“Search for the resonance absorption of solar axions emitted in the M1 transition of Kr-83 and Fe-57 nuclei in the sun”

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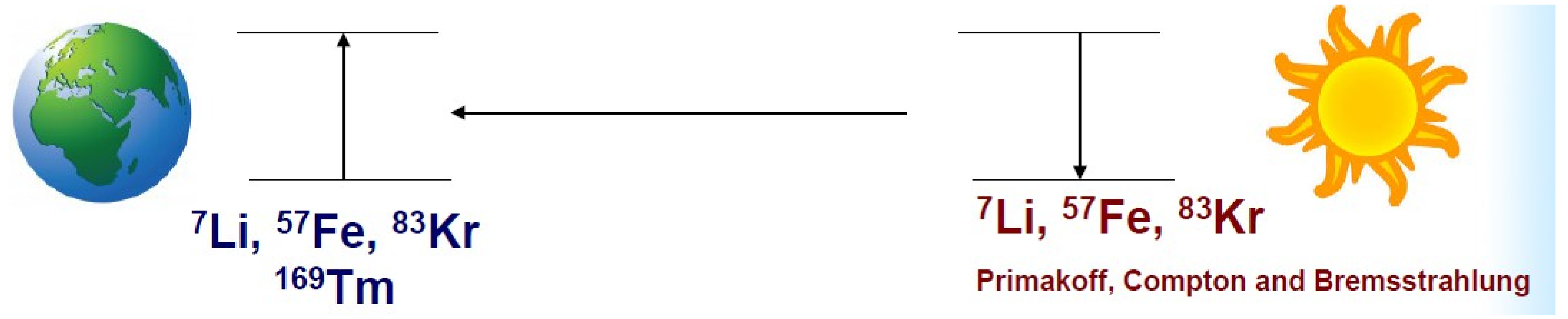
“Axions are among the most fascinating particles on the long list of those proposed but not yet observed or ruled out. Their existence would provide an elegant resolution of the strong CP problem. Even more exciting is the possibility that the missing mass needed to close the universe is composed of axions, and that axions are «cold dark matter» which seems to be necessary for galaxy formation. ...”
Mark Srednicki, “Axion couplings to matter (I). CP-conserving parts”, Nucl. Phys. B260 (1985) 689-700.

“...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. ...”
David B. Kaplan, “Opening the axion window”, Nucl. Phys. B260 (1985) 215-226.

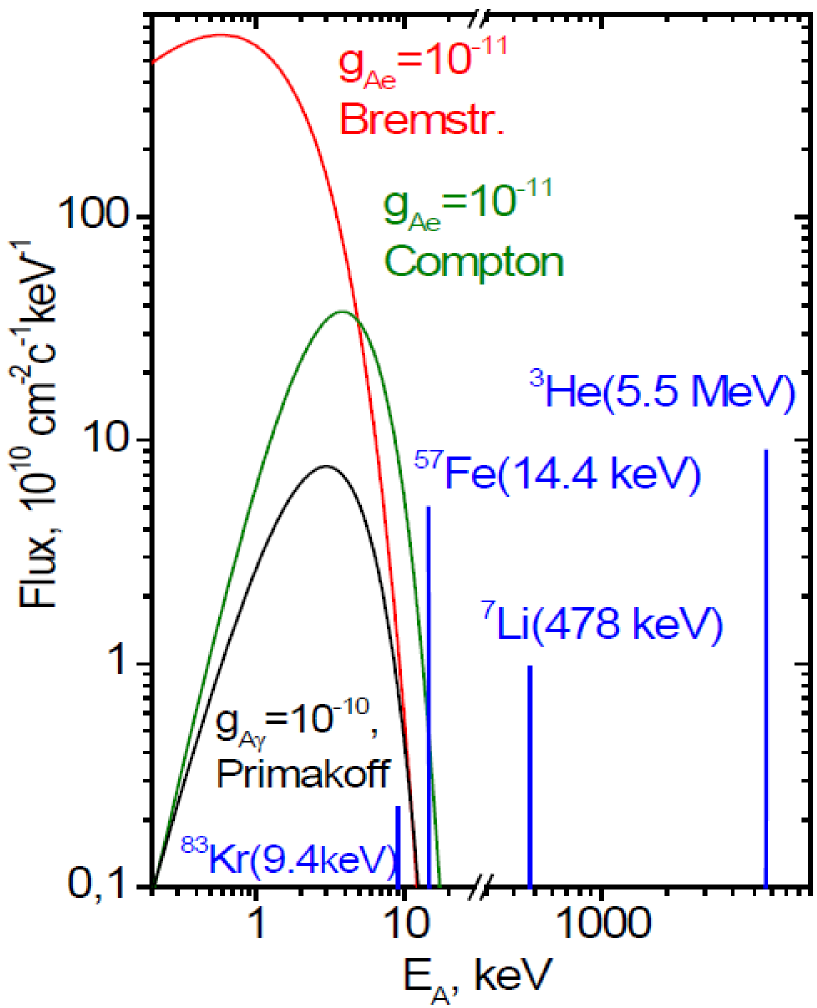
“The most attractive solution of the strong CP problem is to introduce the Peccei-Quinn global symmetry which is spontaneously broken at energy scale f_a. The original axion model assumed that f_a is equal to the electroweak scale. Although it has been experimentally excluded, variant “invisible” axion models are still viable in which f_a is assumed to be very large. ... Such models are referred to as hadronic and Dine-Fischler-Srednicki-Zhitnitskii axions. ....”
Shigetaka Moriyama, “Proposal to search for a monochromatic component of solar axions using ^{57}Fe”, Phys. Rev. Lett. v.75 №8 (1995) 3222-3225.

