Search for resonant absorption of solar axions by ^{83}Kr-nuclei. New limits on $g_{A\gamma}$ and g_{Ae}.

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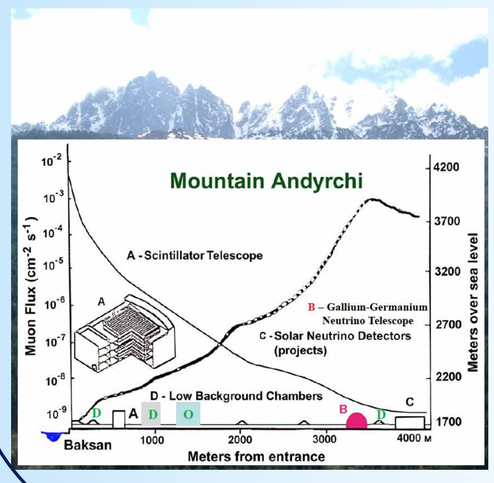
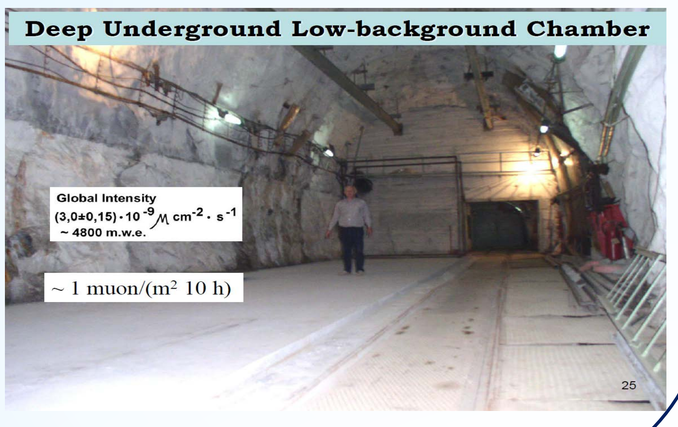
Kr-counter in Baksan ν-Observatory

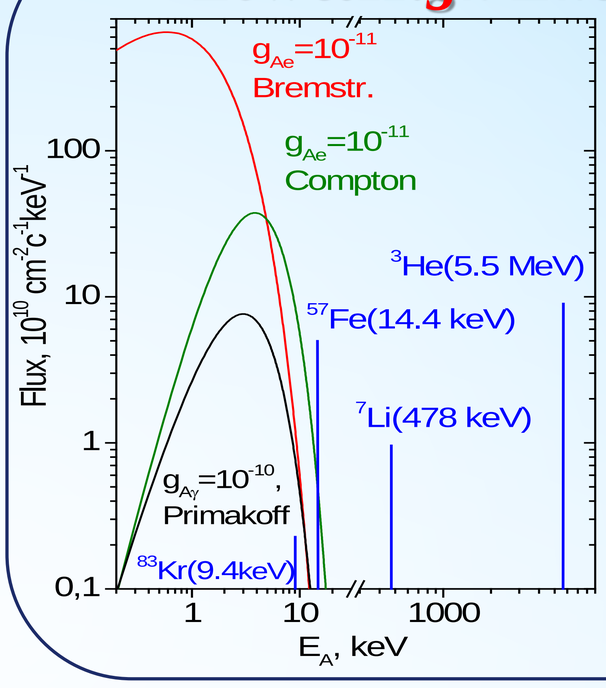
A large proportional counter (LPC) with a casing of copper is used. The LPC is a cylinder with inner and outer diameters of 137 and 150 mm, respectively. A gold-plated tungsten wire of 10 μm in diameter is stretched along the LPC axis and is used as an anode. The fiducial length of the LPC is 595 mm, and the volume is 8.77 L. Gas pressure is 5.6 bar, and corresponding mass of the 83Kr-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 at the depth of 4700 m w.e., where the cosmic ray flux is reduced by ~10^7 times and evaluated as 2.6 muons m^{-2} d^{-1}.





