Search for Resonant Absorption of Solar Axions by Atomic Nuclei.

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in collaboration with

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Introduction

- Interaction of axions with ordinary matter is described in terms of effective coupling constants: g_{AN}, g_{Ae}, $g_{A\gamma}$.
- The idea of experimental search for resonant absorption of the axions by atomic nuclei is based on assumption that through the coupling of axions with nucleons (g_{AN}), they can undergo resonant absorption and emission in nuclear transitions of magnetic type.

Sun as the Axion Source

- If axions do exist, the Sun has to be an intense source of these particles.
- **Mechanisms of axion production in the Sun:**
  - **Primakoff conversion** of the photon in the e/m field.
  - M1-type **nuclear transitions**.
  - **Compton effect** and **bremsstrahlung** axions.
- **Experiments performed:**

1. Source: ^{57}**Fe** (14.4 keV)

Detection: Resonant absorption by ^{57}**Fe** target.

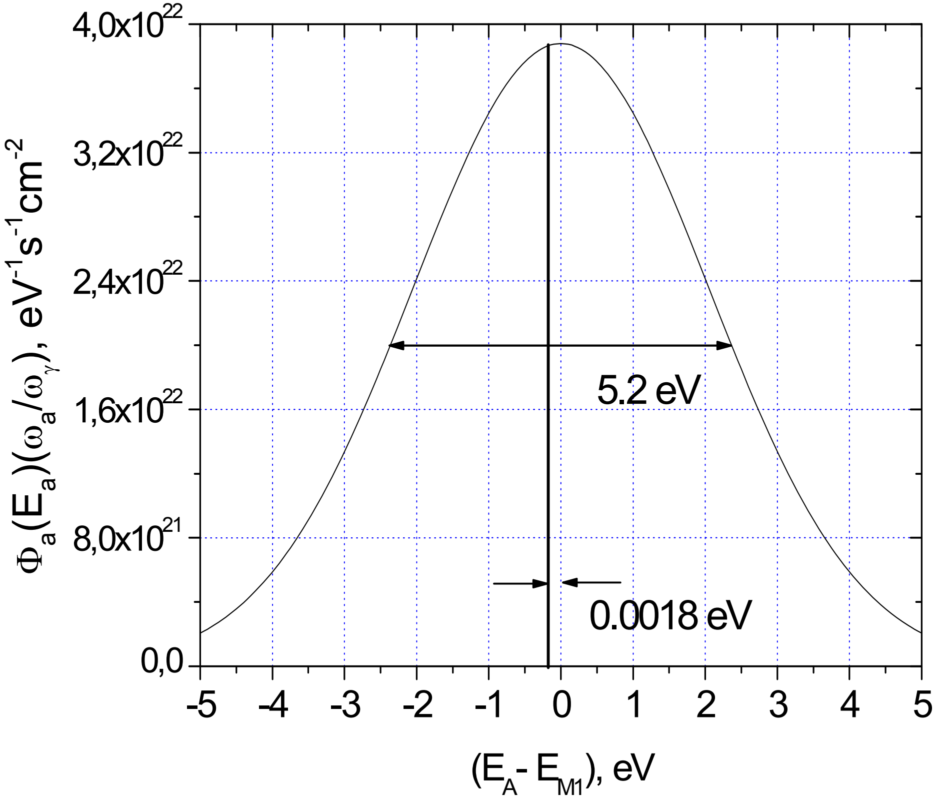
2.1 Source: **Primakoff effect**.

Detection: Resonant absorption by ^{169}**Tm** target.

2.2 Source: **Bremsstrahlung** **+** **Compton effect**.

Detection: Resonant absorption by ^{169}**Tm** target.

^{57}Fe Axion Flux



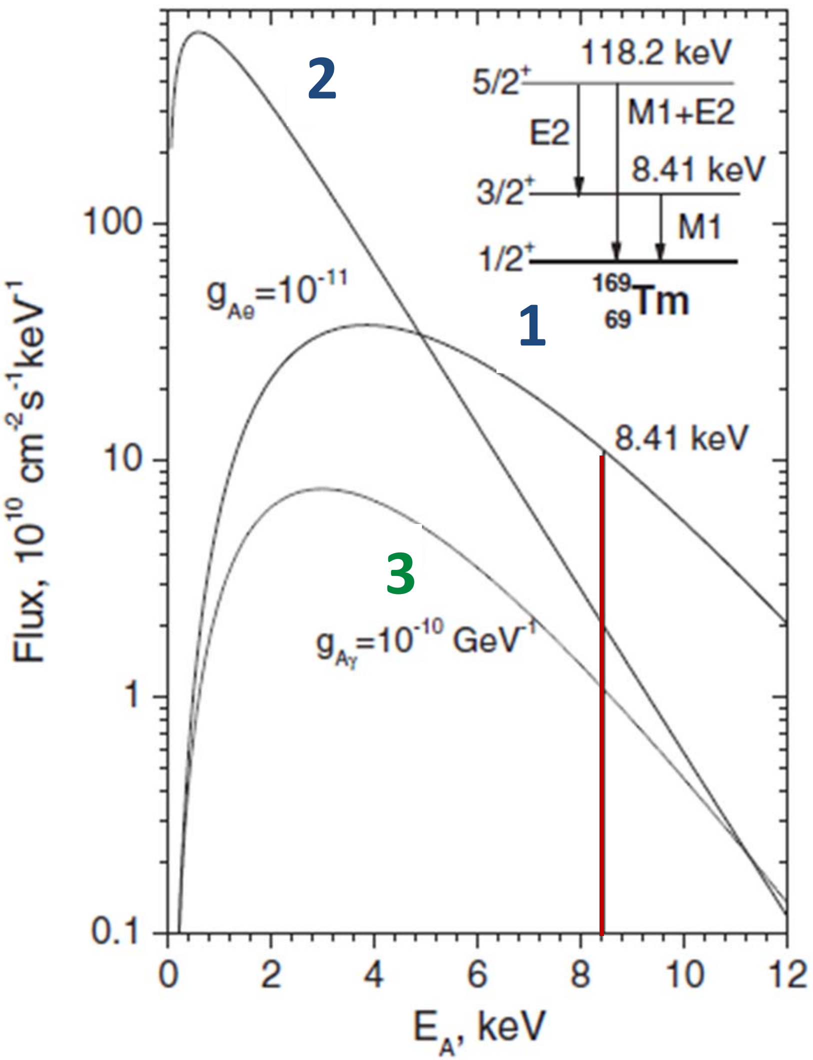
$$\Phi_A = N \frac{2\exp(-E_\gamma / kT)}{1 + 2\exp(-E_\gamma / kT)} \frac{\omega_A}{\tau_\gamma \omega_\gamma}$$

The most intense **mono-chromatic axion line** is caused by M1-transition of the **^{57}Fe** nucleus (g_{AN}).

