New Constraints on the Axion–Electron Coupling Constant for Solar Axions

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Received May 25, 2022; revised May 25, 2022; accepted May 27, 2022

The resonant excitation of the $^{83}$Kr first excited nuclear level ($E = 9.4$ keV) by solar axions whose fluxes depend on the axion–electron coupling constant $g_{Ae}$ is sought. The $\gamma$- and X-ray photons and the conversion and Auger electrons from the excited-level relaxation are detected with a gas proportional counter of a low-background detector in the underground Baksan Neutrino Observatory (Institute for Nuclear Research, Russian Academy of Sciences). As a result, a new constraint $\leq 1.50 \times 10^{-17}$ (90% C.L.) has been obtained for the axion–electron and axion–nucleon coupling constants, which corresponds to new constraints on the axion mass $m_A \leq 320$ eV and $m_A \leq 4.6$ eV in the KSVZ and DFSZ axion models, respectively.

DOI: 10.1134/S0021364022601075

1. INTRODUCTION

Light pseudoscalar particles, axions, were introduced in the theory to solve the $CP$ problem of strong interactions [1–3]. Despite negative results of intensive experimental searches for axions, they are still well-justified candidates for the dark-matter constituents [4]. The anomalous transparency of the Universe to high-energy $\gamma$ rays [5] and the overly fast cooling of some star systems compared to the predictions of theoretical models [6] can be treated as promising astrophysical indications of the existence of axions.

The interaction of axions with matter is specified by the quantity $f_A$ at which the Peccei–Quinn symmetry [1] is broken and is determined by the effective axion–photon ($g_{A\gamma}$), axion–electron ($g_{Ae}$), and axion–nucleon ($g_{AN}$) coupling constants. The axion mass $m_A$ and the parameter $f_A$ are related to the respective characteristics of the $\pi^0$ meson as $m_A f_A = m_{\pi^0} f_{\pi^0}$. The corresponding expression for $m_A$ in terms of $f_A$ has the form [7, 8]

$$m_A = 5.69(5) \left( \frac{10^5 \text{GeV}}{f_A} \right) \text{eV}.$$  

The original PQWW model of the “standard” axion [1–3] implies that PQ symmetry is broken at the electroweak scale $f_A = (\sqrt{2} G_F)^{-1/2} \approx 250$ GeV. The constant $f_A$ in two classes of new models KSVZ [9, 10] and DFSZ [11, 12] of the “invisible” axion can be arbitrarily large up to the Planck mass $m_P \sim 10^{19}$ GeV, thus reducing both the expected axion mass and the interaction of the axion with matter.

Stars should be intense sources of axions. Intense fluxes of axions can be formed in the Sun in a number of processes whose probabilities depend on the axion coupling constants $g_{A\gamma}$, $g_{Ae}$, and $g_{AN}$. The constant $g_{A\gamma}$ specifies the probability of conversion of photons to axions in the electromagnetic field of the solar plasma (Primakoff axions). The constant $g_{AN}$ determines the emission of axions in nuclear magnetic transitions that are thermally excited at high temperatures in the center of the Sun or appear in nuclear reactions of the $\text{p}\text{p}$ chain and CNO cycle. The constant $g_{Ae}$ specifies the axion fluxes from bremsstrahlung $e + Z \rightarrow Z + e + A$ and Compton process $\gamma + e \rightarrow e + A$, as well as in discharge and recombination processes in atoms $I^* \rightarrow I + A \rightarrow e + I \rightarrow I^* + A$. The spectra and fluxes of axions appearing in the above processes were calculated in [13–17] and are shown in Fig. 1.

Here, we report new results for the axion–electron coupling constant $g_{Ae}$ determined from the complete set of data obtained in experiments on the search for the resonant absorption of solar axions by $^{83}$Kr nuclei with a large krypton proportional counter [18, 19]. The
cross section for the resonant excitation of a nuclear level depends on the constant $g_{AN}$; consequently, the rate of absorptions of axions in an experiment depends on the product of the constants $g_{Ae}$ and $g_{AN}$.