Mountain Anadur, 4 km tunnel and LB camera. From www.inr.troitsk.ru

Low&High Energy Solar axions

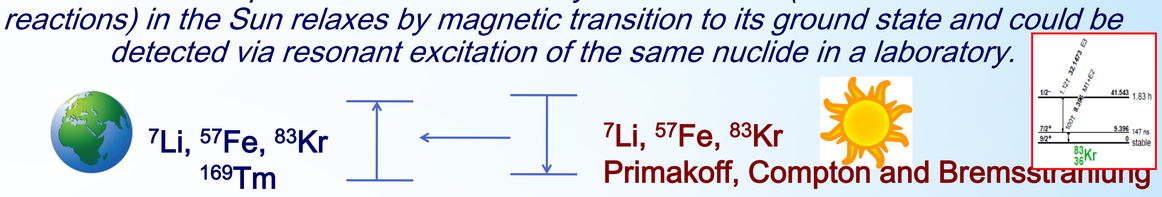


The main sources of solar axions:

1. Reactions of main solar chain. *The most intensive fluxes are expected from M1-transitions in ^{7}Li and ^{3}He nuclei* (g_{AN}):
   ^{7}Be + e$^-$ → ^{7}Li*+ γ; ^{7}Li* → ^{7}Li+A (478 кэВ)
   p + d → ^{3}He + A (5.5 МэВ).
2. Magnetic type transitions *in nuclei whose low-lying levels are excited due to high temperature in the Sun* (^{57}Fe,^{83}Kr) (g_{AN})
3. Primakoff conversion *of photons in the electric field of solar plasma* ($g_{A\gamma}$).
4. Bremsstrahlung: e + Z(e) → Z + A. (g_{Ae})
5. Compton process: γ + e → e + A. (g_{Ae})
6. axio-recombination: e + I → I$^-$ + A and axio-deexcitation: I* → I + A. *PRD 83 023505 (2011) CAST 1302.6283, 1310.0823*

Detection of axions via resonant excitation

The axions can be produced when thermally excited nuclei (or excited due to nuclear reactions) in the Sun relaxes by magnetic transition to its ground state and could be detected via resonant excitation of the same nuclide in a laboratory.

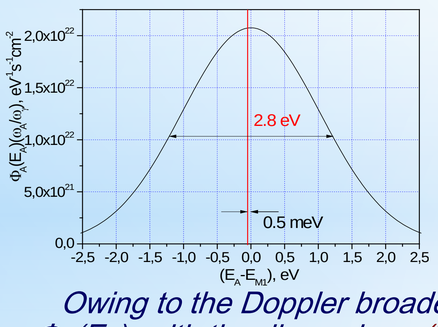


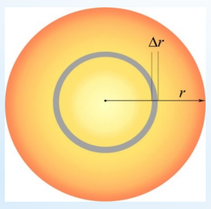
The monochromatic axions emitted by ^{7}Li, ^{57}Fe and ^{83}Kr nuclei can excite the same nuclide in a laboratory, because the axions are Doppler broadened due to thermal motion of the axion emitter in the Sun and some axions have needed energy to excite the nuclide.

The axions from Primakoff, Compton and bremsstrahlung processes with wide continues energy spectra can also excite low-lying levels of some nuclei. The more suitable isotopes are ^{83}Kr and ^{169}Tm.

Flux of monochromatic solar ^{83}Kr axions

The total axion flux Φ_A depends on the level energy E_γ = 9.4 keV, temperature T, nuclear level lifetime τ_γ = 3.6 μs, the abundance of the ^{83}Kr isotope on the Sun N, and the branching ratio of axions to photons emission ω_A/ω_γ:



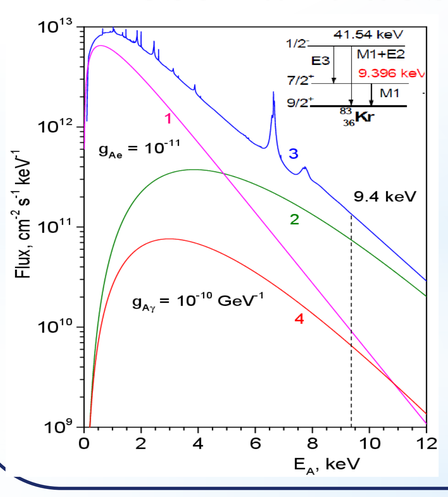


$$\Phi_A = \int N(r)\frac{2\exp(-E_\gamma/kT(r))}{1+2\exp(-E_\gamma/kT(r))}\frac{\omega_A}{\tau_\gamma\omega_\gamma}dr$$

$$\Phi_A(E_{M1}) = 5.97\times10^{23}\left(\frac{\omega_A}{\omega_\gamma}\right)\text{cm}^{-2}\text{s}^{-1}\text{keV}^{-1}$$

