Search for 14.4 keV solar axions using a proportional Kr counter

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search for axions with an energy of 14.4 keV, arising in the nuclear M1 transition of the ^{57}Fe isotope in the Sun, was performed using the axioelectric effect in Kr atoms. A gas proportional counter in a low-background setup located in the underground laboratory of the BNO INR RAS was used for the search. As a result, a new upper limit was established for the product of the coupling constant of an axion with an electron and the effective coupling constant with nucleons: $|g_{Ae}g_{AN}^{eff}| \leqslant 3.2 \cdot 10^{-16}$ for 90% confidence level.

Keywords: axions, dark matter, axion-like particles.

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Just like the spectrum of solar neutrinos, the expected energy spectrum of solar axions contains both a continuous part and monochromatic lines. Axions produced in the course of conversion of photons in the electromagnetic field of plasma and axions arising in bremsstrahlung and Compton processes have a continuous spectrum. Monochromatic axions are emitted in nuclear reactions of the pp chain and the CNO cycle and in magnetic transitions in certain nuclei with their the low-lying levels (^{169}Tm, 8.4 keV; ^{83}Kr, 9.4 keV; ^{57}Fe, 14.4 keV) excited due to the high (1.3 keV) temperature at the center of the Sun. When a nuclear level discharges, an axion may be emitted instead of a γ-quantum or a conversion electron. Since abundance N_{Fe} of iron atoms in the Sun is relatively high ($N_{\mathrm{Fe}}/N_{\mathrm{H}} = 3.1 \cdot 10^{-5}$), the most intense flux of monochromatic axions is expected from the ^{57}Fe isotope. Various methods were used to search for ^{57}Fe axions with an energy of 14.4 keV in different studies [1,2]. In the present study, the possibility of detection of these axions in the axioelectric effect reaction with a large proportional counter filled with krypton gas was investigated.

Measurements with a Kr counter in a low-background setup featuring passive and active protection were carried out in the underground Baksan Neutrino Observatory of the Institute for Nuclear Research of the Russian Academy of Sciences over a period of 777 days. The counter has a copper body with a total volume of 10.8 l and is filled with krypton at a pressure of 1.8 bar. The mass of krypton in the working volume of the counter is 58 g. The detector spectrum measured within the range of 5–22 keV is shown in Fig. 1. The primary goal of the experiment is the search for resonant absorption of solar axions by ^{83}Kr nuclei, which causes excitation of the ^{83}Kr nuclear level with an energy of 9.4 keV. The experiment was discussed in detail in [3–5].

Flux Φ_A of ^{57}Fe axions at the Earth's surface depends on the energy of the excited level and its lifetime, as well as on the abundance of the ^{57}Fe isotope in the Sun, the temperature distribution inside the Sun, and the ratio of probabilities of axion and photon emission [6]. We use the calculated total flux of ^{57}Fe axions expressed in $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$:

$$\Phi_A = 4.56 \cdot 10^{23} (g_{AN}^{eff})^2 \left(\frac{k_A}{k_\gamma}\right)^3, \qquad (1)$$

where $g_{AN}^{eff} = (-1.19 g_{AN}^0 + g_{AN}^3)$ is the effective coupling constant of axion with nucleons, which has isoscalar g_{AN}^0 and isovector g_{AN}^3 parts [7], and k_γ and k_A are the photon and axion momenta, respectively.

The axioelectric effect, which is analogous to the photoelectric effect, was chosen as a reaction for detection of axions with an energy of 14.4 keV. Axioelectric effect cross section σ_{ae} is proportional to photoelectric effect cross section σ_{pe} and axion–electron coupling constant g_{Ae} [8]:

$$\sigma_{ae}(E_A, m_A) = \sigma_{pe} \frac{3 g_{Ae}^2 E_A^2}{16\pi\alpha m_e^2 \beta_A} \left(1 - \frac{\beta_A^{2/3}}{3}\right), \qquad (2)$$

where $\beta_A = v/c = p_A/E_A$ is the axion velocity, m_e is the electron mass, and $\alpha = 1/137$ is the fine structure constant.

The axioelectric effect produces an electron accompanied by characteristic X-ray atomic radiation. It is important that the binding energy of an electron at the K shell of a krypton atom is 14.33 keV. Consequently, krypton is the atom most suitable for detection of axions with an energy of 14.41 keV, which corresponds to the maximum cross section of the photoelectric effect for K-shell electrons. The energy of a photoelectron ejected from the K shell is just 80 eV. The energies of follow-up X-ray radiation are $K_{\alpha 1,2} \approx 12.65$ keV, $K_\beta \approx 14.2$ keV, and $L_{\alpha 1} \approx 1.6$ keV. Only the K-series X-ray quanta may actually escape the working volume of the

