Search for hadronic solar axions

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1. Introduction

The experimental search for axions and axion-like particles is stimulated by two circumstances. First, these hypothetical particles can solve the problem of conservation of combination of charge conjugation symmetry (C) and parity symmetry (P) in the strong interactions [1]. Second, they are good candidates for the dark-matter constituents [2]. Furthermore, axions and axion-like particles can explain the faster than expected cooling of some stars [3] and the anomalous transparency of the Universe to γ-rays [4].

If the axion exists, the Sun should be one of the most intense sources of these particles. This paper reports on the search for axions formed in the Sun through thermal-photon conversion.
in the electromagnetic field of the solar plasma (the Primakoff effect) \[5\] and also on search for monochromatic axions with an energy of 9.4 keV emitted in the M1 transition in the \( ^{83} \text{Kr} \) nuclei in the Sun \[6\]. The rate for axion absorption by \( ^{83} \text{Kr} \) defined as

\[
R = 4.53 \times 10^{27} \frac{g_A^2 \omega_A \gamma}{\omega_\gamma} \quad (1)
\]

\[
= 6.70 \times 10^{27} \frac{g_A^3 (g_{AN} - g_{AN}^0)^2}{p_A p_\gamma^3} \quad (2)
\]

\[
= 1.10 \times 10^{12} \frac{g_A^2 m_A^2 p_A}{p_\gamma} \quad (3)
\]

\[
= 1.56 \times 10^{-7} m_A^4 \left( \frac{p_A}{p_\gamma} \right)^3 \quad (4)
\]

in case of Primakoff effect, and

\[
R = 4.23 \times 10^{21} \left( \frac{\omega_A}{\omega_\gamma} \right)^2 \quad (5)
\]

\[
= 8.53 \times 10^{21} (g_{AN}^3 - g_{AN}^0)^4 \left( \frac{p_A}{p_\gamma} \right)^6 \quad (6)
\]

\[
= 2.41 \times 10^{-10} m_A^4 \left( \frac{p_A}{p_\gamma} \right)^6 \quad (7)
\]

in case of monochromatic axions. Here axion absorption rate is expressed in \( \text{g}^{-1}\text{day}^{-1} \), coupling constants \( (g_A, g_{AN}^3, g_{AN}^0) \) in GeV\(^{-1}\) and axion mass in eV; \( \omega_A \) and \( \omega_\gamma \) to be probabilities of the axion- and \( \gamma \)-mediated transitions, \( p_A \) and \( p_\gamma \) to be axion and photon momenta.

2. Experimental setup

A large proportional counter (LPC) filled with \( ^{83} \text{Kr} \) (99.9\%) was used to detect x-rays and gammas, as well as conversion and Auger electrons, appearing in the decay of the excited level with an energy of 9.4 keV. The LPC is a cylinder with inner diameter of 137 mm. A gold-plated tungsten wire of 10 \( \mu \text{m} \) in diameter is stretched along the LPC axis and is used as an anode. The length of the working area of the LPC was 595 mm, which corresponded to a volume of 8.77 l. The LPC operated at a pressure of 1.8 bar. The mass of \( ^{83} \text{Kr} \) isotope in the working volume is 58 g. The passive shield of the counter is formed by layers of copper, lead, and polyethylene with thicknesses of 20, 20, and 8 cm, respectively. The detector is deployed at the underground low-background laboratory of the Baksan Neutrino Observatory at a depth of 4900 m of water equivalent, where the muon flux amounts to \( 2.6 \pm 0.1 \text{ m}^{-2}\text{day}^{-1} \) \[7\]. Details of the experimental setup and of the pulse-shape analysis can be found in \[8, 9\].

3. Results

The measurements were carried out over a live time of 713 days. The energy spectrum of the signals detected in a range of 4–22 keV is shown in figure 1. The distinct peak observed at an energy of 8.04 keV arises from the x-ray K-lines of copper (\( K_{\alpha 1} = 8.048 \text{ keV}, K_{\alpha 2} = 8.028 \text{ keV}, \) and \( K_{\beta} = 8.905 \text{ keV} \)). The second peak observed at an energy of 13.5 keV has a more complex structure. This is partially due to the activity of the \( ^{83} \text{Kr} \) cosmogenic isotope with \( \tau = 3.3 \times 10^5 \text{ yr} \) formed in the atmosphere via the \( ^{82} \text{Kr}(n,2n)^{81} \text{Kr} \) and \( ^{80} \text{Kr}(n,\gamma)^{81} \text{Kr} \) reactions. Electron capture by the \( ^{81} \text{Kr} \) nucleus forms the \( ^{81} \text{Br} \) ground state with a probability of 99.7\%, and the latter emits x-rays with a net energy of 13.47 keV corresponding to the electron binding energy for the K-shell of the bromine atom. The discussed peak also includes contributions from
**Figure 1.** The resulting spectrum: red solid line—fit result; 1—peak formed by characteristic x-ray of Cu; 2—peak formed by K-capture of $^{81}$Kr and characteristic x-ray of Kr; 3—modeled peak from axions.

x-ray photons emitted by krypton ($K_{\alpha_{12}} = 12.65$ keV) and bromine ($K_{\alpha_{12}} = 11.92$ keV) beyond the sensitive volume of the counter.