Owing to the Doppler broadening, the axion spectrum is a sum of Gaussian curves, $\Phi_A(E_A)$, with the dispersion $\sigma(T) = E_\gamma (kT/M)^{1/2}$, where T is the temperature at the point where the axion is emitted and M is the mass of the ^{83}Kr nucleus.

Resonant absorption by ^{83}Kr nucleus



The rate of solar axion absorption by the ^{169}Tm:

$$R_A = \pi\sigma_{0\gamma}\Gamma\frac{d\Phi_A}{dE_A}(E_A=9.4)\left(\frac{\omega_A}{\omega_\gamma}\right).$$

*where $\sigma_{0\gamma}$ is a maximum cross section of γ-ray absorption. The experimentally derived value of $\sigma_{0\gamma}$ for ^{83}Kr nucleus is **1.22×10^{-18} cm²**. Width of energy level **Γ = 2.95×10^{-9} eV**.*

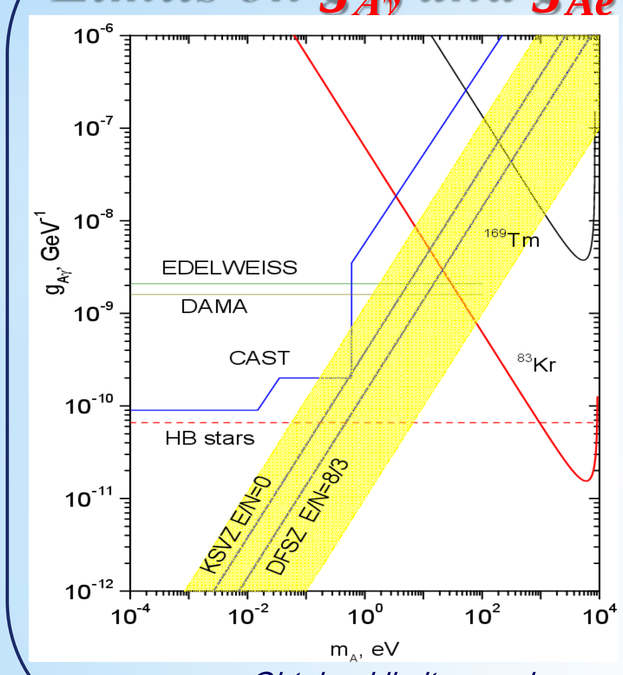
$$\frac{\omega_A}{\omega_\gamma} = \frac{1}{2\pi\alpha}\frac{1}{1+\delta^2}\left[\frac{g^0_{AN}\beta+g^3_{AN}}{(\mu_0-0.5)\beta+\mu_3-\eta}\right]^2\left(\frac{p_A}{p_\gamma}\right)^3$$

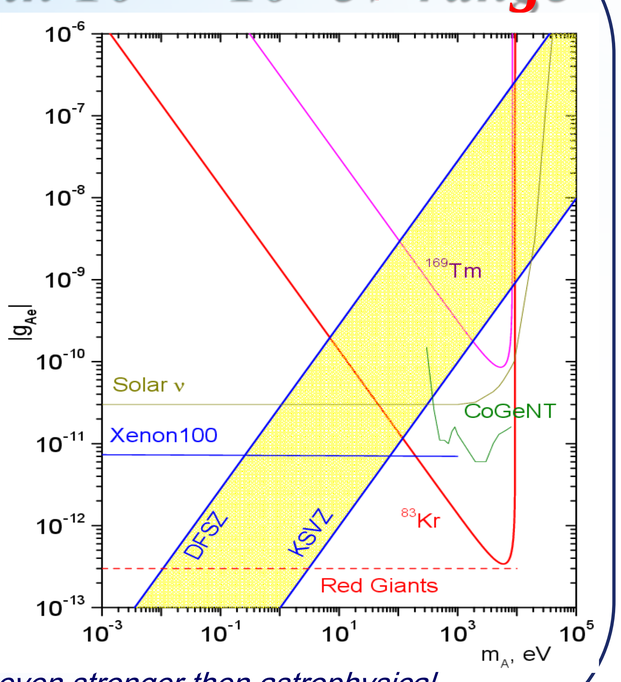
The ratio of the nuclear transition probability with the emission of an axion ω_A to the probability of magnetic type transition ω_γ