The dimensionless coupling constant $g_{Ae}$ in the DFSZ model is expressed in terms of the parameter $f_A$, which determines the axion mass $m_A$, and the free parameter $\cos^2 \beta$:

$$g_{Ae} = (1/3)\cos^2 \beta \frac{m_e}{f_A},$$

where $m_e$ is the mass of the electron and $\beta$ is an arbitrary angle. For the maximum value $\cos^2 \beta = 1$ and taking into account Eq. (1), we obtain $g_{Ae} = 2.99 \times 10^{-11} m_A$, where $m_A$ is in electronvolts.

In the KSVZ model, the axion does not interact with the electron; the effective axion–electron coupling constant calculated for the one-loop correction is $[20, 21]$

$$g_{Ae} = \frac{3\alpha^2 m_e}{4\pi^2 f_0} \left( \frac{E}{N} \ln f_A - \frac{24 + z + w}{31 + z + w} \ln \Lambda \right),$$

where $\alpha = 1/137$ is the fine-structure constant, $z = m_u/m_d = 0.56$ and $w = m_s/m_u = 0.029$ are the ratios of the masses of the $u$, $d$, and $s$ quarks, $\Lambda \approx 1$ GeV is the scale cutoff in QCD, and $E/N$ is the model-dependent parameter about unity, which is equal to $8/3$ and 0 in the DFSZ axion model and the original KSVZ axion model, respectively. The interaction of the hadron axion with the electron is suppressed by a factor of at least $\sim \alpha^2$.

According to Eqs. (2) and (3), the coupling constant $g_{Ae}$ is proportional to $m_A$, with the coefficient of proportionality including unknown parameters $\cos^2 \beta$ and $E/N$ for the DFSZ and KSVZ axions, respectively. The axion coupling constants $g_{A\gamma}$, $g_{Ae}$, and $g_{AN}$ determine both the probabilities of production of axions in various processes and cross sections for the reactions used to detect them.

The best known experiments are aimed at the search for solar axions produced through thermal-photon conversion in the field of the solar plasma. Under the assumption of the axion–photon coupling,
researchers attempt to detect axions through the inverse axion–photon conversion in a laboratory magnetic field [22, 23] or in a crystal field [24, 25]. Photon count rates expected in these experiments are proportional to \( g_{\text{AE}}^4 \). In this work, to detect solar axions appearing in reactions involving the electron, the resonant absorption of axions by \(^{83}\text{Kr}\) nuclei is employed. In this case, the expected count rate is proportional to the dimensionless product \( g_{\text{AE}}^2 \times S_{\text{AA}}^2 \).

In our previous works, using a krypton proportional counter, we attempted to detect monochromatic solar axions emitted in the relaxation of the \(^{83}\text{Kr}\) first excited nuclear level, which is excited because of the high temperature of the Sun [18], and Primakoff axions, which resonantly excite the \(^{83}\text{Kr}\) nucleus [19]. Theoretical and experimental studies of the axion problem are reviewed in [8].

2. RESONANT EXCITATION OF THE \(^{83}\text{Kr}\) FIRST EXCITED NUCLEAR LEVEL BY SOLAR AXIONS

Figure 1 shows the energy spectrum of axions produced in the processes caused by the axion–electron coupling that was calculated with the axion–electron coupling constant \( g_{\text{AE}} = 10^{-11} \) [17] and is used in further calculations. The average energy of axions is 1.6 keV and their flux almost vanishes at energies above 15 keV. The flux of axions at an energy of 9.4 keV, which corresponds to the \(^{83}\text{Kr}\) first excited nuclear level, is \( 1.32 \times 10^{11} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \) [17], which is a factor of 60 lower than the maximum flux reached at an energy of 0.7 keV.

