A Search for Solar Axion Using the ^{169}Tm-containing Bolometers

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Outline

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Strong CP-problem

- Originally, the axion hypothesis arise as a mean of solving the Strong CP-problem.
- QCD Lagrangian contains a term, describing the gluon field interaction.

θ-term of QCD Lagrangian

$$L_\theta = \theta \frac{g_s^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$$

- This term is not invariant towards P and T transformations, therefore the CP-violation should be observed in strong interactions.

Strong CP-problem

- As a consequence of such violation a non-zero electric dipole moment (EDM) of neutron should exist.

Neutron EDM

$$d_n \sim \theta \times 10^{-16} e \cdot \mathrm{cm}$$

The experimental limit on *n* EDM

$$|d_n| < 2.9 \times 10^{-26} e \cdot \mathrm{cm}\ (90\%\ \mathrm{c.l.}) \Rightarrow \theta < 10^{-10}$$

- The question why θ is so small is known as the **strong** CP**-problem.**

Peccei-Quinn Solution

- In 1979 R.D. Peccei and H. Quinn proposed a solution by introducing a new chiral symmetry $\mathrm{U}(1)_{\mathrm{PQ}}$.
- The spontaneous breaking of this new symmetry at some energy f_A completely compensates the CP-violating term in QCD Lagrangian.

θ-term compensation

$$L_\theta = \left(\theta - \frac{A}{f_A}\right) \frac{g_s^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a$$

- In 1978 S. Weinberg and F. Wilczek showed that as a result of $\mathrm{U}(1)_{\mathrm{PQ}}$ breaking a new neutral pseudoscalar particle should be produced.

The Axion

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The Axion

Axion Properties

- The value of the axion *mass* (m_A) and the strength of an effective axion coupling with *nucleons* ($g_{AN} = g^0_{AN} + g^3_{AN}$), *electrons* ($g_{Ae}$), and *photons* ($g_{A\gamma}$) appear to be inversely proportional to f_A.

Axion Mass

$$m_A \approx \left(\frac{f_\pi m_\pi}{f_A}\right)\left(\frac{\sqrt{z}}{(1+z)}\right)$$

Axion Coupling Constants

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

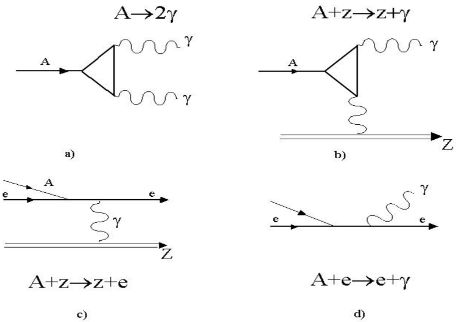
$$g^3_{AN} = -\frac{m_N}{2f_A}\left((D+F)\frac{1-z}{1+z+w}\right)$$

$$g_{A\gamma} = \frac{\alpha}{2\pi f_A}\left(\frac{E}{N} - \frac{2(4+z+w)}{3(1+z+w)}\right)$$

Outline

1. Axion Search Motivation
   - Theoretical Introduction
   - Axion Interaction With Matter
2. Experimental Axion Searches
   - Overwiew
   - Axion Experiments
     - $g_{A\gamma}$ Detection
     - g_{Ae} Detection
     - g_{AN} Detection
3. Tm-containing Bolometer Project
   - LNGS cryogenic setup

Possible reactions



1. $\mathbf{g_{A\gamma}}$: $A \to 2\gamma$ decay (a) and inverse Primakoff effect (b) (axion conversion in the electromagnetic field).
2. $\mathbf{g_{Ae}}$: axio-electric (c) and compton-like (d) processes.
3. $\mathbf{g_{AN}}$: as a pseudoscalar particle axion can be absorbed and emitted in magnetic-type transitions.

Original Axion Model

- The original theoretical model (PQWW-axion) assumed f_A value to be of electroweak scale: $f_A = (\sqrt{2}G_F)^{-1/2} \approx 250$ GeV
- Axion mass m_A and coupling constants in this model were precisely estimated

Expected Mass of PQWW-Axion

$$m_A \approx 25N(X + 1/X) \geq 150 \text{ keV}$$

- Existence of PQWW-axion has been disproved by experiments on reactors and accelerators and with artificial radioactive sources

Invisible Axion Models

- Two classes of new theoretical models of an *invisible* axion were developed.
- Axion was retained in the form required for solving the CP-problem of strong interactions.
- Arbitrary f_A value which suppresses axion interaction with matter.