$$\frac{\omega_A}{\omega_\gamma} = 1.48\,(g^0_{AN} - g^3_{AN})^2(p_A/p_\gamma)^3$$

The detection probability of the axions is depends on the product $g^2_{A\gamma}\times g^2_{AN}$ which is bigger than $g^4_{A\gamma}$ for small $g_{A\gamma}$ values.

Limits on $g_{A\gamma}$ and g_{Ae} in 10^{-4} - 10^4 eV range

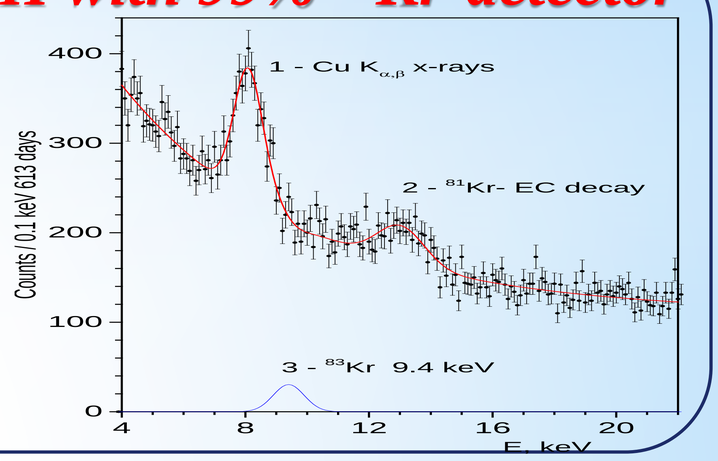




Obtained limits are close or even stronger then astrophysical constraints for axions with mass about 1 keV

613 days of Phase II with 99% ^{83}Kr-detector

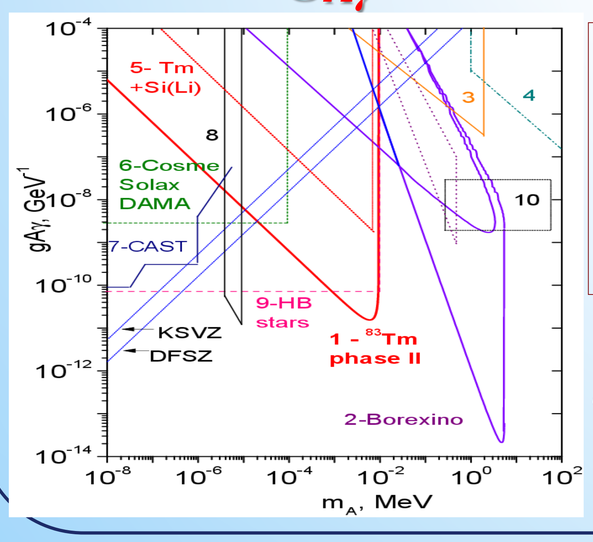
Spectra of Kr-chamber measured during 613 days of livetime before (on the left) and after (on the right) cuts taking in to account front of the signal and amplitude of afterpulses. The peak of 13.5 keV from K-capture of ^{81}Kr is in 1.2×10^3 times less intensive than Phase I results. Since the proportional chamber is prepared from cupper and Cu X-rays are clear visible.



Limits on axion-nucleon coupling g_{AN}

The obtained model independent upper limit on axion-nucleon couplings allowed us to set the new upper limit on the hadronic axion mass with the generally accepted values S=0.5 and z=0.56: $|g^3_{AN} - g^0_{AN}| \le 8.4\times10^{-7}$, $m_A \le 65$ eV at 95% C.L.

