for the Primakoff process or through axion decay into two photons is shown in the right panel of Fig. 1. It has been found that in the small mass limit ($m_a \lesssim 10$ keV) the JUNO sensitivity reaches $|g_{3aN} \times g_{a\gamma}| \lesssim 6.5 \times 10^{-12}\,\text{GeV}^{-1}$ at 90 % C.L., whereas for $10\text{ keV} \lesssim m_a < 5$ MeV $|g_{3aN} \times g_{a\gamma}| \times m_a^2 \lesssim 3.3 \times 10^{-12}$ eV .

5. Conclusion

In this work, we have analyzed the sensitivity of the forthcoming neutrino detector JUNO to probe 5.49 MeV solar axions produced in the $p(d,^3\text{He})a$ reaction. It has been found that the possible detection through Compton conversion would allow JUNO to probe the combination $|g_{3aN} \times g_{ae}| \gtrsim 6.33 \times 10^{-14}$ at 90 % C.L. for $m_a \lesssim 1$ MeV. For masses $m_a \geqslant 1.2$ MeV, axions can decay into electron-positron pairs and the JUNO sensitivity reaches $|g_{3aN} \times g_{ae}| \sim 10^{-8}$. Besides this, due to the inverse Primakoff process JUNO will probe the combination $|g_{3aN} \times g_{a\gamma}| \gtrsim 6.5 \times 10^{-12}$ GeV^{-1} for $m_a \lesssim 10$ keV, while for larger masses the axion decay into photons leads to the sensitivity $|g_{3aN} \times g_{a\gamma}| \times m_a^2 \lesssim 3.3 \times 10^{-12}$ eV.

JUNO detector will be able to set the strongest experimental limits on the combinations $|g_{3aN} \times g_{ae}|$ and $|g_{3aN} \times g_{a\gamma}|$ due to its large exposure time and the excellent energy resolution, improving by more than one order of magnitude the Borexino bounds, and it has the best sensitivity among the current and proposed neutrino experiments, such as Hyper-Kamiokande. This study has shown an example of the physics potential of large underground neutrino detectors in probing axions.

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