Search for the resonance absorption of solar axions emitted in the M1 transition of ^{83}Kr and ^{57}Fe nuclei in the Sun

A.M. Gangapshev[1],*, Z.A. Akhmatov[5], S.S. Berezin[4], Yu.M. Gavrilyuk[1], A.V. Derbin[3], I.S. Drachnev[3], V.V. Kazalov[1], A.Kh.-A. Khokonov[5], V.V. Kuzminov[1], V.N. Muratova, S.I. Panasenko[2], S.S. Ratkevich[2], D.A. Tekueva[1], S.P. Yakimenko[1], E.V. Unzhakov[3], A.Yu. Zavrazhnov[4]

[1] Institute for Nuclear Research RAS, Moscow, Russia; gangapsh@list.ru

[2] Kharkov National University, Ukraine

[3] St. Petersburg Nuclear Physics Inst., NRCKI, Gatchina, Russia

[4] Voronezh state university, Voronezh, Russia

[5] Kabardino-Balkarian State University, Nalchik, Russia

Abstract A search for resonant absorption of the solar axions 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 limits on axion-nucleon, - photon,- electron couplings are $|g^3_{AN}-g^0_{AN}|\leq 8.4\times10^{-7}$, $|g_{A\gamma}\times m_A| \leq 6.3\times10^{-17}$, $|g_{Ae}\times m_A| \leq 1.4\times10^{-9}$ eV. The upper limit on axion mass is $m_A \leq 65$ eV at 95% C.L. New experiment using resonant absorption of the solar axions by Fe-57 nuclei is proposed. Different materials containing of Fe-57 which can be used as detectors working media are described

Keywords: Axion, Solar model, Proportional counter, Krypton, Iron.

1. Introduction

A solution of the strong CP problem based on the global chiral symmetry U(1) was proposed by Peccei and Quinn (PQ) [1]. The existence of the axions was predicted by Weinberg [2] and Wilczek [3] as result of spontaneous breaking of the PQ-symmetry at the energy f_a. The axion mass (ma) and the strengths of an axion's coupling to an electron (g_{ae}), a photon ($g_{a\gamma}$) and nucleons (g_{aN}) are proportional to the inverse of f_a. At the moment there are two classes of models for the axion: KSVZ-model (hadronic axion) [4, 5] and DFSZ-model [6, 7].

"Axions are among the most fascinating particles on the long list of those proposed but not yet observed or ruled out. Their existence would provide an elegant resolution of the strong CP problem. Even more exciting is the possibility that the missing mass needed to close the universe is composed of axions, and that axions are «cold dark matter» which seems to be necessary for galaxy formation" [8].

"The composite axion is a particular example of a "hadronic" axion, resulting from a theory where only exotic fermions carry U(1)PQ charges. Hadronic axions don't couple to leptons, which are neutral under SU(3)xU(1)PQ. Nor do they couple to heavy quarks, which are integrated out of the theory above 1GeV, where QCD gets strong. Hadronic axions will still couple to nucleons as well as to photons" [9].

The axion mass in both models is defined as:

$$m_a = \frac{f_\pi m_\pi}{f_A}\left(\frac{z}{(1+z+w)(1+z)}\right) , \tag{1}$$

where $f_\pi \approx 93$ MeV - pion decay constant, $z = m_u/m_d \approx 0.56$ and $w = m_u/m_s \approx 0.029$ - quark-mass ratios. It gives m_A [eV] $\approx 6.0 \times 10^6/f_A$ [GeV].

The main difference between models is that in contrast to the DFSZ-model in KSVZ-model axions have no coupling to leptons and ordinary quarks at the tree level. As result the interaction of the KSVZ axion with electrons through radiatively induced coupling is strongly suppressed [8].

If axions do exist, then the Sun and other stars 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 [10]. 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 [11]. Searches for resonant absorption of solar axions emitted in the nuclear magnetic transitions were performed with ^{57}Fe [12, 13, 14, 15, 16, 17], ^{7}Li [18, 19, 20] and ^{83}Kr [21] nuclei.

The expected rate of resonance axion absorption by the ^{83}Kr nucleus as a function of the probability for axion emission ω_A/ω_γ; the parameter (g_3-g_0), which describes axion-nucleon interaction; and the axion mass in the KSVZ model can be represented in the form (S=0.5, z= 0.56)[22]:

$$R_A = [g^{-1}day^{-1}] = 4.23 \cdot 10^{23}\left(\omega_A/\omega_\gamma\right)^2 \tag{2}$$

$$= 8.53 \cdot 10^{21}(g_3 - g_0)^2\left(p_A/p_\gamma\right)^6 \tag{3}$$

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

2. Experimental setup

The experimental technic is based on registration of the γ-quantum and conversion electrons appearing after deexcitation of the ^{83}Kr nuclei. To register this process a large proportional counter (LPC) with a casing of copper is used. The krypton enriched with ^{83}Kr (99.9%) is used as working media of the LPC. The LPC is a cylinder with inner and outer diameters of 137 and 150 mm, respectively. 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 (3 mm in diameter and 38.5 mm in length) electrically connected to the anode. These segments operate as an ionization chamber with no gas amplification. Taking into account teflon insulators dimensions, the distance from operation region to the flange is 70 mm. The fiducial length of the LPC is 595 mm, and the corresponding volume is 8.77 L. Gas pressure is 1.8 bar, and corresponding mass of the ^{83}Kr-isotope in fiducial volume of the LPC is 58 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 [23], at the depth of 4700 m w.e., where the cosmic ray flux is reduced by ~ 10^7 times in comparison to that above ground, and valuated as (3.0 ± 0.1) × 10^{-9} cm−2 s^{-1} [24].