Hadronic Axion

- KSVZ
  (Kim, Shifman, Vainshtein, Zakharov)
- New heavy quark

GUT Axion

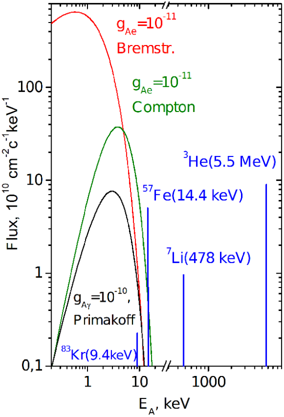
- DFSZ
  (Dine, Fischer, Srednicki, Zhitnycki)
- Additional Higgs field

Invisible axion – a viable Dark Matter candidate.

The Sun as an Axion Source

- Thermonuclear reactions
- $\sim$ keV-scale temperatures at the core
- Strong magnetic fields
- Well-established theoretical description (SSM)
- The nearest star relative to Earth

Solar Axion Energy Spectrum



1. **Reactions of the main solar chain (g_{AN})**
   - $p + d \to {}^3\mathrm{He} + A$
     5.5 MeV (*pp*-neutrino flux)
   - ${}^7\mathrm{Be} + e^- \to {}^7\mathrm{Li}^* + \nu;\ {}^7\mathrm{Li}^* \to {}^7\mathrm{Li} + A$
     478 keV (^{7}Be-neutrino flux)
2. **Thermal excitation of low-energy nuclear levels (g_{AN})**
   Nuclei with keV-scale excited states (Fe, Kr) can emit axions (has to be magnetic type)
3. **Primakoff effect ($g_{A\gamma}$)**
   Photon-axion conversion inside the electromagnetic field.
4. **Axion bremmstrahlung (g_{Ae})**
5. **Compton process (g_{A3})**

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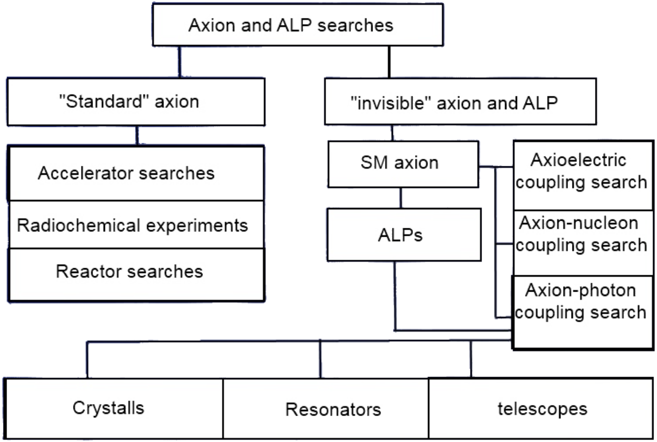
Axion Detection

- In order to detect axions we have to rely on the same possible axion interactions:
  1. $g_{A\gamma}$ – Reverse axion-photon conversion in magnetic field
  2. g_{Ae} – Axioelectric effect
  3. g_{AN} – Resonant absorption by atomic nuclei with subsequent γ-quantum emission.

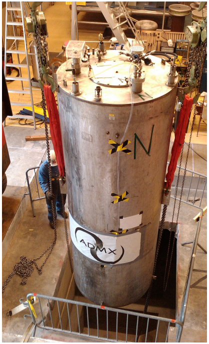
Experimental limit: $\boxed{g_A\ \textbf{production} \times g_A\ \textbf{detection}}$