Thermal widening creates a Gaussian spectrum with σ = 2.2 eV.

The energy of the recoil nucleus is 0.0018 eV which is negligibly small compared to the width of the Gaussian.

Axion Flux



1. **Compton process (g_{Ae})**

$$\frac{d\Phi_A}{dE_A}(E_A) = \frac{1}{R_\odot^2}\int_0^{R_\odot}\int_{E_A}^{\infty}\frac{dN_\gamma}{dE_\gamma}\frac{d\sigma^c}{dE_A}dE_\gamma N_e(r)r^2dr.$$

2. **Bremsstrahlung (g_{Ae})**

$$\frac{d\Phi_A}{dE_A} = \frac{1}{R_\odot^2}\int_0^{R_\odot}\int_{E_A}^{\infty}\frac{dN_e}{dE_e}v_e\frac{d\sigma^b}{dE_A}dE_e\sum_{Z,A}Z^2N_{Z,A}r^2dr,$$

A. Derbin et al., Phys. Rev. D 83, 023505 (2011)

3. **Primakoff conversion**

$$\frac{d\Phi_A}{dE_A} = (g_{A\gamma})^2 \cdot 3.82 \cdot 10^{30}\frac{(E_A)^3}{\exp(E_A/1.103)-1}$$

K. van Bibber et al., Phys. Rev. D39, 2089 (1989).

- These axions could be detected via **resonant absorption by ^{169}Tm** nuclei (8.41 keV).

Resonant Absorption

- The cross-section of the axion resonant absorption is given by the expression similar to that for the photon absorption, multiplied by ω_A/ω_γ – probability ratio.

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

- The ω_A/ω_γ ratio calculated in the long-wave approximation has the following view:

$$\frac{\omega_A}{\omega_\gamma} = \frac{1}{2\pi\alpha}\cdot\frac{1}{1+\sigma^2}\left[\frac{g^0_{AN}\beta + g^3_{AN}}{(\mu_0 - 0{,}5)\beta + \mu_3 - \eta}\right]^2\left(\frac{p_A}{p_\gamma}\right)^3$$

Here, p_γ and p_A - photon and axion momenta,
$\mu_0 = \mu_p + \mu_n \approx 0.88$ and $\mu_3 = \mu_p - \mu_n \approx 4.71$ are isoscalar and isovector nuclear magnetic momenta, β and η are parameters depending on the particular nuclear matrix elements.

Resonant Absorption

- The values $\beta = -1{,}19$ and $\eta = 0{,}8$ for M1-transition of ^{57}Fe nucleus were calculated by W.C. Haxton and K.Y. Lee. (Phys. Rev. Lett. 66, 2557 1991)

- In the case of the ^{169}Tm nucleus, which has an odd number of nucleons and an unpaired proton, in the one-particle approximation the values of β and η can be estimated as $\beta \approx 1{,}0$ and $\eta \approx 0{,}5$.

Axion Absorption Rate

In the hadronic axion models (KSVZ), g^0_{AN} and g^3_{AN} constants can be represented in the following form:

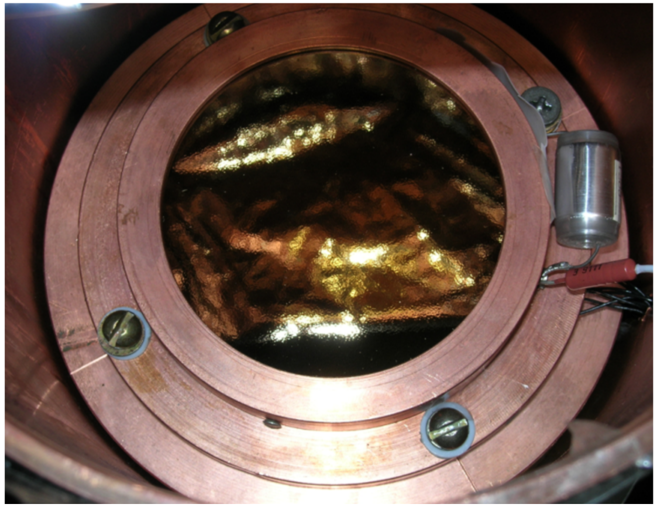
$$g^0_{AN} = -\frac{m_N}{6 f_A}\left[2S + (3F - D)\frac{1+z-2w}{1+z+w}\right] \qquad g^3_{AN} = -\frac{m_N}{2 f_A}\left[(D+F)\frac{1-z}{1+z+w}\right]$$