The intensity of the putative 9.4-keV axion peak is estimated using the maximum-likelihood technique [5]. The best fit of the energy spectrum corresponding to a minimum sum of the squares of the residuals value of is depicted by the solid line, see figure 1.
At the minimum, the area under the 9.4-keV peak less than 160 eV at 95% coincidence level (C.L.). Assuming registration efficiency of 14.4 keV gammas equal to 0.935 the axion counting rate is

\[ R \leq 4.11 \times 10^{-3} \text{ g}^{-1}\text{day}^{-1}. \]  

Taking into account that \( p_A/p_\gamma \cong 1 \) for \( m_A \leq 2 \text{ keV} \) from equations (1)–(4) in case of Primakoff effect we obtain

\[
|g_A\gamma(g_3^{AN} - g_0^{AN})| \leq 7.89 \times 10^{-16}, \tag{9}\]

\[
|g_A\gamma m_A| \leq 6.16 \times 10^{-8}, \tag{10}\]

\[
m_A \leq 12.6 \text{ eV} \tag{11}\]

at 95% C.L. In case of monochromatic axions from equations (5)–(7) we obtain

\[
\left( \frac{\omega_A}{\omega_\gamma} \right) \leq 9.9 \times 10^{-13}, \tag{12}\]

\[
|g_3^{AN} - g_0^{AN}| \leq 8.3 \times 10^{-7}, \tag{13}\]

\[
m_A \leq 64 \text{ eV} \tag{14}\]

at 95% C.L.

4. \(^{57}\text{Fe}\)

Another possible way to search for hadronic solar axions is to use detector with a working media containing \(^{57}\text{Fe}\). The search is in the same way as in [6], i.e., search for monochromatic axions appearing after deexcitation of 1-st excited state of the \(^{57}\text{Fe}\) nuclei being in the Sun bulk. In this case one of the possible candidate for a such media is pyrite (FeS\(_2\)). Pyrite has been proposed as an abundant, inexpensive material in low-cost photovoltaic solar panels. Synthetic iron sulfide was used with copper sulfide to create the photovoltaic material.

Pyrite is a semiconductor, the band gap in pyrite is about 0.9 eV and the dominant charge carriers can be either electrons or holes. Sometimes, both n-type and p-type semiconducting regions can be found within single naturally occurring crystals. Resistivity (natural crystals): \(10^{-5}\) to \(10^{0}\) Omm. On the other hand the high purity pyrite should have much higher resistivity (comparable with high purity germanium) and so could be used as semiconductor detector.

Now we are working upon development a new semiconductor detector based on high purity pyrite or solid solution GaS:Fe. The main advantage of using these materials is a much higher expected rate of resonance axion absorption by the \(^{57}\text{Fe}\) in the detector in comparison with \(^{83}\text{Kr}\). The ratio of rates is

\[
\frac{R_{\text{Fe-57}}}{R_{\text{Kr-78}}} = 3.51 \times 10^3. \tag{15}\]

Using the semiconductor detector with the iron contaminating working media will allow one to search for hadronic axions with masses \(\simeq 1\) eV, which is most interesting mass region.

5. Conclusions

Resonance absorption of 9.4-keV solar axions by the \(^{83}\text{Kr}\) nucleus leading to the excitation of the \(^{83}\text{Kr}\) first nuclear level has been sought. The \(\gamma\) and x-ray photons and the conversion and Auger electrons have been detected using a large proportional counter filled with \(^{83}\text{Kr}\). The detector is deployed in the low background laboratory at the Baksan Neutrino Observatory. A new constraint has been imposed on the product of the axion–photon coupling constant and the axion mass: \(|g_A\gamma m_A| \leq 6.16 \times 10^{-17}\). Within the hadronic-axion model, this translates to a constraint on the axion mass: \(m_A \leq 12.6\) eV at 95% C.L.
In case of pure hadronic interaction the upper limit for axion-nucleon coupling is $|g_{3AN}^3 - g_{0AN}^0| \leq 8.3 \times 10^{-7}$ at 95% C.L., which corresponds to upper limit for hadronic axion mass: $m_A \leq 64$ eV at 95% C.L. with the generally accepted values $S = 0.5$ and $z = 0.56$.

As in the case of $^{57}$Fe nucleus the obtained limit on axion mass strongly depends on the exact values of the parameters $S$ and $z$.

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