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 thus some axions have needed energy to excite the nuclide.

Solar axions spectra vs $g_{A\gamma}$, g_{Ae} and g_{AN}



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}):

$^{7}Be+e^{-} \rightarrow Li^{*}+\gamma$; $^{7}Li^{*} \rightarrow {}^{7}Li+A$(478кэВ)

$p + d \rightarrow {}^{3}He + A$ (5.5 МэВ).

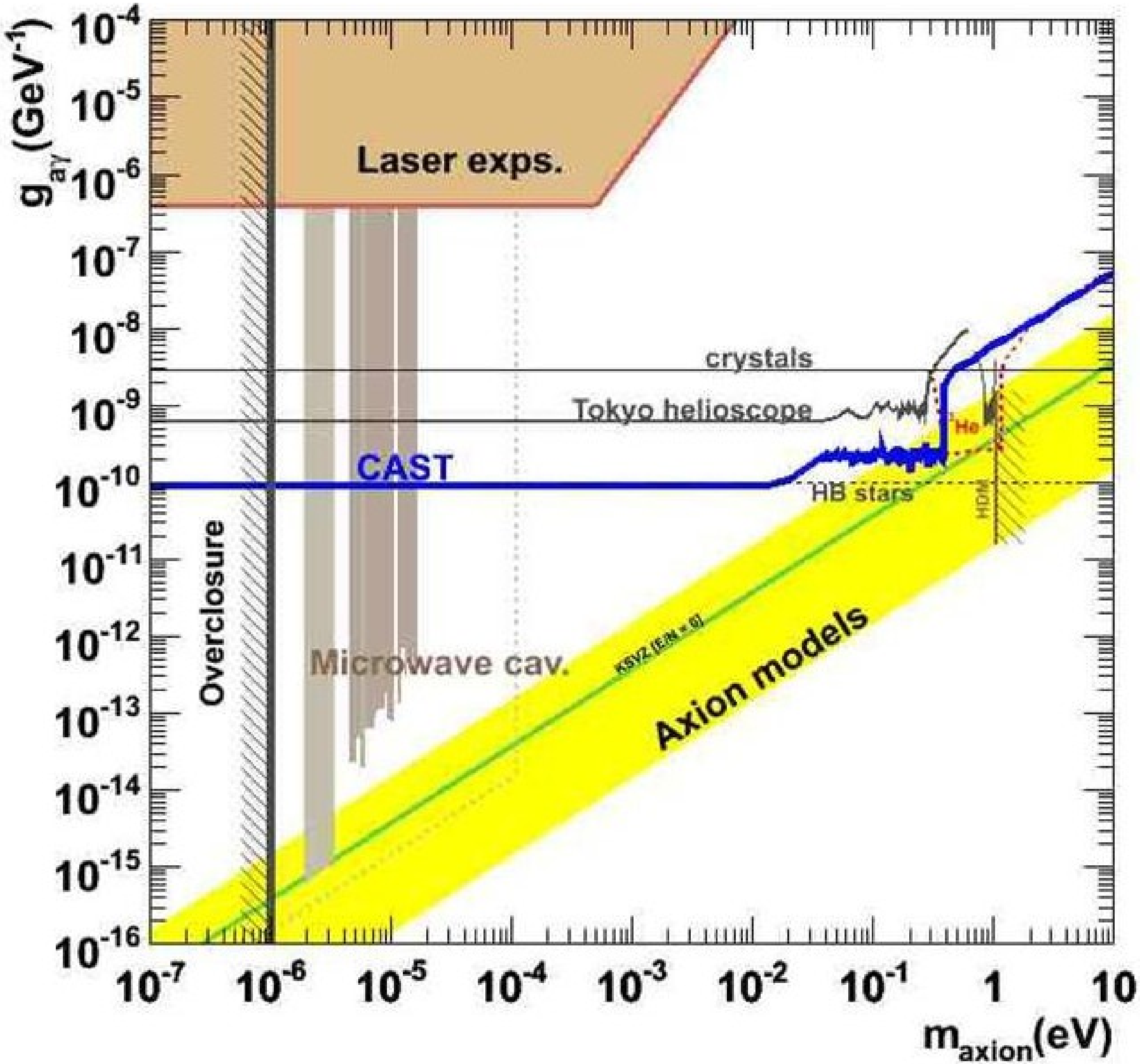
2. Magnetic type transitions in nuclei whose low-lying levels are excited due to high temperature in the Sun(^{57}Fe, ^{83}Kr)(g_{AN})