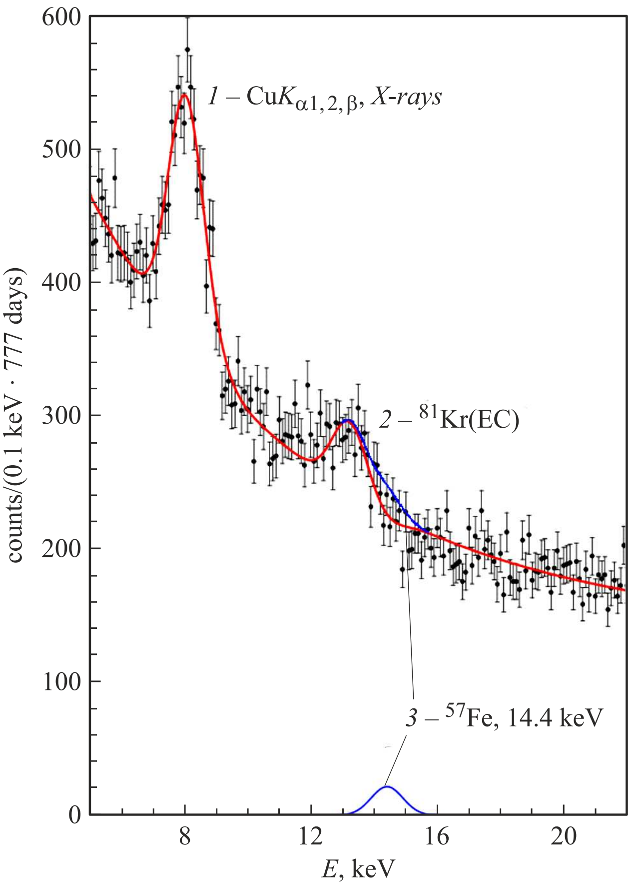

Figure 1. Kr counter spectrum and fitting results. *1* — Copper X-ray peak; *2* — peak associated with ^{81}Kr decay; *3* — expected peak at 14.4 keV containing $3S_{\lim}$ events (its contribution to the full spectrum is also indicated).

counter; all photons of the L series and Auger electrons are recorded by the detector. The resulting response function of the Kr counter detecting axions with an energy of 14.4 keV is a Gaussian peak at the same energy with a width determined by the energy resolution of the detector.

The measured counter spectrum was fitted with an expression characterizing the continuous background, Gaussian functions with a known energy, and the sought-for „axion" peak at an energy of 14.4 keV. The fitting results are presented in Fig. 1, *b*. Two well-defined peaks are associated with characteristic X-ray emission of body copper ($K_{\alpha 1} = 8.048$ keV, $K_{\alpha 2} = 8.028$ keV, and $K_\beta = 8.905$ keV) and the decays of long-lived radioactive ^{81}Kr, which forms from stable isotopes ^{82}Kr and ^{80}Kr under the influence of neutrons and decays by electron capture to the ground state of ^{81}Br in 99.7% of all cases. The absorption of characteristic X-rays and Auger electrons of bromine in the sensitive volume of the counter forms a peak at an energy of 13.47 keV, corresponding to the binding energy of an electron at the K shell of a Br atom. X-ray quanta of krypton ($K_{\alpha 1,2} = 12.65$ keV) and bromine ($K_{\alpha 1,2} = 11.92$ keV) escaping from the inactive region of the detector produce an additional contribution to the broadened peak at 13.47 keV. Thus, three Gaussian functions characterized the known X-ray peaks $K_{\alpha 1,2}$ and K_β of copper and the broad peak at 13.47 keV, which had its position and variance as free parameters. The fourth Gaussian characterized the axion peak, and its position and variance were tied to the parameters of the$K_{\alpha 1,2}$ copper peak.

No statistically significant peak was detected at 14.4 keV; the upper limit on the number of events in the peak determined from the χ^2 profile was $S_{\lim} = 90$ at 90% CL (confidence level). Expected number S of detected axions is given by

$$S = \sigma_{ae}\Phi_A T N \varepsilon. \tag{3}$$

Here, N is the number of Kr atoms in the counter, T is the measurement time, and ε is the detection efficiency. Coupled with expressions (1) and (2), condition $S \leqslant S_{\lim}$ allows one to impose an upper limit on the product of constants g_{Ae}^2 and $(g_{AN}^{eff})^2$:

$$|g_{Ae} g_{AN}^{eff}| \leqslant 3.2 \cdot 10^{-16} \ \ (90\,\%\text{CL}). \tag{4}$$

The obtained constraint (4) is at the level of the best results reported in the CUORE ($|g_{Ae} g_{AN}^{eff}| \leqslant 2.7 \cdot 10^{-16}$) and Edelweiss ($|g_{Ae} g_{AN}^{eff}| \leqslant 4.7 \cdot 10^{-17}$) experiments, where TeO_2– and Ge bolometers were used to search for dark matter particles.