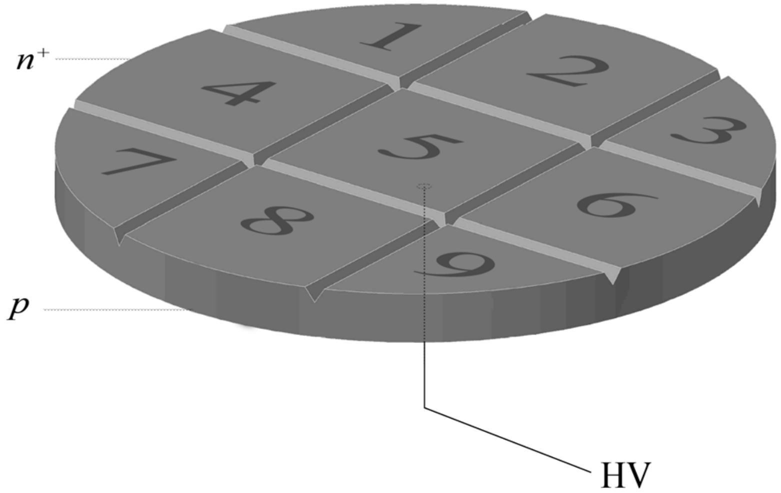
where $m_N \approx 939$ MeV is the nucleon mass. Axial coupling parameters F and D are obtained from hyperon semileptonic decays with high precision: D = 0.808 ± 0.006, F = 0.462 ± 0.011.

$$R_A = 1.56\cdot 10^{-3}\left(\omega_A/\omega_\gamma\right)^2$$
$$= 5.16\cdot 10^{-3}\left(g^0_{AN}\beta + g^3_{AN}\right)^4\left(p_A/p_\gamma\right)^6$$
$$= 9.29\cdot 10^{-34}\left(m_A\right)^4\left(p_A/p_\gamma\right)^6$$

$$R_A = 104\cdot g^2_{A\gamma}\left(g^0_{AN} + g^3_{AN}\right)^2\left(p_A/p_\gamma\right)^3$$
$$= 4.80\cdot 10^{-13} g^2_{A\gamma} m^2_A\left(p_A/p_\gamma\right)^3$$
$$= 6.64\cdot 10^{-32} m^4_A\left(p_A/p_\gamma\right)^3$$

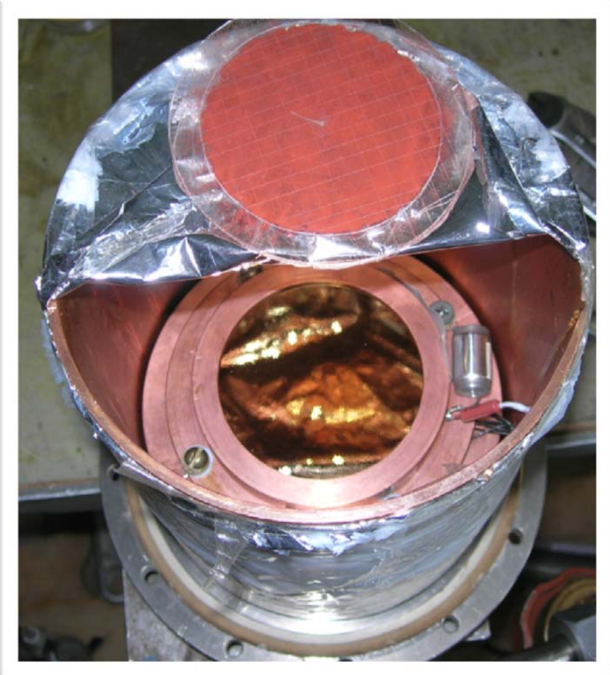
Detector





- Planar **Si(Li)** detector: sensitive area **diameter 66 mm**, **thickness 5 mm**.
- The surface of the detector was divided into **9 sub-sections**, in order to decrease the electric capacity, which leads to the increase in overall energy resolution.
- Incisions were made on the n^+-contact. HV was supplied to the common p-contact.

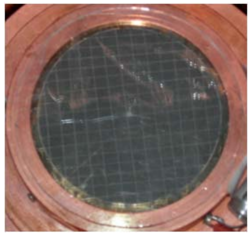
Experimental Setup



- Si(Li) detector was located inside the vacuum cryostat and cooled by the liquid nitrogen. ^{57}Fe and ^{169}Tm targets were and placed 1.5 mm above detector surface inside the cryostat.