3. Primakoff conversion of photons in the electric field of solar plasma($g_{A\gamma}$).

4. Bremsstrahlung: $e+Z(e) \rightarrow Z+A$.(g_{Ae})

5. Compton process :$\gamma+e \rightarrow e+A$.(g_{Ae})

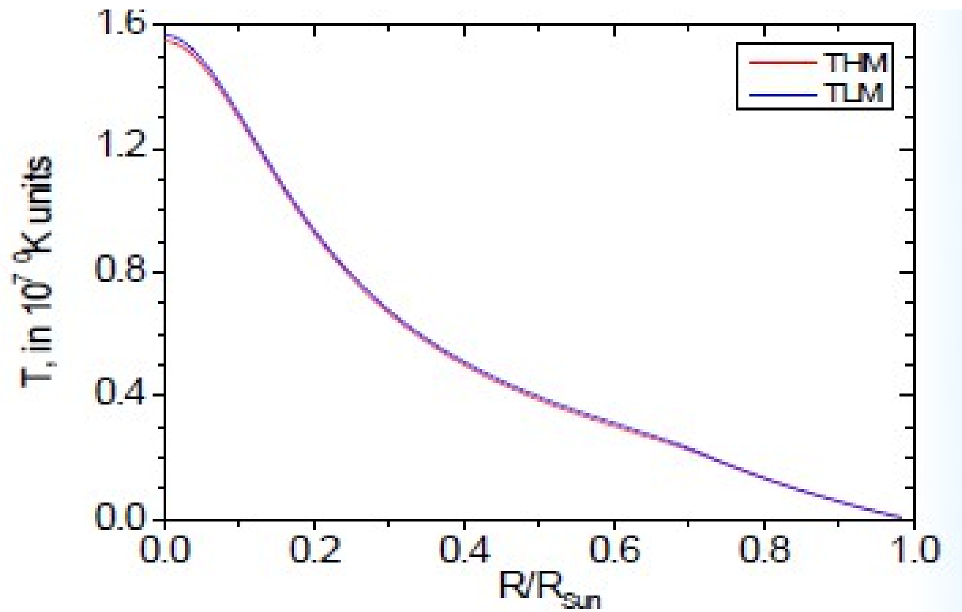
6. axio-recombination: $e + I \rightarrow I^{-} + A$ and axio-deexcitation: $I^{*} \rightarrow I + A$. PRD 83 023505 (2011) CAST 1302.6283, 1310.0823



$g_{a\gamma}$ (GeV^{-1})
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
Laser exps.
crystals
Tokyo helioscope
CAST
HB stars
He
HDM
Overclosure
Microwave cav.
Axion models
KSVZ [E/N = 0]
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
m_{axion}(eV)

Flux of solar ^{83}Kr axions

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



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

$$\Phi_A(E_{M1}) = 5.97 \times 10^{23} \left(\frac{\omega_A}{\omega_\gamma} \right) \text{cm}^{-2}\text{s}^{-1}\text{keV}^{-1}$$

$$m_a = \frac{\sqrt{z}}{1+z} \frac{f_\pi m_\pi}{f_a} = 1\text{eV} \frac{\sqrt{z}}{1+z} \frac{1.3 \cdot 10^7}{f_a / GeV}$$

where m_π и f_π – mass and decay constant of neutral pion, $z=m_u/m_d$=0.56 – quark mass ratios.

$f_\pi \cong$ 93 MeV.

Resonant absorption by ^{83}Kr nucleus

$$\sigma(E_A)=2\sqrt{(\pi)}\,\sigma_{0\gamma}\exp\left[\frac{-4(E_A-E_{M1})}{\Gamma^2}\right]\frac{\omega_A}{\omega_\gamma}$$

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

where δ – quenching factor for M1 transition, $\alpha \approx 1/137$, $\mu_0 \approx 0.88$ and $\mu_3 \approx 4.71$ – izoscalar and izovector nuclear magnetic moments, β=-1 and η=0.5 – nuclear matrix constants.

$$g_{AN}^0=-7.8\cdot10^{-8}\left(\frac{6.2\cdot10^6}{f_a/GeV}\right)\left(\frac{3F-D+2S}{3}\right)$$

$$g_{AN}^3=-7.8\cdot10^{-8}\left(\frac{6.2\cdot10^6}{f_a/GeV}\right)\left((D+F)\frac{1-z}{1+z}\right)$$

