New limit on the mass of 9.4-keV solar axions emitted in an M1 transition in ^{83}Kr nuclei

A.V. Derbin[2], *A.M. Gangapshev*[1], *Yu.M. Gavrilyuk*[1], *V.V. Kazalov*[1], *H.J. Kim*[5], *Y.D. Kim*[6], *V.V. Kobychev*[4], *V.V. Kuzminov*[1], *Luqman Ali*[5], *V.N. Muratova*[2], *S.I. Panasenko*[1,3], *S.S. Ratkevich*[1,3], *D.A. Semenov*[2], *D.A. Tekueva*[1], *S.P. Yakimenko*[1], *E.V. Unzhakov*[2]

[1] Institute for Nuclear Research, RAS, Moscow, Russia
[2] Petersburg Nuclear Physics Institute, St. Petersburg, Russia
[3] Kharkov National University, Kharkov, Ukraine
[4] Institute for Nuclear Research of NAS Ukraine, Kiev, Ukraine
[5] Department of Physics, Kyungpook National University, Daegu, Republic of Korea
[6] Institute of Basic Science, Daejeon, Republic of Korea

DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-03/derbin_alexander

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 $|g_3 - g_0| \leq 1.69 \times 10^{-6}$ allowed us to set the new upper limit on the hadronic axion mass of $m_A \leq 130$ eV (95% C.L.) with the generally accepted values S=0.5 and z=0.56.

1 Introduction

If axions do exist, then the Sun should be an intense source of these particles. In 1991 Haxton and Lee calculated the energy loss of stars along the red-giant and horizontal branches due to the axion emission in nuclear magnetic transitions in ^{57}Fe, ^{55}Mn, and ^{23}Na nuclei [1]. In 1995 Moriyama proposed experimental scheme to search for 14.4 keV monochromatic solar axions that would be produced when thermally excited ^{57}Fe nuclei in the Sun relax to its ground state and could be detected via resonant excitation of the same nuclide in a laboratory [2]. Searches for resonant absorption of solar axions emitted in the nuclear magnetic transitions were performed with ^{57}Fe, ^{7}Li and ^{83}Kr (see [3] and refs therein).

In this paper we present the results of the search for solar axions using the resonant absorption by ^{83}Kr nuclei [4]. The energy of the first excited $7/2^+$ nuclear level is equal to 9.405 keV, lifetime $\tau = 2.23 \times 10^{-7}$ s, internal conversion coefficient $\alpha = 17.0$ and the mixing ratio of 1 and 2 transitions is $\delta = 0.013$.

In accordance with indirect estimates the abundance of the krypton in the Sun (Kr/H) = 1.78×10^{-9} atom/atom [5] that corresponds to $N = 9.08 \times 10^{13}$ of ^{83}Kr atom per 1 g material in the Sun. The axion flux from a unit mass is equal

$$\delta\Phi(T) = N \frac{2\exp(-\beta_T)}{1 + 2\exp(-\beta_T)} \frac{1}{\tau_\gamma} \frac{\omega_A}{\omega_\gamma}, \tag{1}$$

where N - number of ^{83}Kr atoms in 1 g of material in the Sun, $\beta_T = E_\gamma/kT$, τ_γ - lifetime of the nuclear level, ω_A/ω_γ - represents the branching ratio of axions to photons emission. The ratio ω_A/ω_γ was calculated in [6, 7, 1] as

$$\frac{\omega_A}{\omega_\gamma} = \frac{1}{2\pi\alpha}\frac{1}{1+\delta^2}\left[\frac{g_0\beta + g_3}{(\mu_0 - 0.5)\beta + \mu_3 - \eta}\right]^2 \left(\frac{p_A}{p_\gamma}\right)^3, \tag{2}$$

where μ_0 and μ_3 - isoscalar and isovector magnetic moments, g_0 and g_3 - isoscalar and isovector parts of the axion-nucleon coupling constant g_{AN} and β and η - nuclear structure dependent terms.

In case of the ^{83}Kr nucleus, which has the odd number of nucleons and an unpaired neutron, in the one-particle approximation the values of β and η can be estimated as $\beta \approx$-1.0 and $\eta \approx$0.5.