^{169}Tm

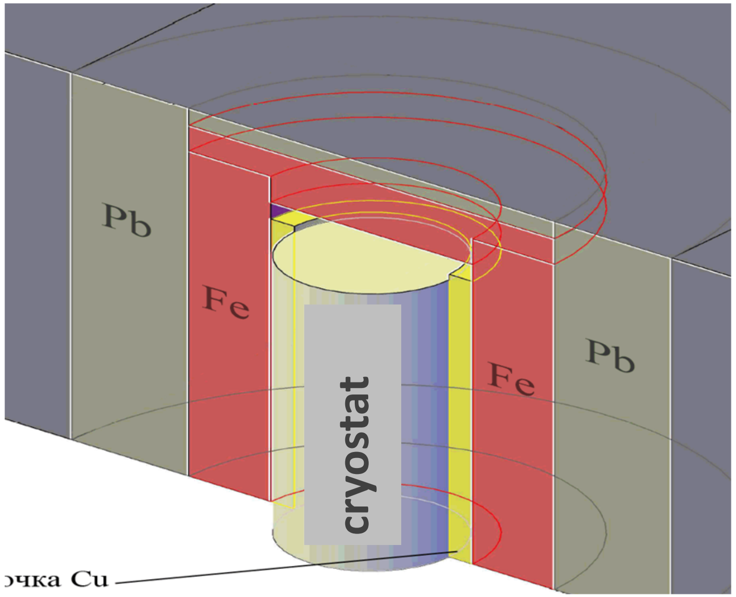
2,00 g



^{79}Fe

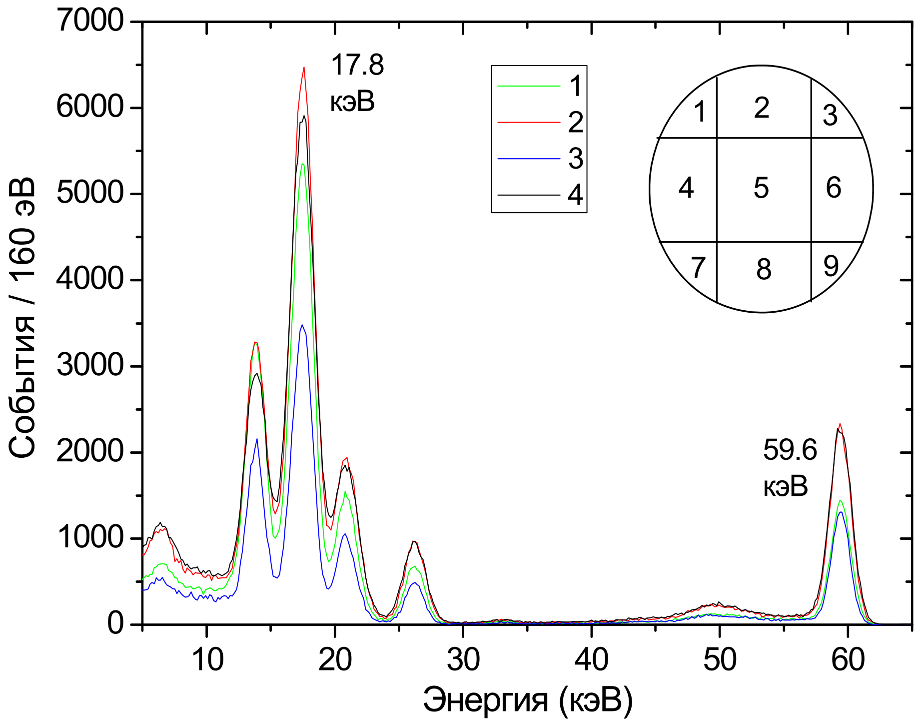
1,26 g

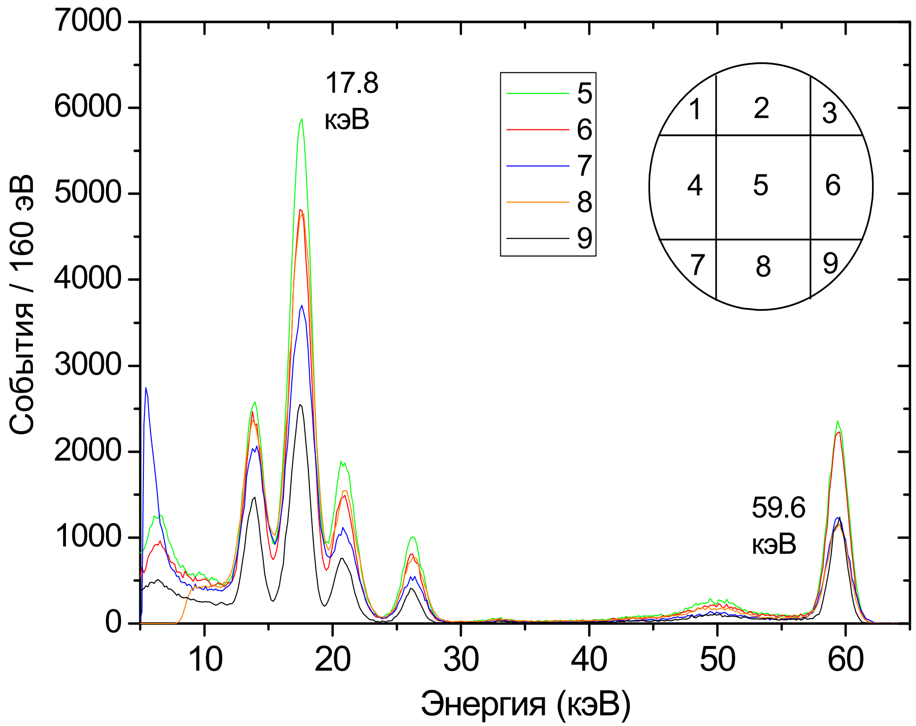
Shielding



- Passive shielding consisted of **10 mm copper** capsule, **35 mm iron** and **50 mm lead** layer. It provided background suppression by the factor of **~500**.
- In order to neutralize effects of cosmic radiation and fast neutrons the active shielding system was used. It consisted of 5 boxes with liquid scintillator that were included in coincidence scheme.