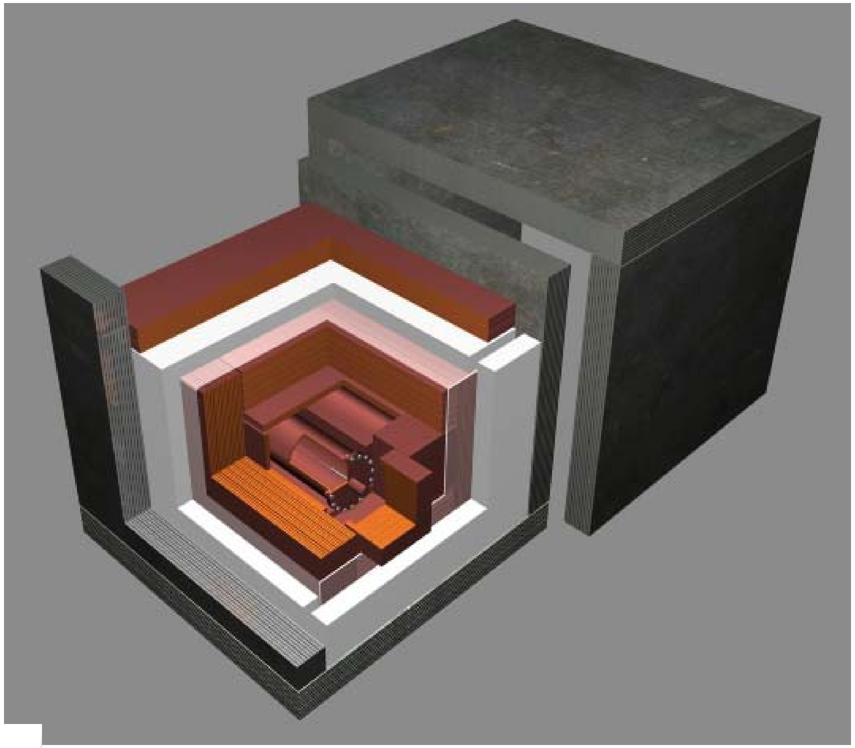
$$R[g^{-1}day^{-1}]=4.23\times10^{21}\left(\frac{\omega_A}{\omega_\gamma}\right)^2=$$

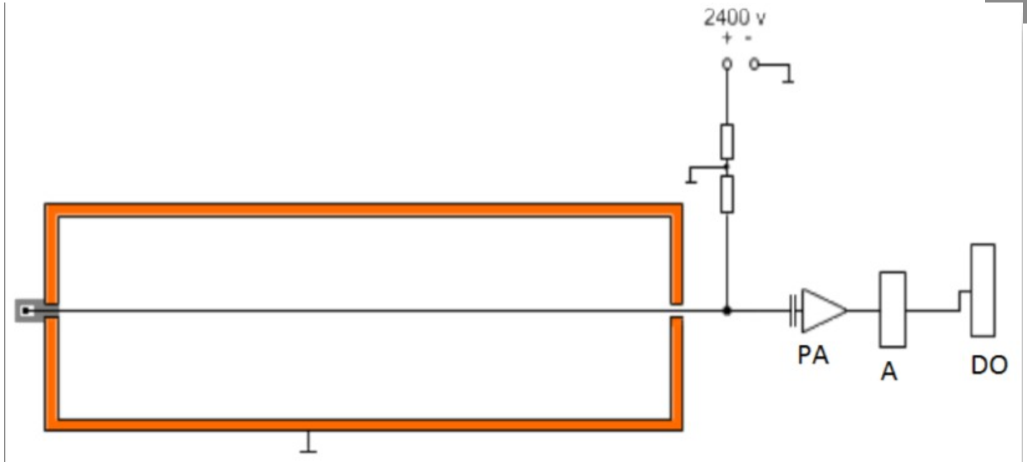
$$=8.53\times10^{21}\left(g_{AN}^3-g_{AN}^0\right)^4\left(\frac{p_A}{p_\gamma}\right)^6=$$