The 9.405-keV \(^{83}\text{Kr}\) first excited nuclear level has the spin and parity \( 7/2^+ \). The transition to the \( 9/2^+ \) ground state is an \( M1 \) magnetic transition (a small fraction of the \( E2 \) transition is \( \delta = 0.0129 \) and can be accompanied by the emission of a \( \gamma \)-ray photon and by the emission or absorption of a pseudoscalar particle, an axion. The electron conversion coefficient important for target–detector experiments, where conversion and Auger electrons are absorbed in the target, is \( \varepsilon/\gamma = 17.1 \) for the transition under study [26].

The ratio of the probabilities of the axion and electromagnetic transitions \( \omega_A/\omega_r \) was calculated in the long-wavelength approximation in [27, 28] in the form

\[
\frac{\omega_A}{\omega_r} = \frac{1}{2 \pi \alpha} \left[ \frac{g_{\text{AA}}^0 \beta^* + g_{\text{AA}}^3}{2(1 + \delta^2)} \right] \left[ (\mu_0 - 0.5 \beta^* + \mu_3 - \eta) \right]^2 \left( \frac{p_A}{p_r} \right)^3,
\]

where \( p_r \) and \( p_A \) are the momenta of the photon and axion, respectively; \( \delta \) is the ratio of probabilities of the \( E2 \) and \( M1 \) transitions; \( \mu_0 = 0.88 \) and \( \mu_3 = 4.71 \) are the isoscalar and isovector nuclear magnetic moments, respectively; and \( \beta^* \) and \( \eta \) are the parameters determined by particular nuclear matrix elements.

The parameters \( \beta^* \) and \( \eta \) for the \(^{83}\text{Kr}\) nucleus with an odd number of nucleons and an unpaired neutron are estimated in the single-particle approximation as \( \beta^* = -1 \) and \( \eta = 0.5 \) [29].

The axion–nucleon coupling constant \( g_{\text{AA}} \) is the sum of the isoscalar \( g_{\text{AA}}^0 \) and isovector \( g_{\text{AA}}^3 \) parts. In the KSVZ axion model, the constants \( g_{\text{AA}}^0 \) and \( g_{\text{AA}}^3 \) can be expressed in terms of the mass of the axion as [19]

\[
\begin{align*}
 g_{\text{AA}}^0 &= -4.03 \times 10^{-8} (m_A/1 \text{ eV}), \\
 g_{\text{AA}}^3 &= -2.75 \times 10^{-8} (m_A/1 \text{ eV}).
\end{align*}
\]

To calculate Eqs. (5), we used the particular axial vector baryon coupling constants \( F = 0.462 \) and \( D = 0.808 \) and the polarization structure function of the proton \( S = 0.5 \) [19], as well as the commonly accepted ratios \( z = m_s/m_d = 0.56 \) and \( w = m_s/m_u = 0.029 \) of the masses of the \( u, d, \) and \( s \) quarks (rather than more modern values \( z = 0.47 \) and \( w = 0.023 \) [8]) to correctly compare to the previous results.

We note that the detection of the resonant absorption of axions on the \( M1 \) transition in the \(^{83}\text{Kr}\) nucleus is complicated by a methodological problem of a negative value of the parameter \( \beta^* \) in Eq. (4). This negative value, together with the existing wide interval of possible \( S \) and \( z \) values, leads to a large uncertainty of the ratio \( \omega_A/\omega_r \), given by Eq. (4). The effect of uncertainties in the parameters \( S \) and \( z \) on the final result through a factor of \((g_{\text{AA}}^0 - g_{\text{AA}}^3)^2\) in Eq. (4) was discussed in [18, 19, 30], where it was shown in particular that the \((g_{\text{AA}}^0 - g_{\text{AA}}^3)^2\) value at the relation \( S \simeq 1.2\)–\(1.7\) can be more than an order of magnitude smaller than the value calculated with \( S = 0.5 \) and \( z = 0.56 \).