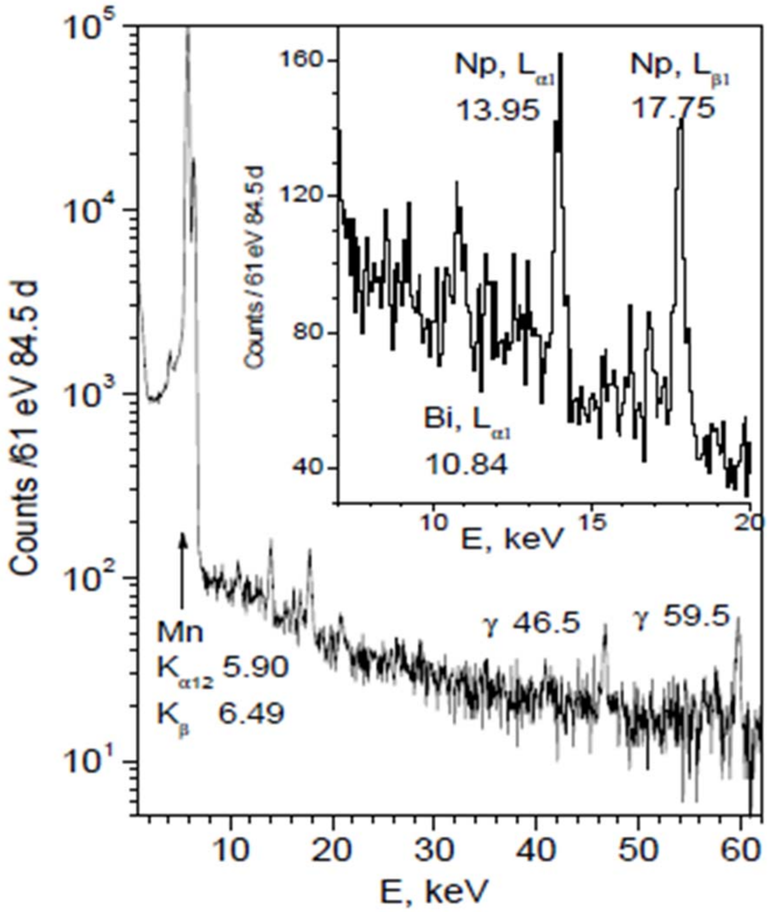
Energy Calibration

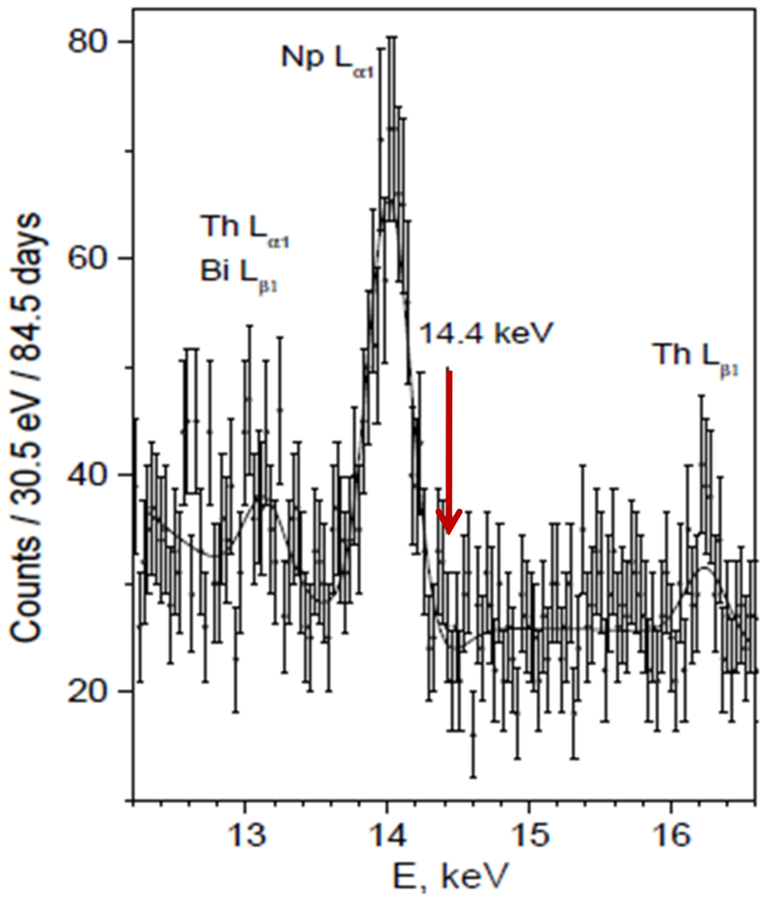




- Energy calibration was performed for each section individually.
- However, in order to obtain the total energy spectrum, data from each section was recalculated into the energy scale.