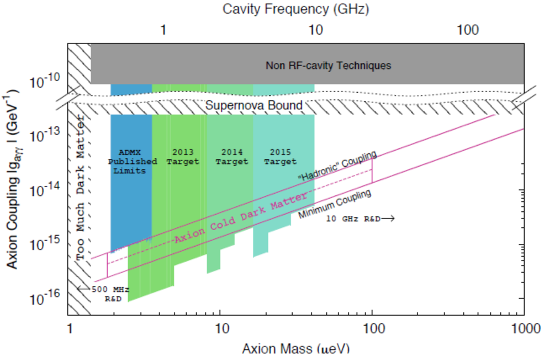
Classification



Outline

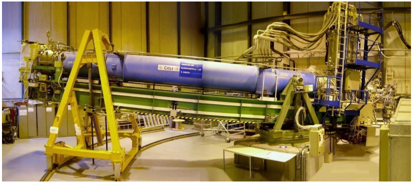
RF-Resonator (ADMX)

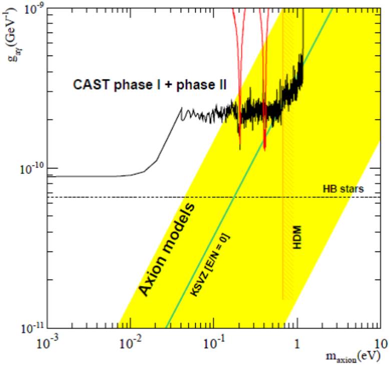




- Microwave resonator chamber ($d = 1$ m, $l = 0.5$ m)
- Artificial magnetic field
- Signal occurs when resonant frequency coincides with m_A

Helioscopes (CAST)





- LHC prototype magnet (∼ 9 Tesla, 10 m.)
- Solar axions (10^{-3} eV - 1 eV mass range.)

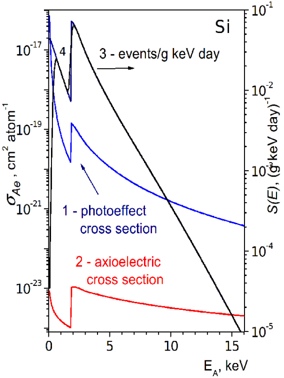
Axion Detection by Axioelectric Effect (g_{Ae})

1. High energy axions
    - A.-E. cross-section for K-shell electrons was calculated (on the assumption that $Z \ll 137$ and $E_A \gg E_b$
    - Complex form: $\sim Z^5$
2. Low energy axions
    - $E_A, m_A < 511$ keV cross-section for the axio-electric effect for nonrelativistic axions is proportional to the cross section for the photoelectric effect for photons with the energy equal to the mass of the axion.
    - Relativistic axions in the case $E_A < m_e$ and $m_A \to 0$, the cross section differs by a factor of about 2/3 and by a change of mA to EA.

Cross-section Approximation

$$\sigma_{abs}(E_A) = \sigma p.e.(E-A)\frac{g_{Ae}^2}{\beta}\frac{3E_A^2}{16\pi\alpha m_2^2}\left(1-\frac{\beta}{3}\right)$$

Axioelectric Effect for Si Target



- Axioelectric effect is similar to photoeffect:

$$\sigma_{Ae}|_{\beta\to 0} \simeq \sigma_{p.e.}(m_a)\frac{3m_A^2}{4\pi\alpha f_A^2\beta}$$

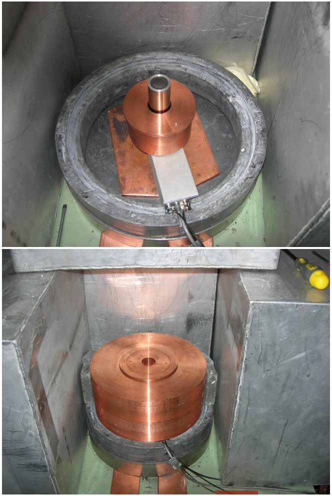
$$\sigma_{Ae}|_{\beta\to 1} \simeq \sigma_{p.e.}(m_a)\frac{3m_A^2}{4\pi\alpha f_A^2\beta}$$

- our approximation for all β values and $g_{Ae} = 2m_e/f_A$:

A.-E. Effect Cross-section

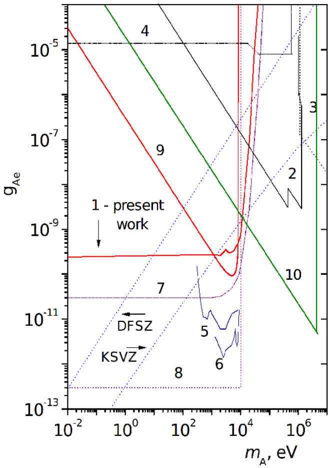
$$\sigma_{abs} = \frac{g_{Ae}^2}{\beta}\frac{3}{16}\frac{E_A^2}{\pi\alpha m_e^2}\sigma_{p.e.}(E_A)(1-\frac{\beta}{3})$$

PNPI Si(Li) Detector Setup



- Si(Li) detector with a sensitive region diameter of 17 mm and a thickness of 2.5 mm (1.4 g).
- Placed in a vacuum cryostat was surrounded by 12.5 cm of copper and 2.5 cm of lead (@14 keV BG reduction ×110).
- Active shielding against cosmic rays and fast neutrons (5 canisters with scintillator).
- Measurement live time: 76.5 days.

Obtained Limit (Si)



- 1 – Axioelectric effect (Si)
- 2 – reactor experiments and 478 keV solar axions
- 3 – beam dump experiments
- 4 – decay of orthopositronium
- 5 – CoGeNT
- 6 – CDMS
- 7 – Solar luminosity
- 8 – red giants He ignition
- 9 – ^{169}Tm resonant absorption
- 10 – Borexino 5.5 MeV axions

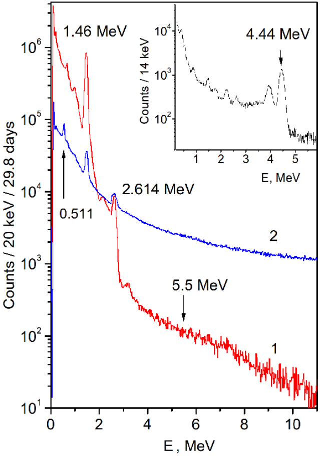
g_{Ae} Limit

$$g_{Ae} < 2.2 \times 10^{-10} \text{ (90\% c.l.)}$$

PNPI BGO Scintillator Setup

- Serach for monochromatic solar axions: 5.5 MeV
- 2.46 kg BGO crystal as scintillator.
- Located on Earth surface: active shielding against cosmic rays and fast neutrons.

Results (BGO Scintillator)



- Measurement live time: 29.8 days.

Sensitivity

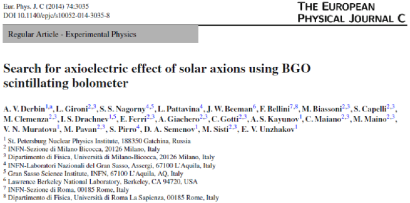
$$S_{\text{A peak}} = \epsilon_{\text{Reg.}} \cdot N_{\text{target nucl.}} \cdot (\Phi_{\text{B.s.}} + \Phi_{\text{Compt.}}) \cdot \sigma_{Ae}$$

g_{Ae} Limit

$$g_{Ae} \leq 1.4 - 9.7 \times 10^{-7}$$

BGO Crystal As A Bolometrer

- A suggestion came from LUCIFER collaboration to use the BGO crystal in *bolometric mode* inside the low-BG cryogenic setup.



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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Search for axioelectric effect of solar axions using BGO scintillating bolometer

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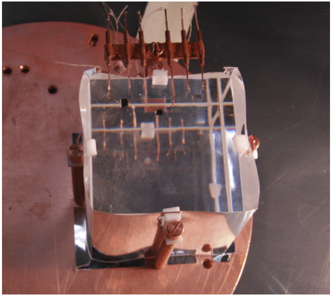
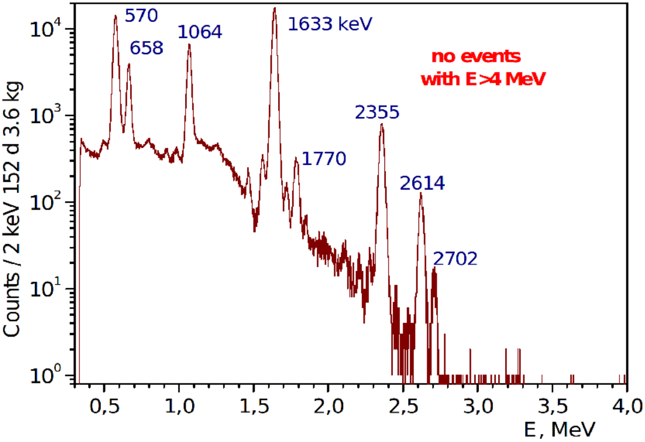
Detector	**σ (keV) at 5.5 MeV**	**S_{lim} (counts/day)**	**mass (g)**
Scintillator	93	$85/30$	2460
Bolometer	16	$2.44/152$	4×890