In the DFSZ axion model, the axion–nucleon coupling constants \( g_{\text{AA}}^0 \) and \( g_{\text{AA}}^3 \) depend on an additional unknown parameter \( \cos^2 \beta \), but they are of the same order of magnitude [20, 31]. At \( \cos^2 \beta = 1 \), the parameter \((g_{\text{AA}}^0 - g_{\text{AA}}^3)^2\) appearing in Eq. (4) for the axion emission probability \( \omega_A/\omega_r \) is a factor of 2.05 larger than this parameter for the KSVZ axion.

The cross section \( \sigma(E_A) \) for axion absorption at the energy \( E_A \) is given by an expression similar to the cross section for the resonant absorption of \( \gamma \)-ray photons with the correction to the ratio \( \omega_A/\omega_r \). The total cross section for axion absorption can be obtained by integrating \( \sigma(E_A) \) over the solar-axion spectrum \( (d\Phi_A/dE_A) \) [30]. As a result, the rate of absorption of solar axions \( R_A \) by the \(^{83}\text{Kr}\) nucleus is given by the expression

\[
R_A = \pi \sigma_0 \Gamma (d\Phi_A/dE_A)(\omega_A/\omega_r),
\]
where $\sigma_{0\gamma} = 1.22 \times 10^{-18}$ cm$^2$ is the maximum $\gamma$-ray absorption cross section and $\Gamma = 2.95 \times 10^{-12}$ keV is the width of the $^{83}$Kr first excited nuclear level.

The flux of these axions is proportional to $g_{\alpha e}^2$, and the ratio $\omega_\alpha/\omega_\gamma$ depends on the parameter $(g_{AN}^3 - g_{AN}^0)^2$. The resulting expression for the rate of axion absorption $R_A$ by the $^{83}$Kr nucleus in units of inverse seconds per atom in terms of the coupling constant has the model-independent form

$$R_A = 2.15 \times 10^{14} g_{\alpha e}^2 (g_{AN}^3 - g_{AN}^0)^2 (p_A/p_\gamma)^3.$$  \hspace{1cm} (7)

Substituting Eqs. (5) for the constants $g_{AN}^0$ and $g_{AN}^3$ in terms of the axion mass $m_A$ obtained in the KSVZ model, the axion absorption rate can be expressed in terms of $g_{\alpha e}$ and $m_A$, the latter being measured in electronvolts,

$$R_A = 3.53 \times 10^{-12} g_{\alpha e}^2 m_A^2 (p_A/p_\gamma)^3.$$  \hspace{1cm} (8)

The total number of detected axions depends on the number of $^{83}$Kr nuclei in the target, measurement time, and detector efficiency. The probability of observing the 9.4-keV peak depends on the background level of the experimental setup.

3. EXPERIMENTAL SETUP

The experimental setup is described in detail in our previous works [18, 19]. Here, we present only the basic characteristics. A detector with a gas proportional counter is located in the low-background underground Baksan Neutrino Observatory (Institute for Nuclear Research, Russian Academy of Sciences) at a depth of 4900 mwe, where the muon flux is $(2.6 \pm 3.3 \times 10^5)$ m$^{-2}$ day$^{-1}$, which is lower than that on the ground by a factor of $5 \times 10^6$ [32].

The cylindrical copper counter has a total volume of 10.8 L. A gold-plated tungsten wire running along the counter axis serves as an anode. To exclude the influence of edge effects on charge collection, the anode diameter is increased, which limits the working volume of the chamber to 8.8 L. The counter is filled with krypton enriched to 99.9% in the $^{83}$Kr isotope at a pressure of 1.8 bar. The mass of the $^{83}$Kr isotope in the working volume of the counter is 58 g. The passive shield of the counter consists of sequential copper, lead, and polyethylene layers. A 12.5-MHz digitizer is used to measure the amplitude of the pulse, the duration of its rising edge, and the secondary photoemission pulse. The procedure of analysis of the pulse shape is described in [33, 34]. The detection efficiency for the $\gamma$-and X-ray photons, as well as Auger and conversion electrons, arising from the relaxation of the $^{83}$Kr 9.4-MeV excited level as estimated through a Monte Carlo simulation with the Geant4 package is $\varepsilon = 0.825$ [19].

