Recent Results of Search for Solar Axions Using Resonant Absorption by $^{83}$Kr nuclei

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Abstract. A search for resonant absorption of the solar axion by $^{83}$Kr nuclei was performed using the proportional counter installed inside the low-background setup at the Baksan Neutrino Observatory. The obtained model independent upper limit on the combination of isoscalar and isovector axion-nucleon couplings $|g_3 - g_0| \leq 8.4 \times 10^{-7}$ allowed us to set the new upper limit on the hadronic axion mass of $m_A \leq 65$ eV (95% C.L.) with the generally accepted values $S=0.5$ and $z=0.56$.

1. Introduction

If the axion exists, the Sun should be one of the most intense sources of these particles. The aim of this work is to search for monochromatic axions with an energy of 9.4 keV emitted in the M1 transition in the $^{83}$Kr nuclei in the Sun [1]. Axions on the Earth can be detected in the inverse reaction of resonance absorption by detecting particles ($\gamma$- and X-ray photons, as well as conversion and Auger electrons) appearing at the decay of an excited nuclear level. The probability of the emission and subsequent absorption of axions depends only on the coupling constant with nucleons, which is minimally model dependent and is proportional to axion-nucleon coupling constant $(g_{AN})$.

The axion flux was calculated in [1] for the standard solar model BS05 [2] characterized by a high metallicity [3]. The differential flux at the maximum of the distribution is [1]:

$$\Phi_A(E_{M1}) = 5.97 \times 10^{23} \left( \frac{\omega_A}{\omega_\gamma} \right) \text{cm}^{-2}\text{s}^{-1}\text{keV}^{-1}. \quad (1)$$

where $\omega_A/\omega_\gamma$ is the branching ratio of axions to photons emission. The cross section for resonance axion absorption is given by an expression similar to the expression for the photon-absorption cross section, the correction for the ratio $\omega_A/\omega_\gamma$ being taken into account.

$$\sigma(E_A) = 2\sqrt{\pi} \sigma_0, \exp \left[ -\frac{4(E_A - E_M)^2}{\Gamma^2} \right] \left( \frac{\omega_A}{\omega_\gamma} \right). \quad (2)$$
where $\sigma_{0\gamma}$ is the maximum cross section of the $\gamma$-ray resonant absorption and $\Gamma = 1/\tau$. The total cross section for axion absorption can be obtained by integrating $\sigma(E_A)$ over the axion spectrum. The expected rate of resonance axion absorption by the $^{83}$Kr nucleus as a function of the ratio $\omega_A/\omega_\gamma$, the combination of isoscalar and isovector coupling constants $|g_3 - g_0|$ and axion mass $m_A$ can be represented in the form ($S = 0.5, z = 0.56$) [1]:

$$R_A[g^{-1}\text{day}^{-1}] = 4.23 \times 10^{21}(\omega_A/\omega_\gamma)^2$$
$$= 8.53 \times 10^{21}(g_3 - g_0)^4(p_A/p_\gamma)^6$$
$$= 2.41 \times 10^{-10}(m_A/1\text{ eV})^4(p_A/p_\gamma)^6.$$  

2. Experimental setup
A large proportional counter filled with of $^{83}$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 diameters of 137 mm. A gold-plated tungsten wire of 10 $\mu$m in diameter is stretched along the LPC axis and is used as an anode. In order to reduce the influence of edge effects on the collection of the charge, the ends of the anode wire were surrounded by copper tubes (3 mm in diameter and 38 mm in length), which were at the anode potential and excluded gas amplification in this region. With the inclusion of Teflon insulators, the distance from the working area to the flanges of the chamber was 70 mm. The length of the working area of the chamber was 595 mm, which corresponded to a volume of 8.77 L. The chamber operated at a pressure of 1.8 bar. The mass of $^{83}$Kr isotope in the working volume was 58 g.

![Figure 1. A large proportional counter (LPC) with a casing of copper inside passive shielding.](image)
The LPC is surrounded by passive shield made of copper (∼20 cm), lead (∼20 cm) and polyethylene (8 cm). The setup is located in the Deep Underground Low-Background Laboratory of Institute for Nuclear Research of Russian Academy of Sciences (BNO INR RAS) [4], at the depth of 4900 m w.e., where the cosmic muon flux is reduced by ∼10⁷ times in comparison to that above ground, and evaluated as (2.6 ± 0.09) × 10⁻⁹ cm⁻²s⁻¹.

A signal from the anode was supplied to a charge-sensitive preamplifier. The shape of the pulse was digitized in a time interval of 164 µs with a frequency of 12.5 MHz and was transmitted to a computer through a USB port. The rise time of the leading edge of the pulse and the ratio of amplitudes of secondary and primary pulses were determined for each event, because these parameter makes it possible to select events near the cathode and non-point events such as multiple Compton scattering. The procedure of the analysis of the shape of pulses was described in more detail in [5].

3. Results

The background spectra collected during 613.25 days and fit result curve are presented in figure 2. Two peaks are clear visible in the energy range (4 – 26) keV. The peak with energy 8.05 keV associates with the detection of $K_{\alpha,\beta}$ X-rays of copper. The structure of the second peak is more complicated, it is mixture of Kr and Br $K_{\alpha,\beta}$ X-rays and 13.5 keV from $K$-capture of cosmogenic $^{81}$Kr. It is seen that the 9.4 keV peak is not manifested.

![Figure 2](image_url)

**Figure 2.** Energy spectra of the Kr LPC measured for 613 days, fitting results (red line) and expected axion peak for $3S_{\text{lim}}$ (blue line).

The maximum likelihood method was used to determine the intensity of the peak. The fit of spectrum corresponding to the minimum $\chi^2$ is shown by red solid line in figure 2. The minimum of $\chi^2$ corresponds to the nonphysical value of the area of the 9.4 keV peak $S_{\text{A}} = -(102 ± 92)$ events. The standard $\chi^2$-profile method was used to determine the upper bound on the number of events in the peak. The upper bound thus determined for the number of events in the peak is $S_{\text{lim}} = 127$ for 95% C.L.
The expected number of registered axions is:

$$S_A = RMT\epsilon \leq S_{\text{lim}},$$

where $M = 58$ g is mass of $^{83}\text{Kr}$ isotope, $T = 613.25$ days is time of data taking, and $\epsilon = 0.825$ is the detection efficiency.

The upper limit on the excitation rate of $^{83}\text{Kr}$ by solar hadronic axions is defined as $R_{\text{exp}} = 4.29 \times 10^{-3}$ g$^{-1}$day$^{-1}$. The relation $R_A \leq R_{\text{exp}}$ limits the region of possible values of the coupling constants $g_0$, $g_3$ and axion mass $m_A$. In accordance with Eqs. (3-5), and on condition that $(p_A/p_\gamma) \cong 1$ provided for $m_A < 3$ keV one can obtain:

$$\frac{\omega_A}{\omega_\gamma} \leq 1.0 \times 10^{-12}$$

$$|g_3 - g_0| \leq 8.4 \times 10^{-7}, \text{ and}$$

$$m_A \leq 65 \text{ eV, at 95% C.L.}$$

The limit (9) is stronger than the constrain obtained with 14.4 keV $^{57}\text{Fe}$ solar axions [6] and is stronger than our previous result obtained in $^{83}\text{Kr}$ experiment [1]. As in the case of $^{57}\text{Fe}$ nucleus the obtained limit on axion mass strongly depends on the exact values of the parameters $S$ and $z$.

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