Scalar g_{AN}^0 and isovector g_{AN}^3 parts of effective constant g_{AN}^{eff} may be expressed through the axion mass in the two most popular KSVZ and DFSZ axion models. The following restrictions on the product of coupling constant g_{Ae} and mass m_A were established as a result based on condition (4):

$$|g_{Ae} m_A| \leqslant 8.5 \cdot 10^{-8}\ \text{eV}, \tag{5}$$

$$|g_{Ae} m_A| \leqslant 1.2 \cdot 10^{-8}\ \text{eV}. \tag{6}$$

Expressions (5) and (6) are valid for axions in the KSVZ and DFSZ models, respectively. The coupling constants of an axion with a proton and a neutron given in [9,10] were used in our calculations. For clarity, relations (4)–(6) are written without factor $(k_A/k_\gamma)^{3/2}$, which starts to differ from unity only at axion masses greater than ~ 5 keV. The ranges of g_{Ae} and m_A values excluded by conditions (5) and (6) are shown in Fig. 2 in comparison with the results of other experiments. The most stringent constraints are those obtained in [5], where a search for the resonant excitation of a nuclear level with an energy of 9.4 keV of the ^{83}Kr isotope by a continuous spectrum of solar axions coupled with constant g_{Ae} was performed (curve *3* in Fig. 2). According to Fig. 2, the upper limits on the axion mass obtained in the present work are $m_A \leqslant 22$ eV and $m_A \leqslant 3.3$ keV for the DFSZ and KSVZ models, respectively.

Thus, a search for the absorption of solar axions with an energy of 14.4 keV by krypton atoms via the axioelectric effect was performed. A large gaseous proportional chamber filled with krypton was used to detect photoelectrons, Auger

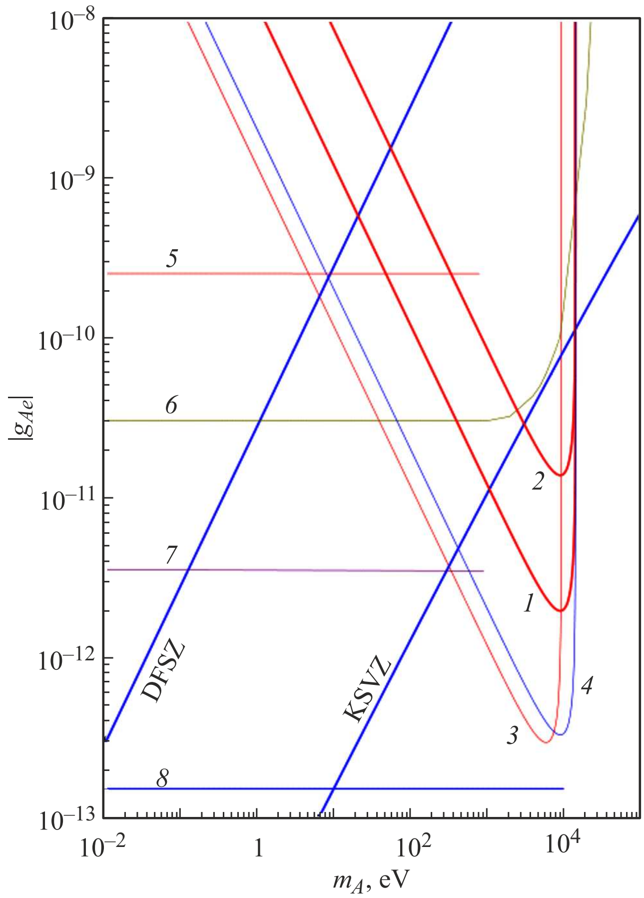

Figure 2. Upper limits on $|g_{Ae}|$ obtained in the present study for the DFSZ model (*1*) and the KSVZ model (*2*) and constraints from other experiments: *3* — ^{83}Kr resonant absorption [5], *4* — Edelweiss experiment [11], *5* — Si(Li) detector [12], *6* — solar neutrino data [13], *7* — LUX experiment [14], and *8* — astrophysical constraints [15].

electrons, and X-ray quanta. The low-background setup was located in the underground laboratory of Baksan Neutrino Observatory (Institute for Nuclear Research, Russian Academy of Sciences). Having analyzed the spectrum with an exposure of 45.1 kg · day, we found a new limit on the product of coupling constants of an axion with an electron and nucleons: $|g_{Ae}g_{AN}^{eff}| \leqslant 3.2 \cdot 10^{-16}$ (90% CL), which yields upper limits on the values of $|g_{Ae}m_A| \leqslant 8.5 \cdot 10^{-8}$ eV and $|g_{Ae}m_A| \leqslant 1.2 \cdot 10^{-8}$ eV and axion mass $m_A \leqslant 3.3$ keV and $m_A \leqslant 22$ eV in the KSVZ and DFSZ axion models, respectively.

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Conflict of interest

The authors declare that they have no conflict of interest.

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