4. RESULTS

The measurements were carried out. The energy spectrum of the proportional gas counter signals detected over a live time of 776.6 day is shown in Fig. 2. The most intense peak observed in the spectrum is due to the X-ray $K$ Cu lines ($K_{\alpha 1} = 8.048$ keV, $K_{\alpha 2} = 8.028$ keV, and $K_{\beta} = 8.905$ keV) from the copper frame of the counter.

The second peak observed at an energy of ~13.5 keV consists of several peaks with close energies. The long-lived $^{81}$Kr isotope ($\tau = 3.3 \times 10^5$ yr) is formed from the stable $^{82}$Kr and $^{80}$Kr isotopes under the action of neutrons and decays through electron capture into the $^{81}$Br ground state with a probability of 99.7%. The absorption of the characteristic X rays and Auger electrons from bromide in the sensitive volume of the detector is responsible for the 13.47-keV peak corresponding to the binding energy of the electron in the $K$ shell of the Br atom. X-ray photons emitted by krypton ($K_{\alpha 1} = 12.65$ keV) and bromine ($K_{\alpha 1} = 11.92$ keV) beyond the sensitive volume of the gas chamber make an additional contribution to the broadened 13.5-keV peak.

The measured spectrum is approximated in the range of 4–20 keV by the sum of a continuous background and four Gaussian peaks. The function describing the continuous background is the sum of a constant component and an exponential function of the energy $E$:

$$S_{\text{bkg}}(E) = a + b \exp(-cE) + \sum_{i=1}^{4} S_i G(E, E_i, \sigma_i),$$  \hspace{1cm} (9)

where $a$, $b$, and $c$ are varying parameters. Three Gaussians describe the known 8.044-keV $K_{\alpha 1}$ Cu and 8.905-keV $K_{\beta}$ Cu peaks and the wide 13.5-keV peak. The fourth Gaussian describes the 9.405-keV axion peak whose position and width are set to the parameters of the $E_1$ peak $K_{\alpha 1}$ Cu.

The approximation of the energy spectrum in the range of 4–20 keV corresponding to $\chi^2 = 156.3/147$ and $P = 0.28$ is shown by the solid line in Fig. 2. The 9.4-keV “axion” peak is not manifested statistically. To establish an upper bound on the number of counts in the 9.4-keV peak, we used the standard method to determine the profile $\chi^2(S_4)$ and the probability function $P(\chi^2(S_4))$. The upper bound on the number of peak events thus determined is $S_{\text{lim}} = 140$ for 90% C.L.

The determined upper bound on the number of events in the 9.4-keV peak provides bounds on the axion–electron coupling constant $g_{\alpha e}^3 (g_{AN}^3 - g_{AN}^0)$, and the axion mass $m_A$ according to Eqs. (7) and (8). The expected number of detected axions is

$$S_A = R_A N_{83\text{Kr}} T \varepsilon \leq S_{\text{lim}},$$  \hspace{1cm} (10)
where \( N_{83\text{Kr}} = 5.24 \times 10^{33} \) is the number of \(^{83}\text{Kr}\) nuclei in the target, \( T = 6.71 \times 10^9 \) s is the measurement time, and \( \epsilon = 0.825 \) is the detection efficiency.

According to Eqs. (7) and (10), under the condition \( (p_A/p_e)^3 \equiv 1 \), which is valid for the masses of the axion \( m_A < 2 \text{ keV} \), we obtain the upper bound

\[
|g_{\text{ae}} (g_{\text{AN}}^0 - g_{\text{AN}}^0)| \leq 1.50 \times 10^{-17} \tag{11}
\]

for 90% C.L. Bound (11) is a model-independent constraint on the coupling constants of the axion or any pseudoscalar axion-like particle to the electron and nucleon.

