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New limit on axion-electron coupling obtained from searching for resonant absorption of solar axions by ^{83}Kr nuclei

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Abstract. A search for resonant excitation of first nuclear level of ^{83}Kr nucleus at 9.4 keV by solar axion fluxes that depend on axion-electron coupling constant g_{Ae} have been performed. The search was carried out via gaseous proportional counter that was installed in a low-background experimental setup located at underground facility of Baksan Neutrino Observatory (INR RAS). The measurement yielded new limit on axion-electron coupling constant and axion mass $|g_{Ae}\ m_A| \leq 1.33 \cdot 10^{-9}$ eV.

Keywords: solar axion, dark matter

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Материалы конференции
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Новый предел на константу связи аксиона с электроном, полученный в результате поиска резонансного поглощения солнечных аксионов ядром ^{83}Kr

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Аннотация. Проведен поиск резонансного возбуждения первого ядерного уровня нуклида ^{83}Kr с энергией 9.4 кэВ потоком солнечных аксионов, образующихся за счет предполагаемого аксион-электронного взаимодействия. Измерения проводились с помощью газонаполненного пропорционального счетчика, установленного в низкофоновой подземной лаборатории Баксанской нейтринной обсерватории (ИЯИ РАН). В результате было получено новое ограничение на константу связи аксиона с электронамии массу аксиона $|g_{Ae}\ m_A| \leq 1.33 \cdot 10^{-9}$ эВ.

Ключевые слова: солнечные аксионы, темная материя

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Introduction

Intense experimental searches for axions are being motivated by two principal factors. Axion hypothesis was originally designed to solve strong CP-problem in QCD while at the same time axion particles eventually became a well-motivated dark matter candidate. In addition, existence of axions could potentially explain excessive cooling rates of particular stars as well as anomalous transparency of the Universe for high-energy gamma-quanta. Axion interactions with baryonic matter depend on Peccei-Quinn symmetry [1] breaking scale f_A and are defined in terms of effective coupling constants for interactions of axions with photons $g_{A\gamma}$, electrons g_{Ae} and nucleons g_{AN} [2, 3]. Detailed review of theoretical and experimental works in axion field can be found in [4] and references therein.

Stars are expected to be powerful axion sources. Intense axion fluxes can be produced within the Sun due to a number of processes. In particular, axions can appear as a result of electron-nucleus bremsstrahlung $e+Z\rightarrow Z+e+A$, Compton-like process $\gamma+e\rightarrow e+A$ or during atomic de-excitation or recombination. Corresponding axion fluxes Φ_{gAe} depend on axion-electron coupling g_{Ae} as $\Phi_{gAe} \propto g_{Ae}^2$ and were calculated in [5–9] (see Fig. 1). For this work, we used axion spectrum calculated in [9], which gives the flux value at energy of 9.396 keV (corresponding to the first excited state of ^{83}Kr) to be equal to $d\Phi/dE = 1.33\cdot10^{11}$ (cm^2·s·keV)$^{-1}$ assuming that $g_{Ae} = 10^{-11}$.

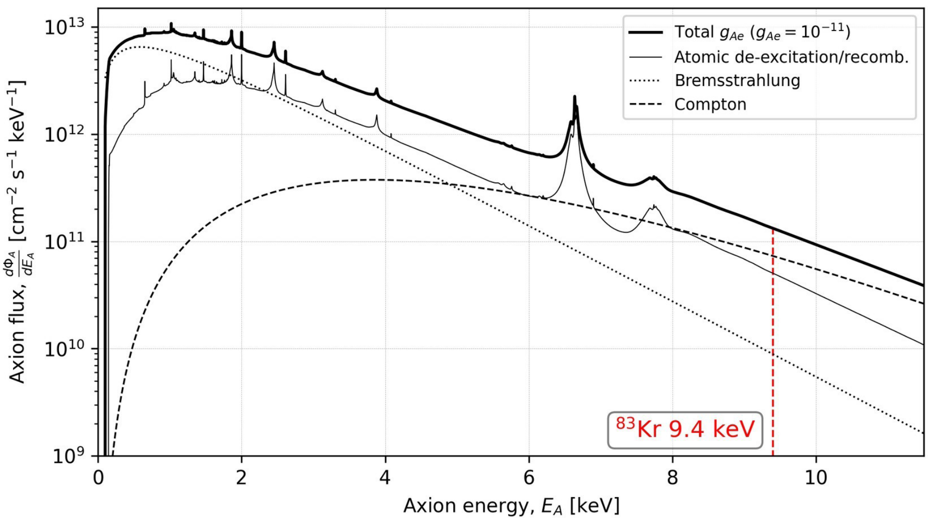

Fig. 1. Spectra of solar axions produced by g_{Ae} related processes calculated assuming $g_{Ae} = 10^{-11}$ for massless axion

The cross-section of resonant absorption of axion by nucleus is defined in similar fashion to the gamma absorption corrected by ratio between gamma-ray ω_γ or axion ω_A emitting transition probabilities.