$$=2.41\times10^{-10}\,m_A^4\left(\frac{p_A}{p_\gamma}\right)^6$$

Experimental Setup

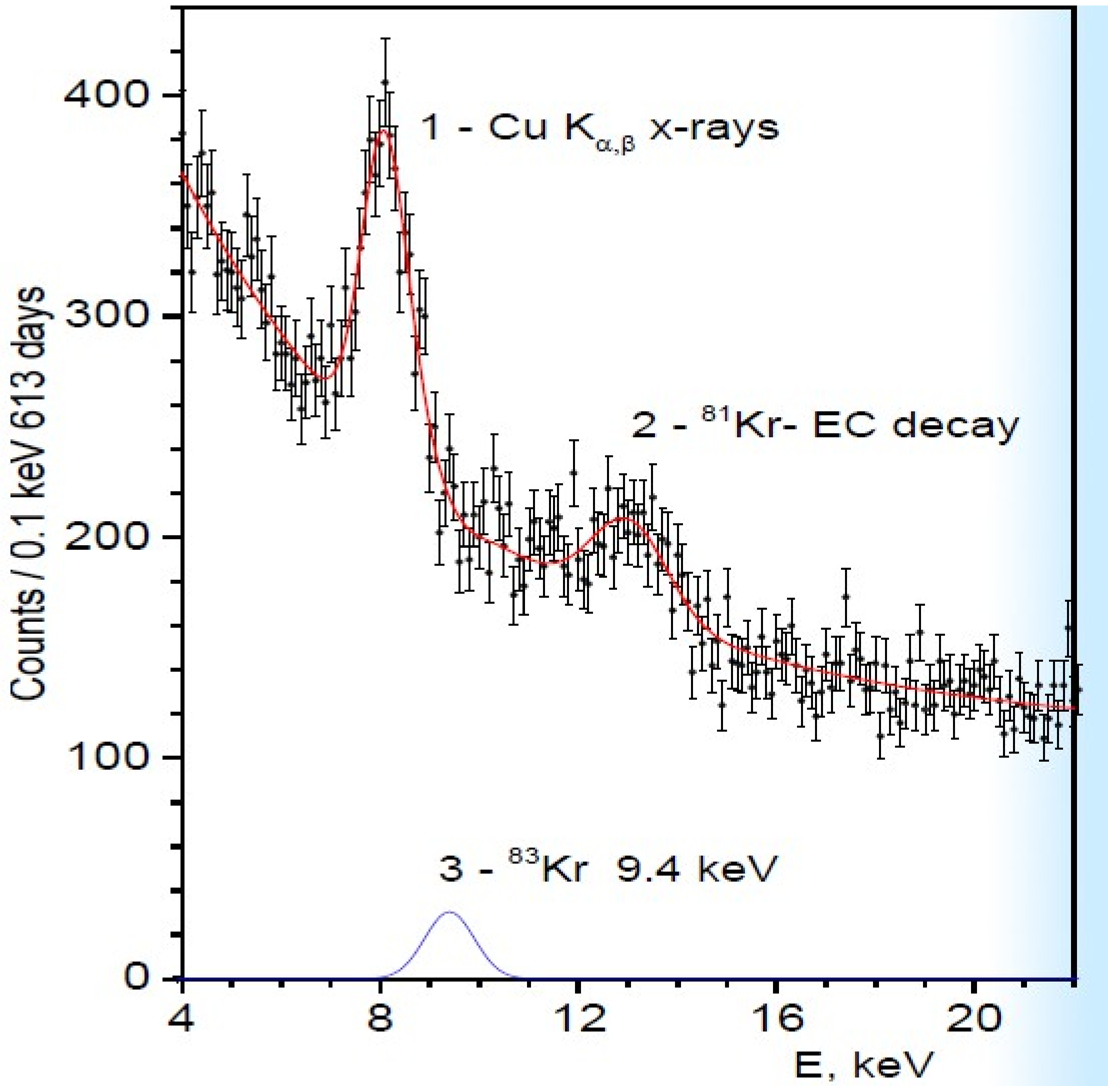
Detector	**Proportional counter**
Shield	**23cm Pb, 8cm PE, 20cm Cu**
Working gas	**99.9% Kr-93**
Diameter (case)	**134 mm**
Anode (gold coated tungsten)	**10 µm**
Fidutial length	**595 mm**
Gas pressure	**1.8 at**