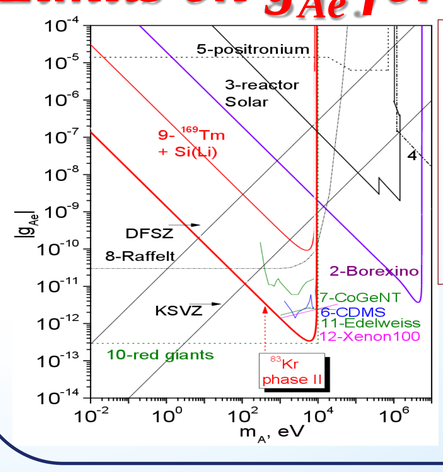
Limits on $g_{A\gamma}$ in 10 meV - 10 MeV m_A range



1 – 83Kr resonant absorption of Primakoff axions; 2 – Borexino, 5.5 MeV axions ;3 – CTF, 478 keV axions; 4 – Reactor experiments; 5 – 169Tm resonant absorptions ; 6 – Cosme, Solax, DAMA ; 7 – CAST; 8 – Tokyo telescope; 9 – HB-stars He burning LT;10 – predictions of SUSY and mirror heavy axion models.

The limit on $|g_{A\gamma}(\text{in GeV}^{-1})\times m_A(\text{in eV})|\le6.3\times10^{-8}$ or $|g_{A\gamma}\times m_A|\le6.3\times10^{-17}$ obtained with ^{83}Kr proportional chamber in comparison with the results of others experiments. KSVZ axion mass is **$m_A \le 12.7$ eV at 95% C.L.**

Limits on g_{Ae} for 10 meV - 10 MeV m_A range



1 – 83Kr resonant absorption of Compton and bremstruhlung axions ; 2 – Borexino, 5.5 MeV axions; 3 – CTF, 478 keV axions and Reactor experiments; 4- beam dump experiments; 5 – ortopositronium decay; 6 – CDMS; 7 – CoGeNT; 8 – solar axion luminosity; 9 – 169Tm resonant absorptions; 10 – red giants; 11 – Edelweiss; 12 – Xenon 100.

The limit on $|g_{Ae}|\times|g^3_{AN} - g^0_{AN}|\le1.78\times10^{-17}$ or $|g_{Ae}\times m_A| \le 1.38\times10^{-9}$ eV obtained with ^{83}Kr proportional chamber in comparison with the results of others experiments.

1. Yu.M. Gavrilyuk, A.N. Gangapshev, A.V. Derbin, I.S. Drachnev, V.V. Kazalov, V.V. Kobychev, V.V. Kuz'minov, V.N. Muratova, S.I. Panasenko, S.S. Ratkevich, D.A. Semenov, D.A. Tekueva, E.V. Unzhakov, S.P. Yakimenko, New Limits on Axion-Photon Coupling Constant for Solar Axions, JETP Letters, 2018, Vol. 107, No. 10, pp. 617–622.
1. Yu.M. Gavrilyuk, A.N. Gangapshev, A.V. Derbin, I.S. Drachnev, V.V. Kazalov, V.V. Kobychev, V.V. Kuz'minov, V.N. Muratova, S.I. Panasenko, S.S. Ratkevich, D.A. Semenov, D.A. Tekueva, E.V. Unzhakov, S.P. Yakimenko, New Experiment on Search for the Resonance Absorption of Solar Axion Emitted in the M1 Transition of 83Kr Nuclei, JETP Letters, 2015, Vol. 101, No. 10, pp. 664–669.
2. Yu.M. Gavrilyuk, A.M. Gangapshev , A.V. Derbin, V.V. Kazalov , H.J. Kim, Y.D. Kim, V.V. Kobychev, V.V. Kuzminov, Luqman Ali, V.N. Muratova, S.I. Panasenko, S.S. Ratkevich, D.A. Semenov, D.A. Tekueva, S.P. Yakimenko, E.V. Unzhakov, First result of the experimental search for the 9.4 keV solar axion reactions with 83Kr in the copper proportional counter, Phys.Part.Nucl. 46 (2015) no.2, 152-156