LNGS BGO Bolometer Setup

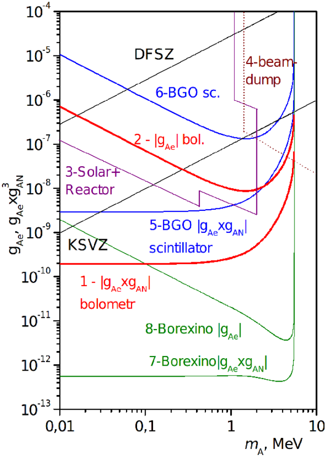


- Array of 4 BGO scinitillating bolometers, containing 1.65 kg of Bi.
- Four cubic (5 × 5 × 5 cm^3) BGO crystals, with all optical faces were arranged in a four-plex module, one single plane set-up.
- The scintillation light produced by a particle interaction in the BGO absorbers was monitored with an auxiliary bolometer made of high-purity germanium, operated as a light detector (LD).
- The detector was operated for a total live time of 151.7 days.

BGO Bolometer Energy Spectrum



Obtained Limit (BGO Bolometer)



- 1,2 – BGO bolometer limits $|g_{Ae} \times g^3_{AN}|$ and $|g_{Ae}|$, correspondingly;
- 3 – solar and reactor experiments;
- 4 – beam dump experiments;
- 5,6 – BGO scintillator limits $|g_{Ae} \times g^3_{AN}|$ and $|g_{Ae}|$;
- 7,8 – Borexino results

g_{Ae} Limit

$$|g_{Ae} \times g^3_{AN}| < 1.9 \times 10^{-10} \text{ 90\% c.l.}$$

One order of magnitude improvement

Axion Detection by Resonant Absorption g_{AN}

- Axions can be observed via the resonant absorption reaction by detecting γ-rays (or conversion e^-'s) emitted in the process of the de-excitation of the excited nuclear level.
- Resonant absorption of axions is governed by the expression similar to that for γ-rays, corrected by the ratio ω_A/ω_γ.

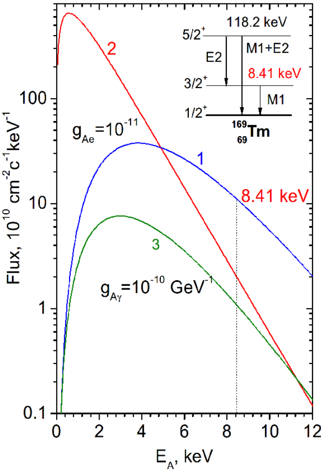
Resonant Absorption Cross-section

$$\sigma(E_A) = 2\sqrt{\pi}\sigma_{0\gamma} \cdot e^{-\frac{4(E_A - E_M)^2}{\Gamma^2}} \left(\frac{\omega_A}{\omega_\gamma}\right)$$

Emission Probability Ratio

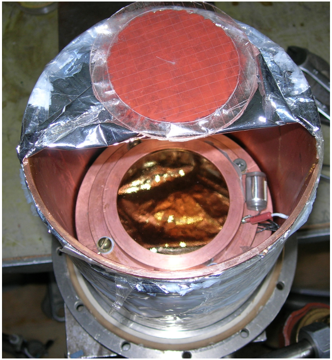
$$\frac{\omega_A}{\omega_\gamma} = \frac{1}{2\pi\alpha}\frac{1}{1+\delta^2}\left[\frac{g^0_{AN}\beta + g^3_{AN}}{(\mu_0 - 0,5)(\beta + \mu_3 - \eta)}\right]^2 \left(\frac{p_A}{p_\gamma}\right)^3$$