^{57}Fe Results

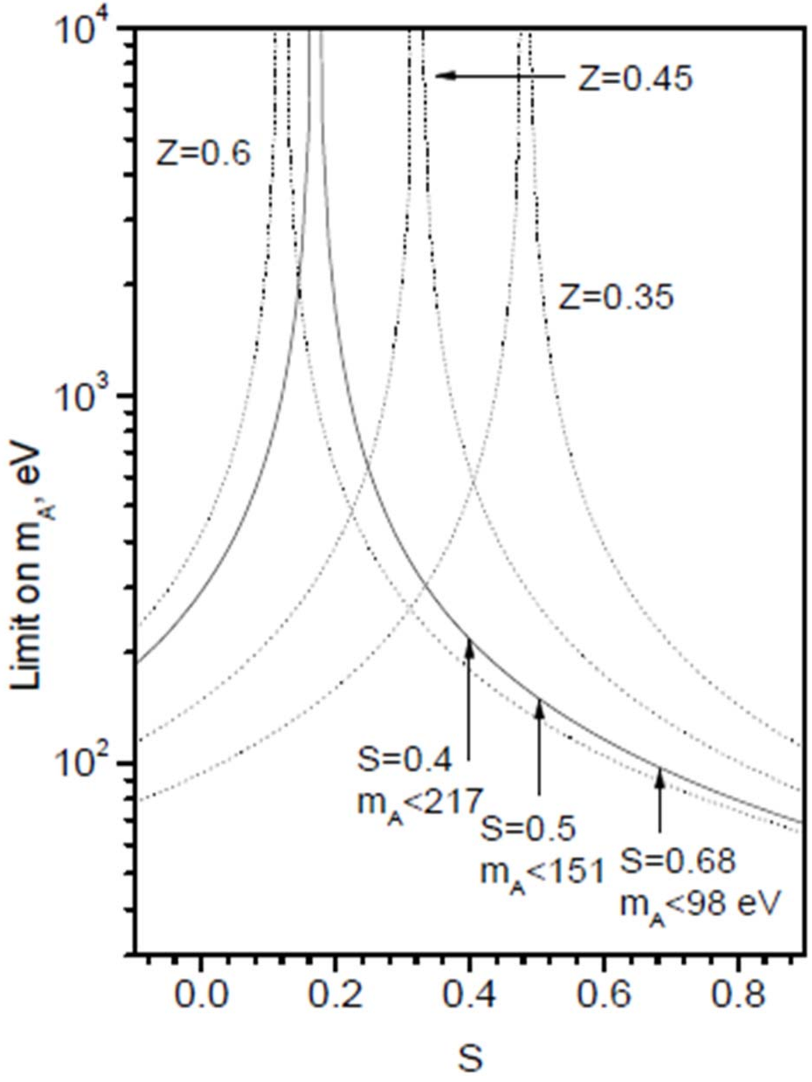




$$\left| -1.19 g_{AN}^{0} + g_{AN}^{3} \right| \leq 3.0 \times 10^{-6}$$

$$m_A \leq 145 \text{ eV}$$

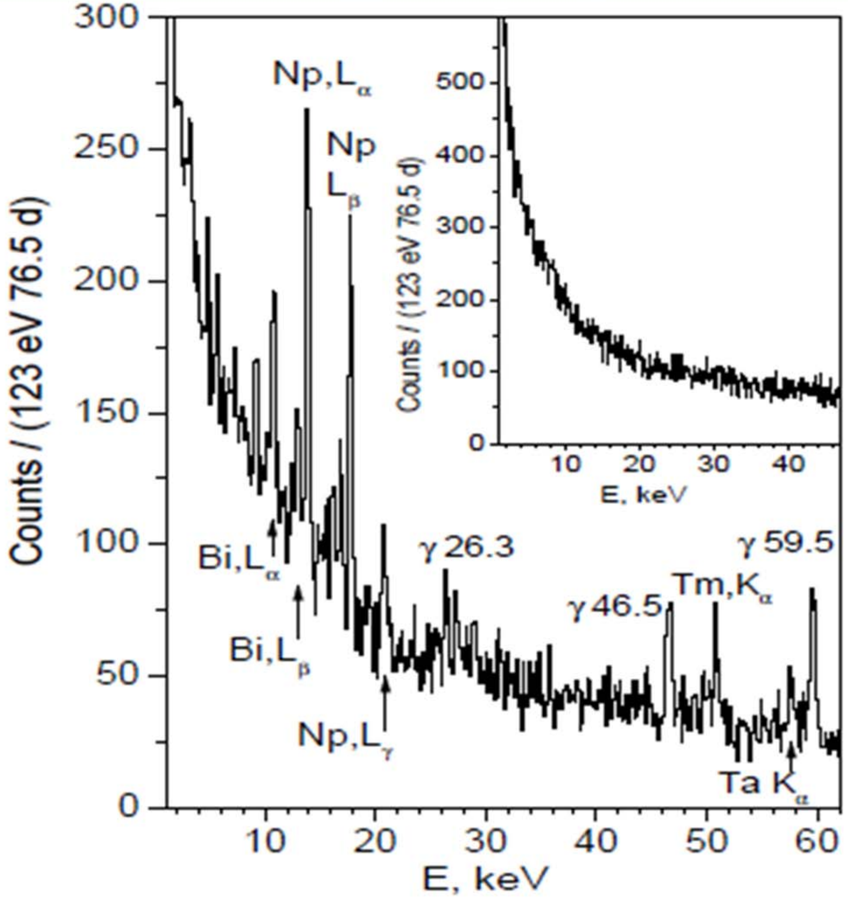
^{57}Fe Results

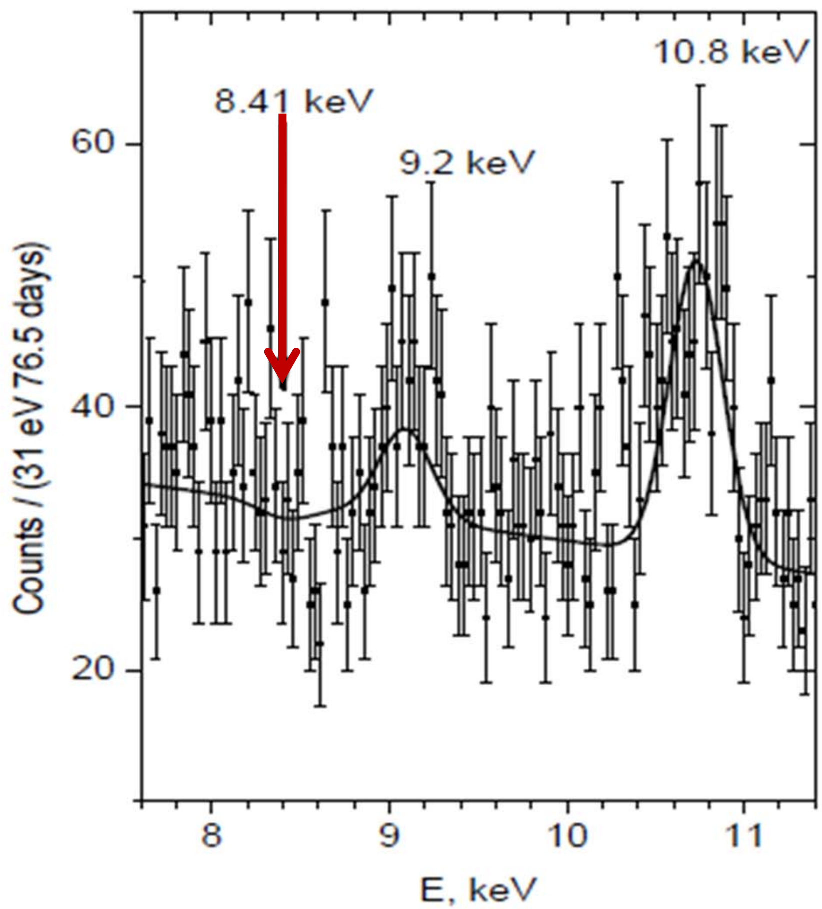


- The main disadvantage of the approach with axions emitted in 14.4 keV M1-transition of ^{57}Fe is that the nuclear-structure-dependent parameter *β* has a negative value.

- Together with a poorly constrained flavor singlet axial-vector matrix element *S*, leads to large uncertainty of the (ω_A/ω_γ) ratio.