In the hadronic axion models, the g_0 and g_3 constants can be represented in the form [8]:

$$g_0 = -\frac{m_N}{6f_A}[2S + (3F - D)\frac{1+z-2w}{1+z+w}], \tag{3}$$

$$g_3 = -\frac{m_N}{2f_A}[(D+F)\frac{1-z}{1+z+w}]. \tag{4}$$

where D and F denote the reduced matrix elements for the SU(3) octet axial vector currents and S characterizes the flavor singlet coupling. The parameter S characterizing the flavor singlet coupling still remains a poorly constrained one [3]. The most stringent boundaries ($0.37 \le S \le 0.53$) and ($0.15 \le S \le 0.5$) were found in [9] and [10], accordingly.

The axion flux was calculated for the standard solar model BS05 [11] characterized by a highmetallicity [12]. The differential flux at the maximum of the distribution is

$$\Phi_A(E_{M1}) = 5.97 \times 10^{23}\left(\frac{\omega_A}{\omega_\gamma}\right)\mathrm{cm^{-2}s^{-1}keV^{-1}}. \tag{5}$$

The width of the resulting distribution, which is described well by a Gaussian curve, is $\sigma =$ 1.2 eV. This value exceeds substantially the recoil-nucleus energy and the intrinsic and Doppler widths of the level of ^{83}Kr target nuclei. 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 ω_A/ω_γ being taken into account.

$$\sigma(E_A) = 2\sqrt{\pi}\sigma_{0\gamma}\exp\left[-\frac{4(E_A - E_M)^2}{\Gamma^2}\right]\left(\frac{\omega_A}{\omega_\gamma}\right), \tag{6}$$

where $\sigma_{0\gamma} = 1.22\times10^{-18}\mathrm{cm}^2$ is the maximum cross section of the γ -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 ω_A/ω_γ, $(g_3 - g_0)$ and m_A can be represented in the form ($S = 0.5$, $z = 0.56$):

$$R_A[\mathrm{g^{-1}day^{-1}}] = 4.23 \times 10^{21}(\omega_\mathrm{A}/\omega_\gamma)^2 \tag{7}$$

$$= 8.53 \times 10^{21}(g_3 - g_0)^4(p_A/p_\gamma)^6 \tag{8}$$

$$= 2.41 \times 10^{-10}(m_A)^4(p_A/p_\gamma)^6. \tag{9}$$

2 Experimental setup

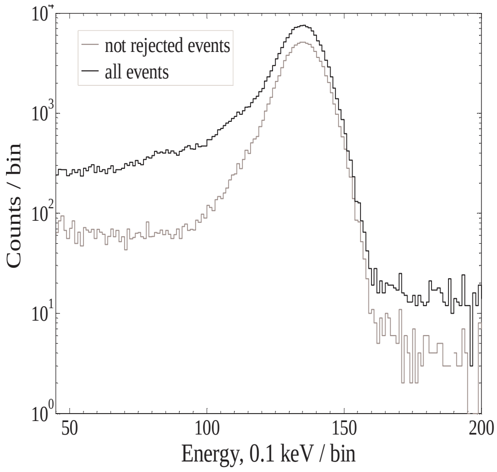

Figure 1: Original energy spectrum and spectrum after rejection of the events with pulse rise time $\geq 3.8\mu$s and $\lambda \leq 0.115$

To register γ-quantum and conversion electrons appearing after deexcitation of the ^{83}Kr nuclei a large proportional counter (LPC) with a casing of copper is used. The gas mixture Kr(99.55%)+Xe(0.45%) is used as working media, krypton consisted of 58.2% of ^{83}Kr. The LPC is a cylinder with inner diameters of 137 mm. A gold-plated tungsten wire of 10 μm in diameter is stretched along the LPC axis and is used as an anode. To reduce the influence of the counter edges on the operating characteristics of the counter, the end segments of the wire are passed through the copper tubes electrically connected to the anode. The fiducial length of the LPC is 595 mm, and the corresponding volume is 8.77 L. Gas pressure is 5.6 bar, and corresponding mass of the ^{83}Kr-isotope in fiducial volume of the LPC is 101 g.

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 at BNO INR RAS [13], at the depth of 4900 m w.e., where the cosmic ray flux is reduced by $\sim 10^7$ times in comparison to that above ground, and evaluated as $(3.0 \pm 0.1) \times 10^{-9}$ cm^{-2}s^{-1} [14].