Resonant Absorption by ^{169} Nucleus



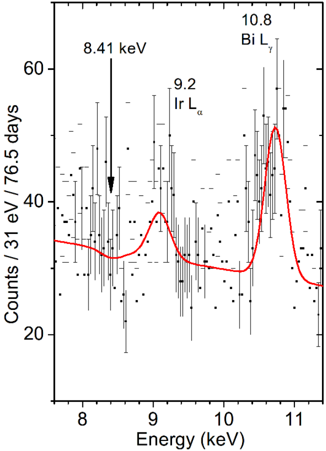
- ^{169}Tm target (Stable isotope).
- $A +^{169}\text{Tm} \rightarrow^{169}\text{Tm}^* \rightarrow^{169}\text{Tm} + \gamma$.
- M1-type transition with E2-transition admixture value of $\delta = 0.11\%$.
- 8.41 keV – sensitive to axions produced by Bremmstrahlung/Compton(g_{Ae}) or Primakoff effect($g_{A\gamma}$).
- Electron conversion ratio $e/\gamma = 263$, maximum cross section of γ-ray absorption is 2.6×10^{-19} cm^2.

Si(Li) Setup With ^{169}Tm



- Low-background setup + Si(Li) detector ($d = 66$ mm $h = 5$ mm).
- $Tm_2\, O_3$ target – 2 g.
- Setup limitations:
  - Low energy (8.4 keV)
    ⇒ Thin layer of material
    ⇒ Limit on the available mass of the target.
  - Increase of detector dimensions
    ⇒ Increase of detector capacitance
    ⇒ Decrease of energy resolution.

Obtained Limit (Tm)



- Measurement live time: 76.5 days.

$g_{A\gamma}$ Limit

$$g_{A\gamma} \times |(g_{AN})^0 + (g_{AN})^3| \leq 9.2 \times 10^{-13}$$

g_{Ae} Limit

$$g_{Ae} \times |(g_{AN})^0 + (g_{AN})^3| \leq 1.36 \times 10^{-14}$$

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3 Tm-containing Bolometer Project
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Sensitivity Improvement

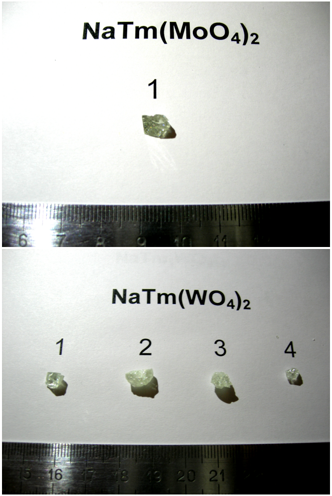
- Coefficient of electron conversion for 8.4 keV transition in the nucleus ^{169}Tm is $\epsilon = e/\gamma = 260$)
- Sensitivity of the experiment can be further increased in $260/\epsilon = 5 \times 10^3$ times ($\epsilon = 0.05$ – detection efficiency of gamma rays emitted from the target by Si(Li) detector)
- Registration of all particles (conversion and Auger electrons and γ- and X-rays) that accompany this transition.

This can be done in the implementation of thulium in the volume of the detector (scintillator or bolometer).

Enhancement factor (1 kg detector)

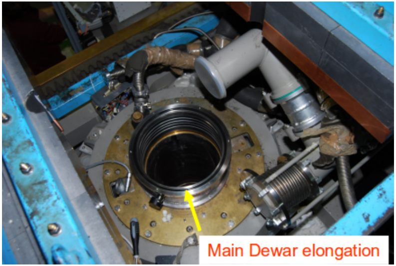
$$(e/\gamma = 260) \times (1/\epsilon = 20) \times (M/m = 500) \times (B_{\sigma_s}/B_{\sigma_b} = 1)^{1/2} = 2.5 \times 10^6$$

Tm-containing Crystals



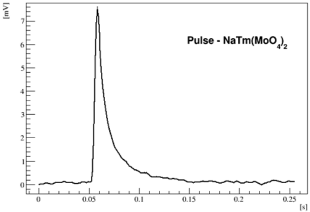
- $NaTm(WO_4)_2$ & $NaTm(MoO_4)_2$ crystals were grown in Novosibirsk State University (Russia).
- Growth: Kyropoulos method, from the flux of Na_2WO_4 and Na_2MoO_4
- Crystal dimensions: $\sim 5 \times 5 \times 5$ mm.
- ^{169}Tm mass is $\sim$ 200 mg per crystal.