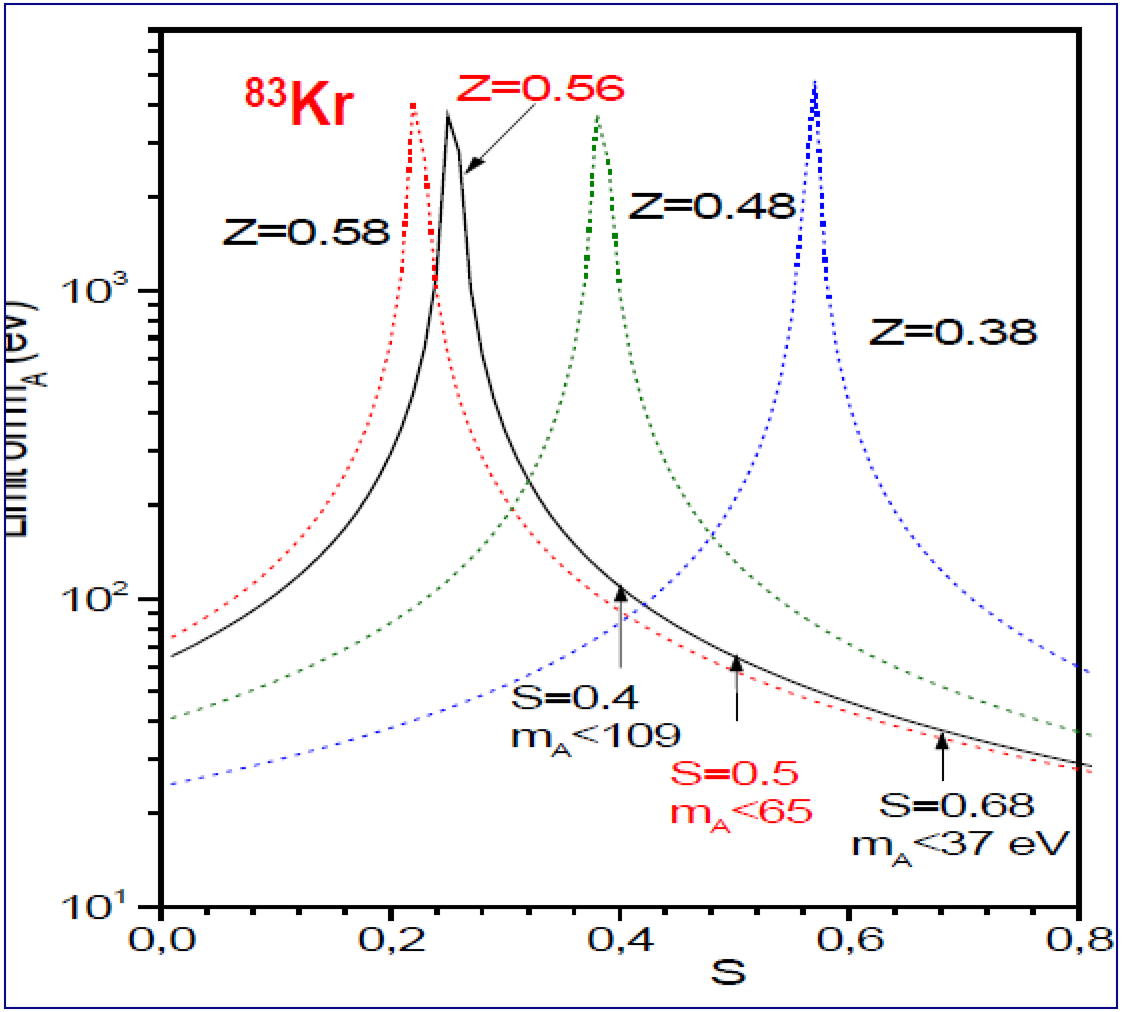
PA – ***Preamplifier***
A1 – Amplifier
DO – FADC (Digitizer)

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



Spectra of Kr-chamber measured during 613 days of livetime. The peak of 13.5keV from K-capture of ^{81}Kr is in $1.2\text{x}10^3$ times less intensive than PhaseI results. Since the proportional chamber is prepared from cupper and Cu X-rays are clear visible.

Results:



$$|g^3_{AN} - g^0_{AN}| \leq 8.4 \times 10^{-7},$$

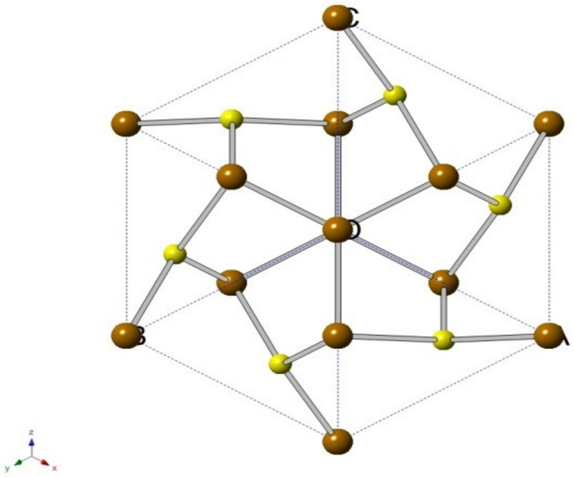
$$m_A \leq 65 \text{ eV at } 95\% \text{ C.L.}$$

Nuclide	Abundance in heliosphere, $\log_{10}s$ ($\log_{10}s(H)=12.00$)	1-st excitation level, keV (transition type)
Fe-57	5,78	14,41 (M1+E2)
Kr-83	2,34	9,40 (M1+E2)
Li-7	0,42	477,6 (M1+E2)

Overview of other experimental results

	Article (nuclide)	Результат
1	M. Krcmar et al., arXive:nucl-ex/9801005v2 (Fe-57)	≤745 eV
2	K. Jakovčić et al., arXive:nucl-ex/0402016v1 (Kr-83)	≤5,5 keV
3	A.V. Derbin et al., Eur. Phys. J. C (2009) 62:755-760 (Fe-57)	≤159 eV
4	F.A. Danevich et al., arXive:nucl-ex/0811383v2 (Fe-57)	≤1,6 keV
5	P. Belli et al., Nucl. Phys. A (2008) 806:388-397 (Li-7)	≤13,9 keV
6	Yu.M. Gavrilyuk, et al., JETP Letters (2015,) (Kr-83)	≤99,5 eV
7	***This work (Kr-81)***	***≤65 eV***
	W.C. Haxton and K.Y. Lee, Phys. Rev. Lett. (1991)	≈3÷20eV

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.

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 semi-conducting regions can be found within single naturally occurring crystals

Monocrystall has a cubic form.