3 Results

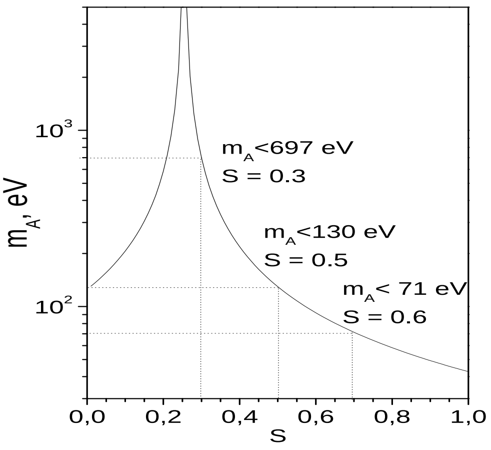

Figure 2: Upper limits on the hadronic-axion mass versus parameter S (z=0.56)

The background spectra collected during 26.5 days and fit result curve are presented in Fig.1. The peak of 13.5 keV from K-capture of ^{81}Kr is well seen. ^{81}Kr is a cosmogenic isotope. The distributions of the events versus pulse rise time and parameter λ (the ratio of amplitudes of secondary and primary pulses) are were investigated [15]. The pulses with rise time longer 4.4 μs are mostly events from the inner surface of the cathode or multisite events. The events with $\lambda < 115$ are mostly close to the edge of the fiducial volume or out of it .

Thus, as we are looking for single site events in the inner volume of the detector. The events with pulse rise time longer 3.8 μs and λ lower then 0.115 are rejected. The resulting spectrum in comparison with original one is presented in Fig.1. There is no visible peak around 9.4 keV from axions. The upper limit on the excitation rate of ^{83}Kr by solar hadronic axions is defined as

$R_{exp} = 0.069 \; \mathrm{g^{-1} day^{-1}}$. This relation $R_A \leq R_{exp}$ limits the region of possible values of the coupling constants g_0, g_3 and axion mass m_A. In accordance with Eqs. (7-9), and on condition that $(p_A/p_\gamma) \cong 1$ provided for $m_A < 3$ keV one can obtain:

$$|g_3 - g_0| \leq 1.69 \times 10^{-6}, \text{ and} \tag{10}$$

$$m_A \leq 130 \text{ eV} \quad \text{at } 95\% \text{ C.L.} \tag{11}$$

The limit (11) is stronger than the constrain obtained with 14.4 keV ^{57}Fe solar axions - ($m_A \leq 145$ eV [3]) and is significantly stronger than previous result obtained in ^{83}Kr experiment [16]. 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 (Fig.2).

The work is supported by Russian Foundation of Basic Research (Grants No. 14-02-00258A, 13-02-01199A and 13-02-12140-ofi-m).

References

[1] Haxton W.C. and Lee K.Y. Phys. Rev. Lett. 66, 2557 (1991)

[2] Moriyama S. Phys. Rev. Lett. 75,3222 (1995)

[3] Derbin A.V. et al. Phys. At. Nucl. 74, 596 (2011)

[4] Gavrilyuk Yu. M. et al. arXiv:1405.1271

[5] Asplund M.et al. Ann. Rev. of Astronomy and Astrophys. 47, 481 (2009)

[6] Donnelly T.W. et al. Phys. Rev. D18, 1607 (1978)

[7] Avignone III F.T. et al. Phys. Rev. D37, 618 (1988)

[8] Srednicki M. NP B260,689 (1985); Kaplan D.B. NP B260, 215 (1985)

[9] Altarelli G., et al. Phys. Lett. B46,337 (1997)

[10] Adams D. et al. Phys. Rev. D56, 5330 (1997)

[11] Bahcall J.H., Serenelli A.M., Basu S., Astrophys. J. 621, L85 (2005)

[12] Grevesse N., Sauval A.J. Space Sci. Rev. 85, 161 (1998)

[13] Gavriljuk Ju.M. et al.NIM A729, 576 (2013)

[14] Gavrin V.N. et al. Preprint INR RAS P-698 (1991)

[15] Gavrilyuk Yu.M. et al. Instr.Exper.Techn. 53, 57 (2010), Phys. Rev. C87, 035501 (2013)

[16] Jakovčić K. et al. Radiat.Phys.Chem. 74, 93 (2004) arXiv:nucl-ex/0402016v1