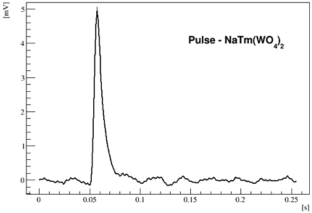
LNGS Cryostat (CUORE-0 R&D)

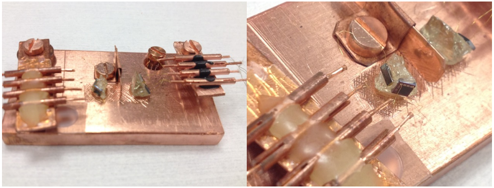


- ^{3}He/^{4}He dilution refrigerator ($T \sim 10^{-3}$K)
- Background suppression:
  - High purity copper structure
  - Underground location: $\simeq$ 3650 m of water equivalent
  - Passive shielding

Tm-crystal Bolometric Setup

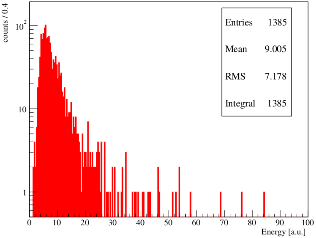


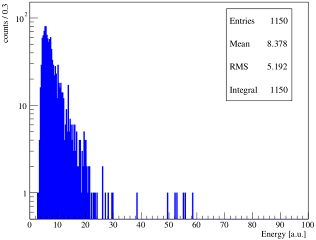




- NTD Ge thermistor – coupled to crystal surface for heat signal readout.
- Signal digitized by 18-bit ADC.
- Software trigger.
- Pulse shape confirms that crystals do work as bolometers.

Preliminary Measurements





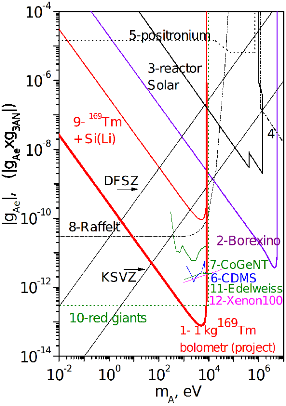
- Background spectra were collected during 135.2 hours.
- Unable to achieve proper energy calibration (unfortunatelly)
- Consider all background events to be axion-induced for estimation.

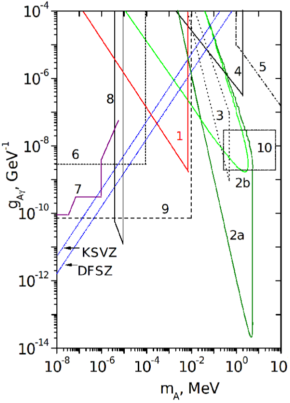
Limit Estimation

$$g_{Ae} \sim 10^{-16},\ g_{A\gamma} \sim 10^{-15}$$

Even conservative estimation shows improvement of the limit strength $\sim \times 10$.

Axion Limit Estimation





With target of 1 kg ^{169}Tm equivalent it is possible to obtain 10^2 limit improvement

Summary

- **Resonant absorption detection techniques** allow us to design relatively high-sensitivity setups with reasonable mass/dimensions of the target.
- **The ability of Tm-containing crystals to function as a bolometer** was confirmed. Also, it is a **perfect way to introduce significant amounts of Tm into the active detector volume**, greatly increasing registration efficiency of potential axion-induced events.
- Altogether, the underground (LNGS) cryogenic setup with **the Tm-containing bolometer** (1 kg of ^{169}Tm equivalent) will **allow us to achieve** $\times 10^2$**-fold improvement** over the current axion limits for g_{Ae} and $g_{A\gamma}$.

- Outlook
  - At the moment, new crystal growth crucible ($d = 20$ mm) is being shipped to NSU for production of a larger crystals.