Resistivity (natiral crystalls): $10^{-5} \div 10^{0}$ Om*m

New detector for Solar hadronic axions

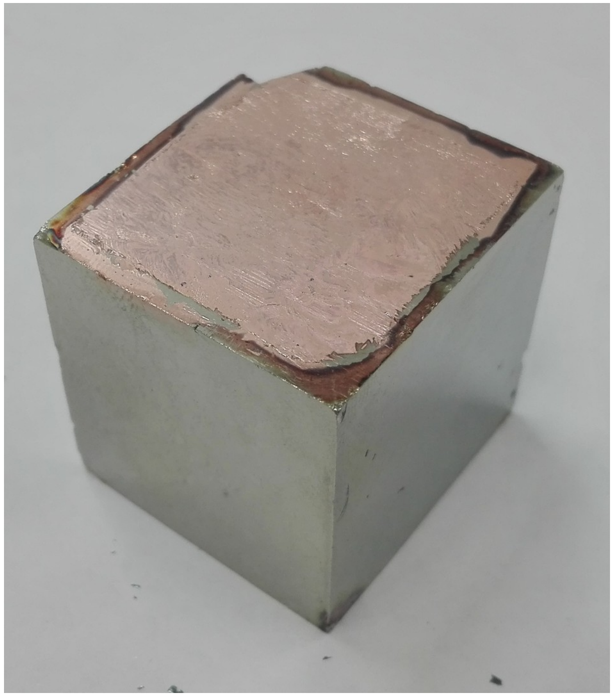
Detector: semiconductor detector based on Pyrite

Hall mobility: 0.5÷3 $cm^2/V*s$

Electron mobility: 10÷50 $cm^2/V*s$

Isotope abundance: ^{54}Fe-5,845%, ^{56}Fe-91,754%,

^{57}Fe-2,119%, ^{58}Fe-0,282%



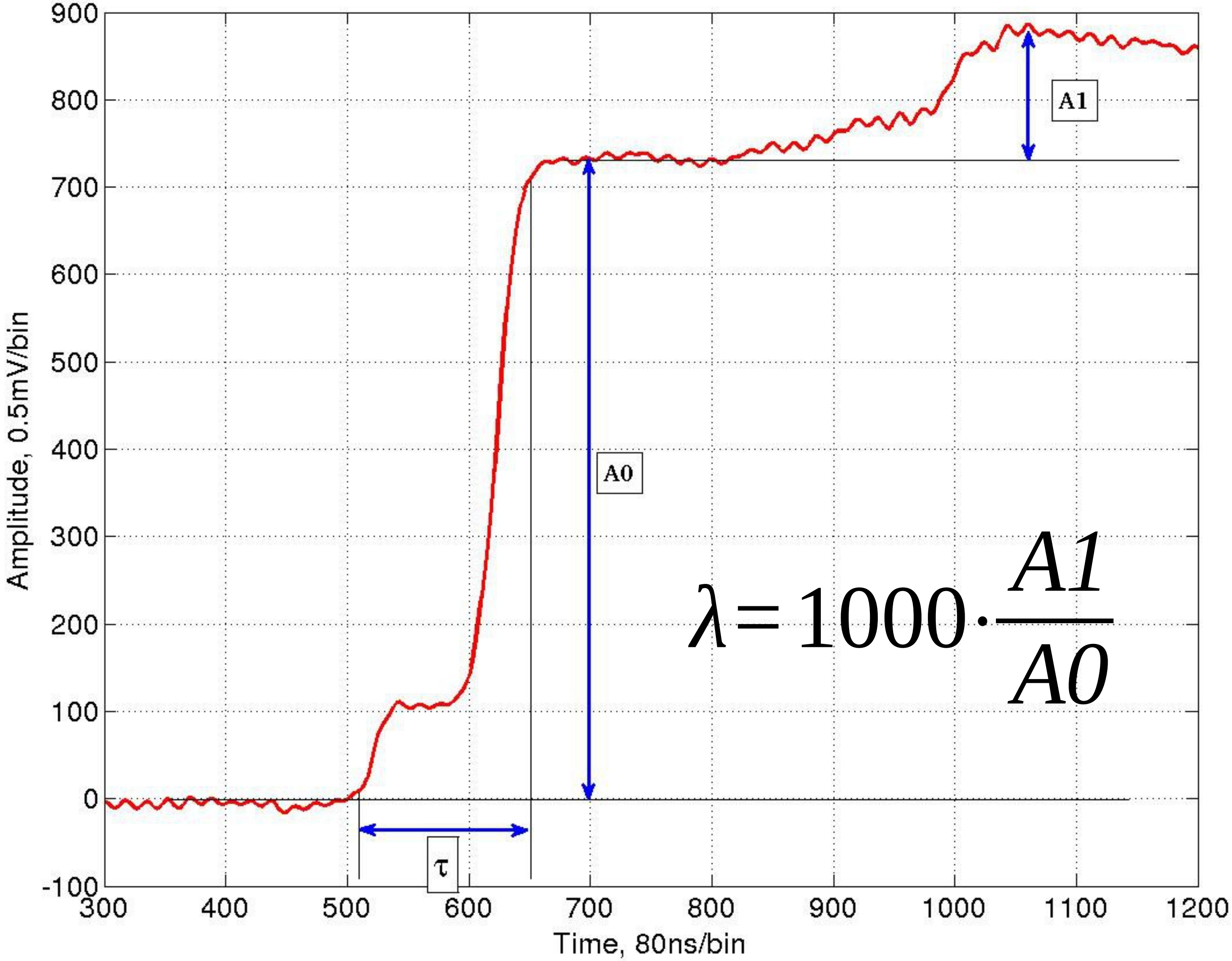
$$R\left[g^{-1}day^{-1}\right]=8.48\times10^{-7}m_A^4\left(\frac{p_A}{p_\gamma}\right)^6$$