^{169}Tm Results

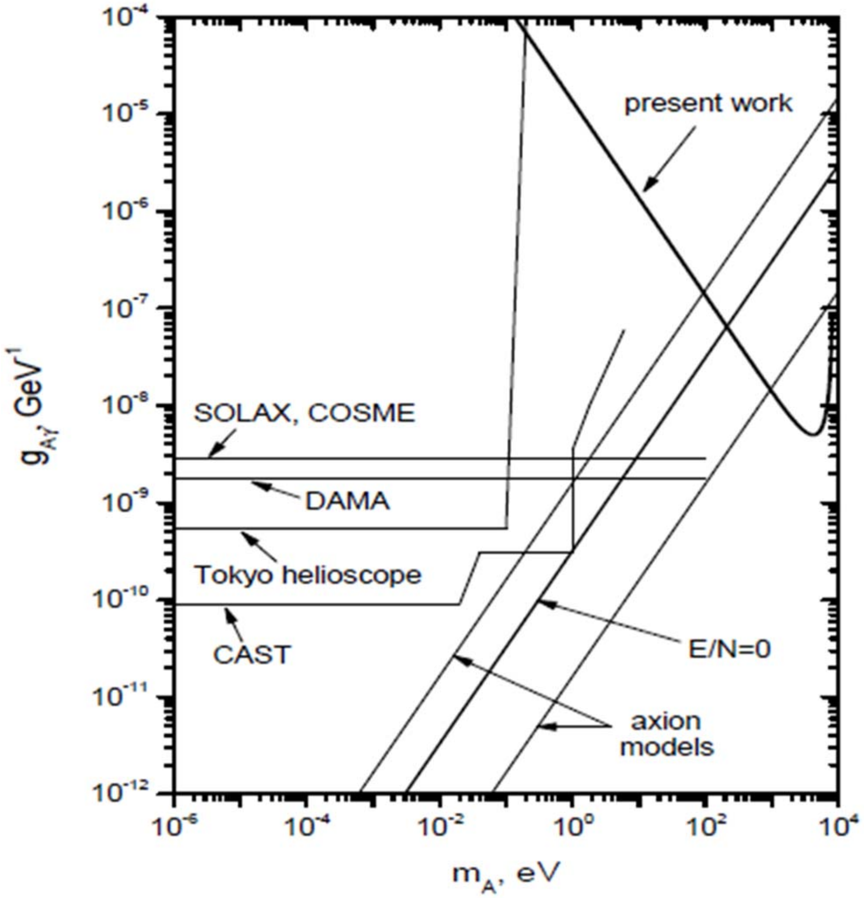


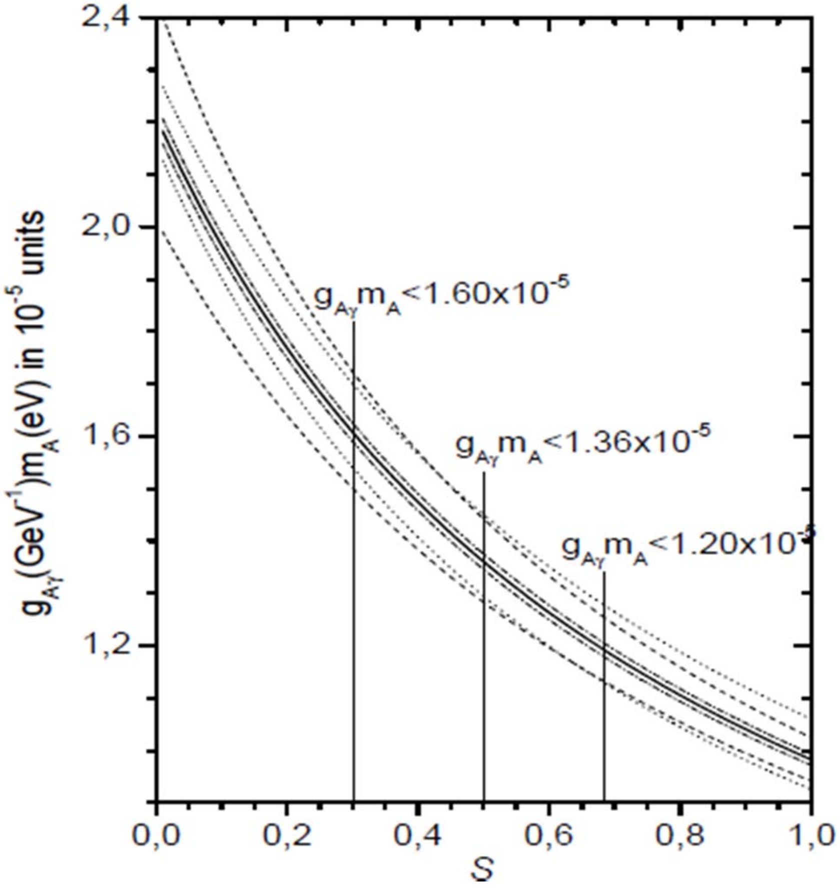


$$g_{A\gamma} \cdot \left|(g_{AN}^{0} + g_{AN}^{3})\right| \leq 7.21 \cdot 10^{-13} \qquad g_{A\gamma}(\mathrm{GeV}^{-1}) \cdot m_A(\mathrm{eV}) \leq 1.06 \cdot 10^{-5}$$

$$m_A \leq 169\,\mathrm{eV}$$

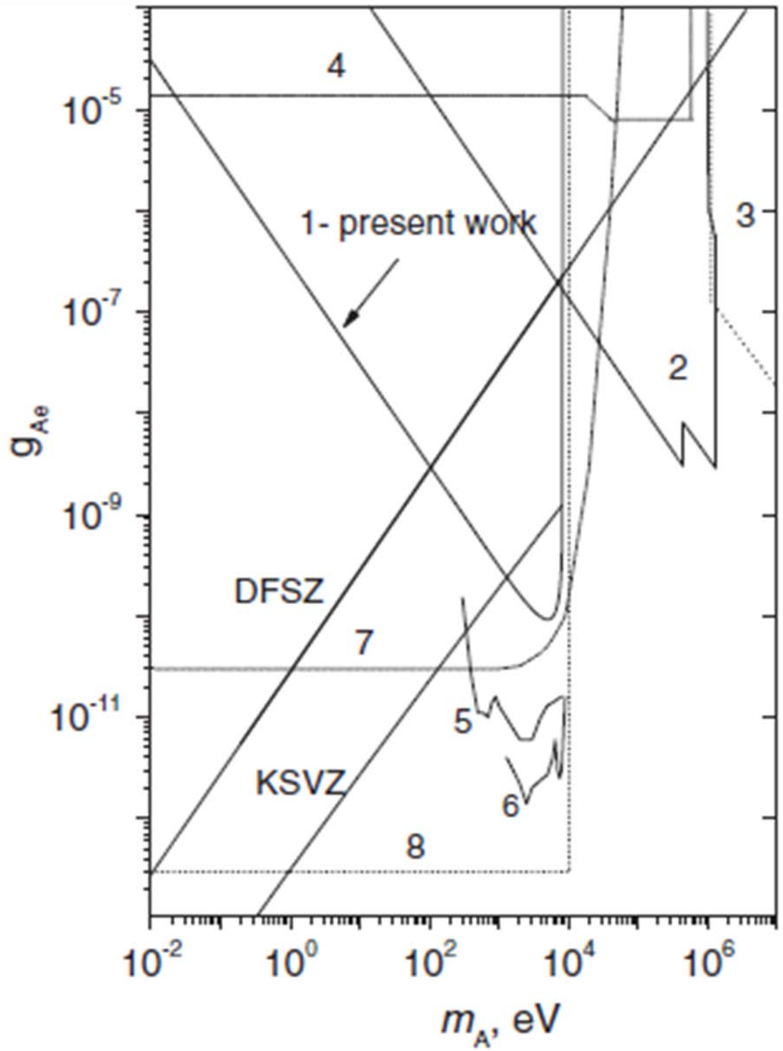
^{169}Tm Results ($g_{A\gamma}$)