3. Results with ^{83}Kr

The background spectra collected during 613.25 days and fit result curve are presented in ***Fig1.*** Two peaks are clear visible in the energy range (4-26) keV. The peak with energy 8.05 keV associates with the detection of $K_{\alpha1,2}$ X-rays of copper. The structure of the second peak is more complicated, it is mixture of Kr and Br $K_{\alpha1,2}$ 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. The maximum likelihood method was used to determine the intensity of the peak. The fit of spectrum corresponding to the minimum χ^2 is shown by red solid line in Fig. 1. The minimum of χ^2 corresponds to the nonphysical value of the area of the 9.4 keV peak S_A=−(102±92) events. The standard χ^2-profile method was used to determine the upper bound on the number of events in the peak.

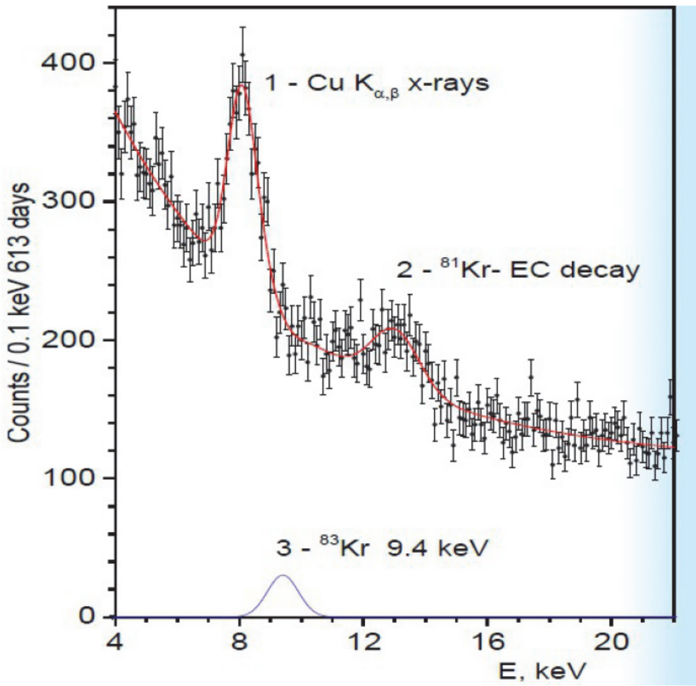

Fig1. *Energy spectra of the Kr LPC measured for 613 days, fitting results (red line) and expected axion peak for 3S_{lim} (blue line).*

The upper bound thus determined for the number of events in the peak is S_{lim}= 127 for 95 % C.L.

The expected number of registered axions is

$$S_A = RMT\epsilon \leq S_{lim} \quad , \qquad (5)$$

where M = 58 g is mass of ^{83}Kr isotope, T = 613.25 days is time of data taking, and ε = 0.825 is the detection efficiency. The upper limit on the excitation rate of ^{83}Kr by solar hadronic axions is defined as $R_{exp}=4.29\times10^{-3}g^{-1}day^{-1}$. The 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. (2-4), and on condition that (p_A/p_γ)≅1 provided for m_A<3 keV one can obtain:

$$\left(\omega_A/\omega_\gamma\right) \leq 1.0 \cdot 10^{-12} \ , \tag{6}$$

$$|g_3 - g_0| \leq 8.4 \cdot 10^{-7} \ , \tag{7}$$

$$m_A \leq 65\ eV\ \ at\ 95\%\ C.L. \tag{8}$$

The limit (8) is stronger than the constrain obtained with 14.4 keV ^{57}Fe solar axions [17]) and is stronger than our previous result obtained in ^{83}Kr experiment [25]. As in the case of 57Fe nucleus the obtained limit on axion mass strongly depends on the exact values of the parameters S and z.

4. Proposal with ^{57}Fe

Another possible way to search for the hadronic soar axions is to use detector with a working media containing ^{57}Fe. One of the possible candidates for a such media is Pyrite. The mineral pyrite, or iron pyrite, also known as fool's gold, is an iron sulfide with the chemical formula FeS_2. Pyrite has been proposed as an abundant, inexpensive material in low-cost photovoltaic solar panels. Synthetic iron sulfide was used with copper sulfide to create the photovoltaic material.

Pyrite is a semiconductor, the band gap in pyrite is about 0.95 eV and the dominant charge carriers can be either electrons or holes. Sometimes, both n-type and p-type semiconducting regions can be found within single naturally occurring crystals. Resistivity (natural crystals): $10^{-5} \div 10^{0} Om * m$. On the other hand, the high purity pyrite should have much higher resistivity (comparable with high purity germanium) and so could be used as semiconductor detector.

Now we are working on development a new semiconductor detector based on high purity pyrite or solid solution GaS:Fe or Ga_2S_3:Fe. The main profit of use these materials is much higher expected rate of resonance axion absorption by the ^{57}Fe in comparison with ^{83}Kr. The ratio of rates is:

$$\frac{R_{Fe-57}}{R_{Kr-83}} = 3.51 \cdot 10^{3} \tag{9}$$

Using the semiconductor detector with the iron contaminating working media will allow one to search for hadronic axions with masses below 10 eV – most interesting mass region.

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