Using Eqs. (8) and (11), one can establish the following upper bound on the product of the constant \( g_{\text{ae}} \) and mass \( m_A \) for the KSVZ axion:

\[
|g_{\text{ae}} \times m_A| \leq 1.17 \times 10^{-9} \text{ eV}. \tag{12}
\]

The upper bound (12) for the DFSZ axion at \( \cos^2 \beta = 1 \) is almost two times lower \( |g_{\text{ae}} \times m_A| \leq 5.72 \times 10^{-10} \) eV. The upper bound (12) on the allowed \( |g_{\text{ae}} \times m_A| \) values makes it possible to compare the results with the results of other experiments on the search for solar axions, in particular, with the results of the search for the axio-electric effect in atoms [36, 37] (Fig. 3).

The upper bound (12) excludes a new region of the coupling constant \( g_{\text{ae}} \) at relatively large masses of the axion \( m_A \) and is a factor of almost 4 lower than the experimental result on the detection of resonant excitation of the \(^{169}\text{Tm}\) first excited nuclear level [16, 35]. Since the 8.4-keV \( M1 \) transition in the \(^{169}\text{Tm}\) nucleus is primarily a proton transition (\( \beta \approx 1 \)), the ratio \( \omega_p/\omega_e \) does not include uncertainty.

Figure 3 shows the band of possible \( g_{\text{ae}} \) and \( m_A \) values in the KSVZ and DFSZ axion models. Using Eqs. (2) and (3) for the axion–electron coupling constant, one can obtain upper bounds on the axion mass.
in these two models from Eq. (12). The upper bound (12) on the product \( g_{Ae} \) and \( m_A \) excludes the axion masses \( m_A > 320 \) eV in the KSVZ model axion \((E/N = 8/3)\). The upper bound on the DFSZ axion at \( \cos^2 \beta = 1 \) and Eq. (2) is much lower: \( m_A \leq 4.6 \) eV.

The upper bounds established in this work on the coupling constant of solar axions to the electrons for masses \( m_A \geq 0.3 \) keV are the most stringent laboratory constraints and are close to astrophysical constraints. It is interesting that the analysis of the luminosity of white dwarfs indicates a nonzero \( |g_{Ae}| \) value in the interval of \((0.7–2.2) \times 10^{-13} \) [8, 38], although the corresponding upper bound is above the bound \( |g_{Ae}| \leq 1.3 \times 10^{-13} \) obtained for red giants in some globular clusters [39] (Fig. 3).

5. CONCLUSIONS

The resonant absorption of 9.4-keV solar axions by \( ^{83}\text{Kr} \) nuclei with the excitation of the first excited nuclear level has been sought. Gamma- and X-ray photons, as well as conversion and Auger electrons, have been detected with a large gas proportional counter that is filled with the \( ^{83}\text{Kr} \) isotope and is placed in a low-background detector in the underground Baksan Neutrino Observatory (Institute for Nuclear Research, Russian Academy of Sciences). As a result, a new upper bound \( |g_{Ae}(g_{3N}^{3N} - g_{AY})| \leq 1.50 \times 10^{-17} \) (90% C.L.) has been obtained for the axion—electron and axion—nucleon coupling constants. This bound corresponds to constraints on the axion—electron coupling constant \( g_{Ae} \) and the axion mass \( m_A \):

\[
\begin{align*}
g_{Ae} \times m_A \leq 1.17 \times 10^{-3} \text{ eV} & \quad \text{and} \quad g_{Ae} \times m_A \leq 5.72 \times 10^{-10} \text{ eV,} \\
& \quad \text{and on the axion mass } m_A \leq 320 \text{ eV and } m_A \leq 4.6 \text{ eV in the KSVZ and DFSZ (cos}^2 \beta = 1) \text{ axion models, respectively.}
\end{align*}
\]

FUNDING
This work was supported by the Russian Science Foundation (project no. 22-22-00017).

CONFLICT OF INTEREST
The authors declare that they have no conflicts of interest.

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Translated by R. Tyapaev