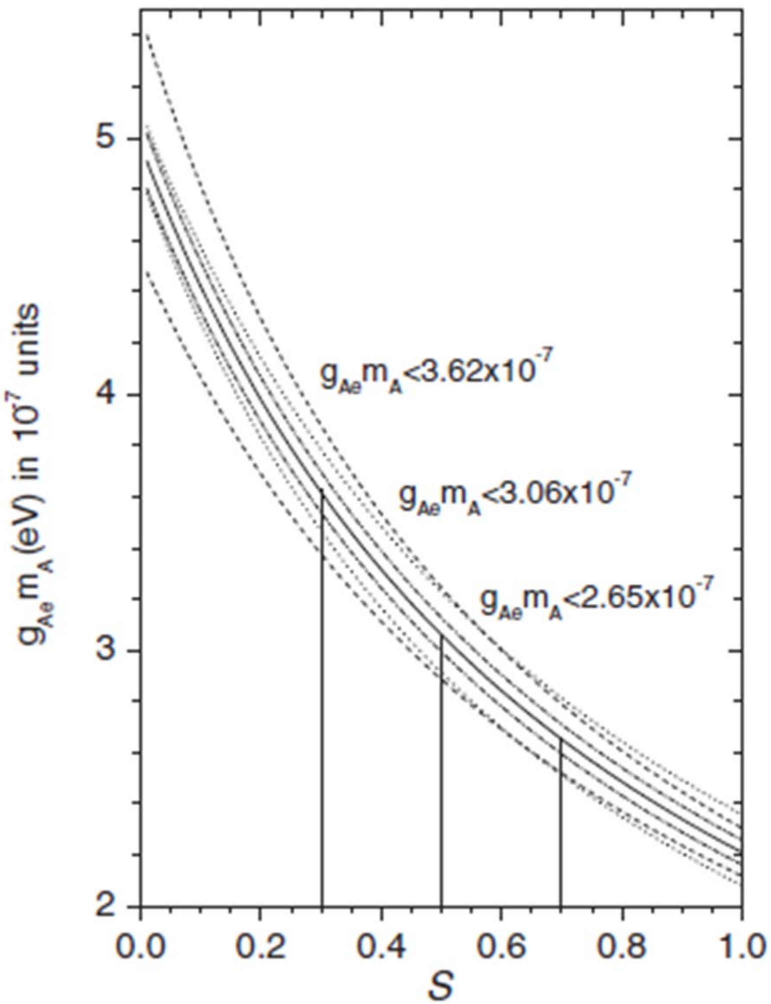




- The obtained limit is applicable to any value of m_A and is new for the m_A > 100 eV.

^{169}Tm Results (g_{Ae})





$$g_{Ae} \times \left|\left(g_{AN}^{0} + g_{AN}^{3}\right)\right| \leq 2.1 \times 10^{-14}$$

$$g_{Ae} \times m_a \leq 3.1 \times 10^{-7} \text{ eV}$$

Conclusions

- The new limits on the axion coupling constants is achieved which, in case of KSVZ model yields axion mass limits of $m_A \leq 169$ eV (90% c.l.) ^{169}Tm, $m_A \leq 145$ eV ^{57}Fe.

- These imits are close to the region of "hadronic axion window" (1-20 eV) that is not covered by astrophysical restrictions or direct laboratory searches.

- The sensitivity of the experiments can be increased further, if we managed to register electrons, produced by the discharge of the excited state, since ^{169}Tm and ^{57}Fe levels have high electron conversion coefficients.

Publications

Axion Source	Detection Method	Obtained m_A limit eV	Публикации
^{57}Fe, 14.4 keV	$A + {}^{57}Fe \rightarrow {}^{57}Fe^*$	145 (95)	Yad. Fiz (2010)
^{57}Fe, 14.4 keV	$A + {}^{57}Fe \rightarrow {}^{57}Fe^*$	151 (90)	Eur. Phys. J. C (2009)
^{57}Fe, 14.4 keV	$A + {}^{57}Fe \rightarrow {}^{57}Fe^*$	360 (95)	JETP Lett. (2007)
$\gamma + (B,E) \rightarrow A$	$A + {}^{169}Tm \rightarrow {}^{169}Tm^*$	169 (90)	Bull. RAS Phys (2010)
$\gamma + (B,E) \rightarrow A$	$A + {}^{169}Tm \rightarrow {}^{169}Tm^*$	191 (90)	Phys. Lett. B. (2007)
$\gamma + e^- \rightarrow e^- + A$ $e^- + Z \rightarrow e^- + Z + A$	$A + {}^{169}Tm \rightarrow {}^{169}Tm^*$	(DFSZ) 105 (KSVZ) 1300 (90)	Phys. Rev D. (2011)

Thank You for Attenion!