The probability ratio ω_A/ω_γ depends on isoscalar $g_{AN}{}^0$ and isovector $g_{AN}{}^3$ components of axion-nucleon coupling, which can be expressed in terms of axion mass m_A in KSVZ and DFSZ axion models [10, 11].

Expected rate of axion absorption R_A depends on axion flux defined by g_{Ae}, and on the cross-section of resonant axion absorption for a given nuclear transition defined by $g_{AN}{}^0$ and $g_{AN}{}^3$:

$$R_A = \pi\sigma_{0\gamma}\Gamma\left(d\Phi_A / dE_A\right)\left(\omega_A / \omega_\gamma\right), \tag{1}$$

where $\sigma_{0\gamma}$ is the maximal cross-section for gamma absorption. Experimentally derived value of $\sigma_{0\gamma}$ in case of ^{83}Kr is $\sigma_{0\gamma} = 1.22\cdot10^{-18}$ cm^2. The lifetime of ^{83}Kr first excited state is $\tau = 223$ ns, thus yielding level width of $\Gamma = 2.95\cdot10^{-12}$ keV.

Consequently, the axion absorption rate R_A expressed in units of (atom·s)$^{-1}$ in model- independent form (i. e. depending exclusively on the values of coupling constants) becomes:

$$R_A = 1.50\times10^{16} g_{Ae}^2\left(g_{AN}^3 - g_{AN}^0\right)^2\left(p_A / p_\gamma\right)^3. \tag{2}$$

Here, (p_A/p_γ) is the ratio between momenta of axion and gamma-quanta. Ultimately, by employing the expressions of $g_{AN}{}^0$ and $g_{AN}{}^3$ in terms of axion mass m_A described in KSVZ model [2, 3] absorption rate can be presented as a function of $g_A\gamma$ and m_A:

$$R_A = 3.53 g_{Ae}^2\left(g_{AN}^3 - g_{AN}^0\right)^2\left(p_A / p_\gamma\right)^3. \tag{3}$$

Total number of registered axion events would depend on the amount of ^{83}Kr nuclei contained within the target, time of exposure and detector efficiency, while the probability of peak observation at 9.4 keV would be determined by background level of experimental setup.

Experimental Setup

A dedicated experiment searching for resonant absorption of solar axions by ^{83}Kr nuclei is underway at Baksan neutrino observatory [10, 11]. The structure of ^{83}Kr nucleus features a low-lying $7/2^+$ level at 9.4 keV. Magnetic type (M1) transition to the ground state 0^+ allows for emission or absorption of a pseudoscalar particle. Principal detector construction is based on a copper chamber filled with Kr gas with 99.9% enrichment in ^{83}Kr isotope. Gaseous counter operates at pressure of 1.8 bar and total mass of ^{83}Kr gas amounts to 58 g. The chamber is surrounded by passive and active shieldings and is located at underground laboratory with 4900 m of water equivalent overburden. Energy resolution of proportional counter at 9.4 keV is equal to 85%.

Results and Analysis

The measurements were carried out in separate series during 713 days. The final background spectrum presented in Fig. 2 contains prominent peaks that are associated with Cu and Br characteristic X-rays, and decays of ^{81}Kr nuclei. Second peak also contains contribution from krypton and bromine X-rays originating from non-sensitive region of the chamber.

Since there is no visible peak within the ROI at 9.4 keV, maximum likelihood methodwas employed in order to set the upper limit on the number of “axion” events. Analytical description of the spectrum was constructed from Gaussian peaks at fixed known energies and continuous exponential background. The best fit corresponding to the minimum $\chi^2 = 156.7/150$ isshown in Fig. 2 by the solid line.

The determined upper limit on the number of events at 9.4 keV ROI yields the consequent limits on axion couplings g_{AN} , g_{Ae} and axion mass m_A , in accordance with equations (2, 3). Assuming that momenta ratio $(p_A/p_\gamma)^3 \approx 1$ when $m_A < 2$ keV, one gets:

$$\left|g_{Ae}\left(g_{AN}^3 - g_{AN}^0\right)\right| \le 1.70\cdot10^{-17}, \tag{4}$$

$$\left|g_{Ae} m_A\right| \leq 1.33 \cdot 10^{-9}\,\text{eV}. \tag{5}$$

The limit (4) is a model-independent bound on couplings of axion (or any other ALP) with electrons and nucleons. The limit (5) sets the region of allowed values in $|g_{A\gamma}\ m_A|$ parameter space and enables the comparison of current result against other axion experiments (see Fig. 3).