$$\frac{R_{Fe-57}}{R_{Kr-83}}=3.51\times10^3$$

goal: $S\left(m_A\right)\simeq 1\,eV$

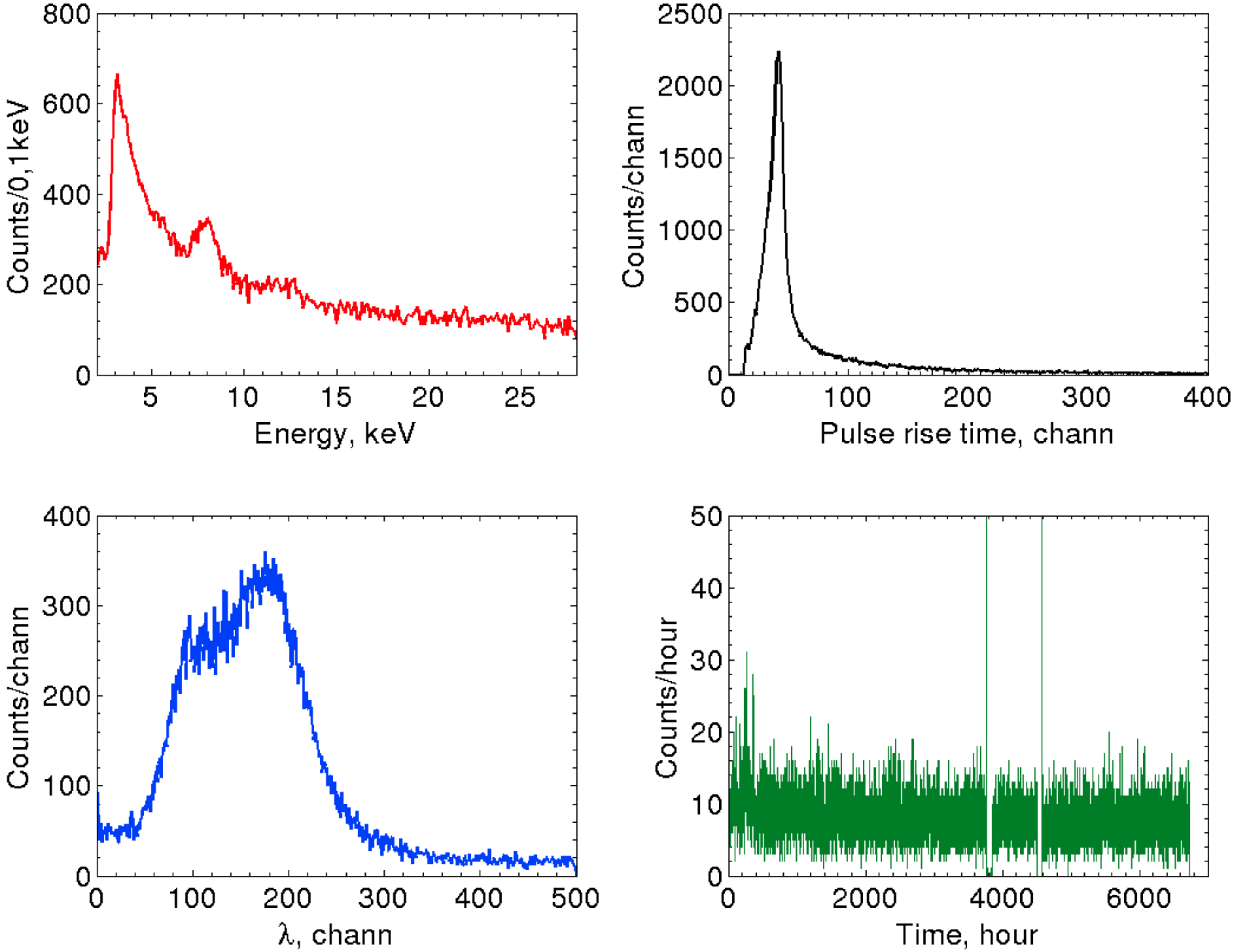
Thank you for attention!

Рабочие параметры сигналов



$$\lambda = 1000 \cdot \frac{A1}{A0}$$

Распределение событий



Спектр после отбора событий (Живое время измерений 6585 часов, прамаетры отбора событий: Фронт<51кан, λ>109 и λ<280)