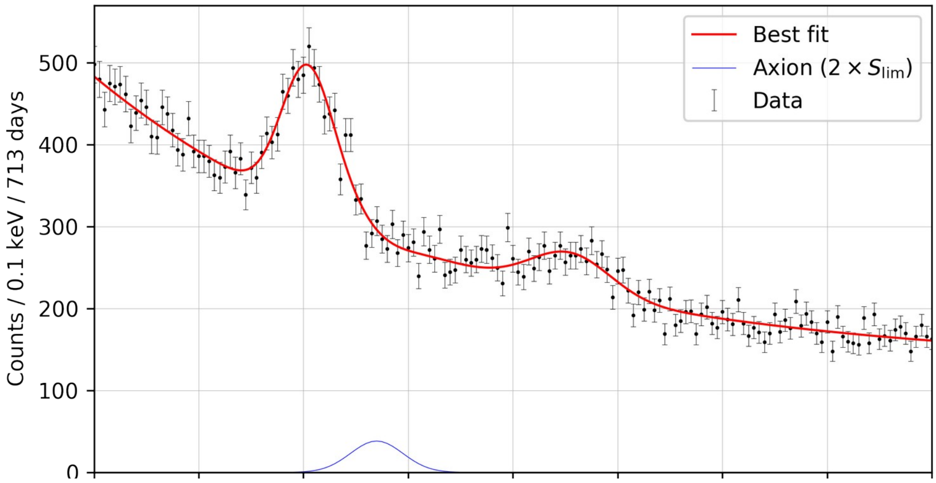

Fig. 2. Spectrum obtained by Kr proportional counter during 713 days and the result of analytical fit. Cu characteristic X-rays (1); ^{81}Kr decays (2); expected 9.4 keV axion peak (3)

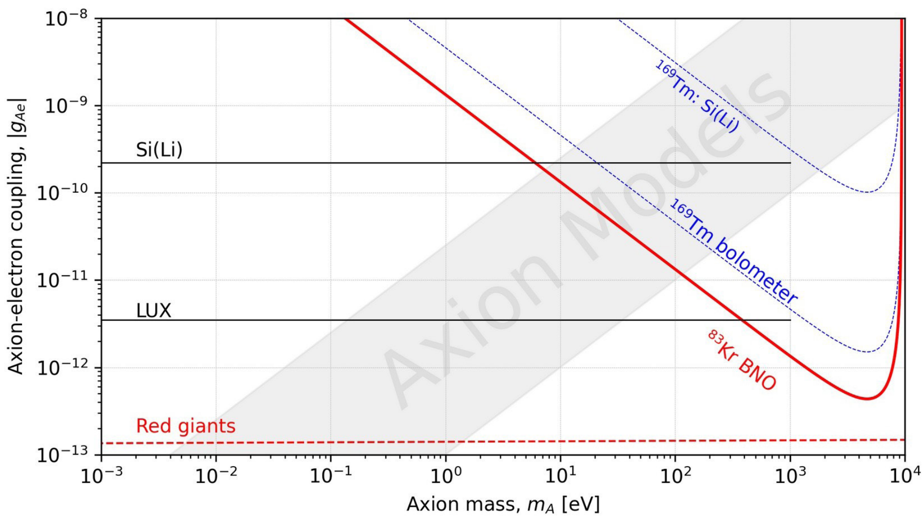

Fig. 3. Upper limits on g_{Ae} coupling constant obtained in current work using ^{83}Kr proportional counter in comparison with previous experiments: search for axioelectric effect on Si(Li) detector [12], resonant absorption by ^{169}Tm nucleus [13], LUX experiment [14] and astrophysical bounds [15]

New limit (5) excludes previously unexplored region of g_{Ae} values at relatively high axion masses allowed by KSVZ and DFSZ models and excludes axion masses above $m_A > 120$ eV in terms of KSVZ-axion. Within axion mass range 0.4 keV $< m_A <$ 9 keV the obtained limit on axion-electron coupling is the most stringent among direct laboratory searches and approaches the astrophysical limit of $g_{Ae} \leqslant 1.5 \cdot 10^{-13}$ derived from observation of red giants from a number of globular clusters.

Conclusion

A search for resonant absorption of solar axions by ^{83}Kr nuclei leading to excitation of 9.4 keV first nuclear level have been performed. Large proportional counter filled with gaseous ^{83}Kr was used in order to register X-rays, gammas, conversion and Auger electrons. Low-background experimental setup was located at the underground facility of Baksan neutrino observatory (INR RAS). As the result, a new limit was set on axion-electron coupling and axion mass $|g_{Ae}\, m_A| \leqslant 1.33 \cdot 10^{-9}$.

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