Joint Institute for Nuclear Research

SCIENCE BRINGING NATIONS TOGETHER

Low neutron flux detectors and an active muon veto system for underground laboratories

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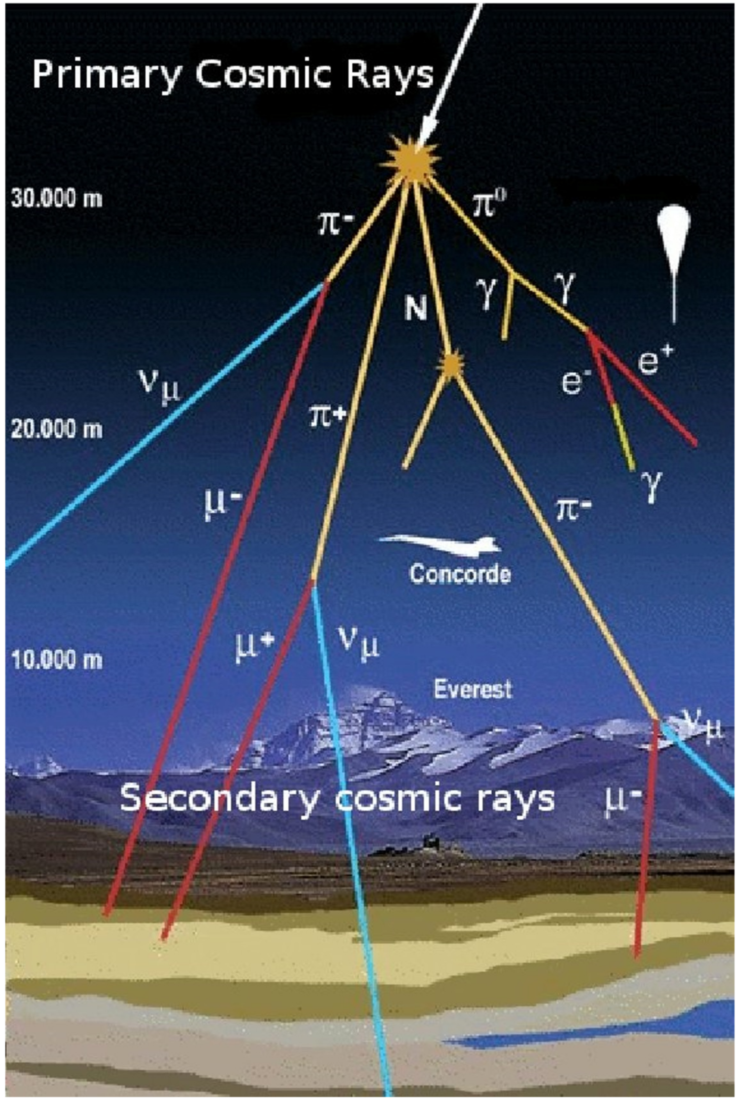
Overview

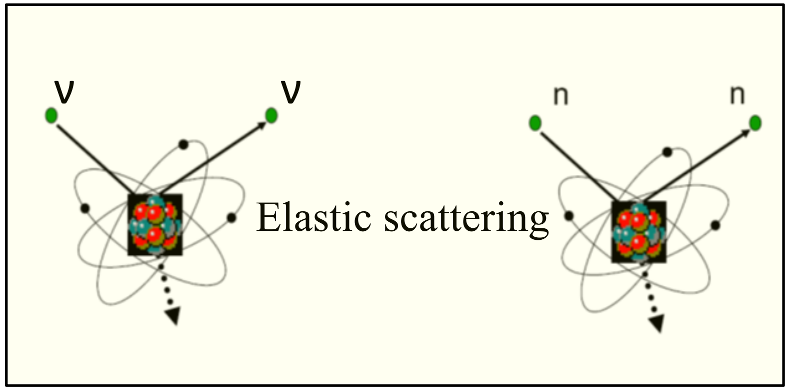
- A classical method of neutron measurements with ^{3}He-counter
- Neutron measurements with solid state scintillators (NaI, CsI, NaI (Tl+Li))
- Fast neutrons measurements with ^{3}He-counter
- A plastic active muon veto system



Giving new life to old equipment. F. Barradas-Solas .
Physics Education 2007, V. 42, N. 1, P. 9-11. DOI 10.1088/0031-9120/42/1/F03

Neutron-induced background

Neutrons can produce exactly the same signature as dark matter or neutrinos.

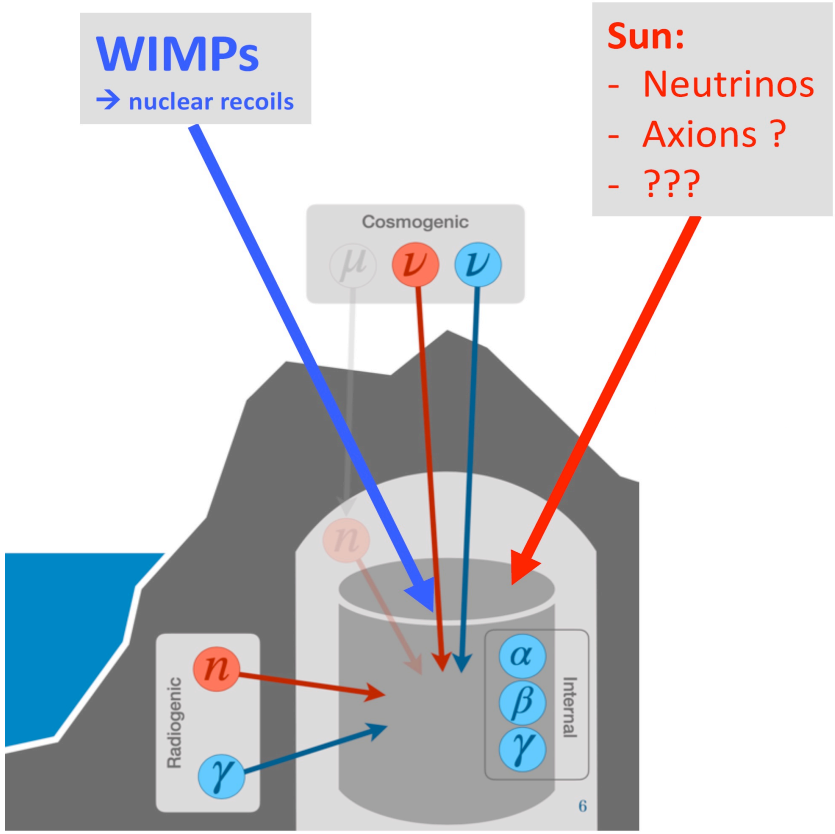


Neutron sources in nature

1. Low energy neutrons induced by U/Th fission and (α,n) reactions in the surrounding rock/concrete or in detector shield
2. High energy neutrons induced by muons

Fight with neutron background:

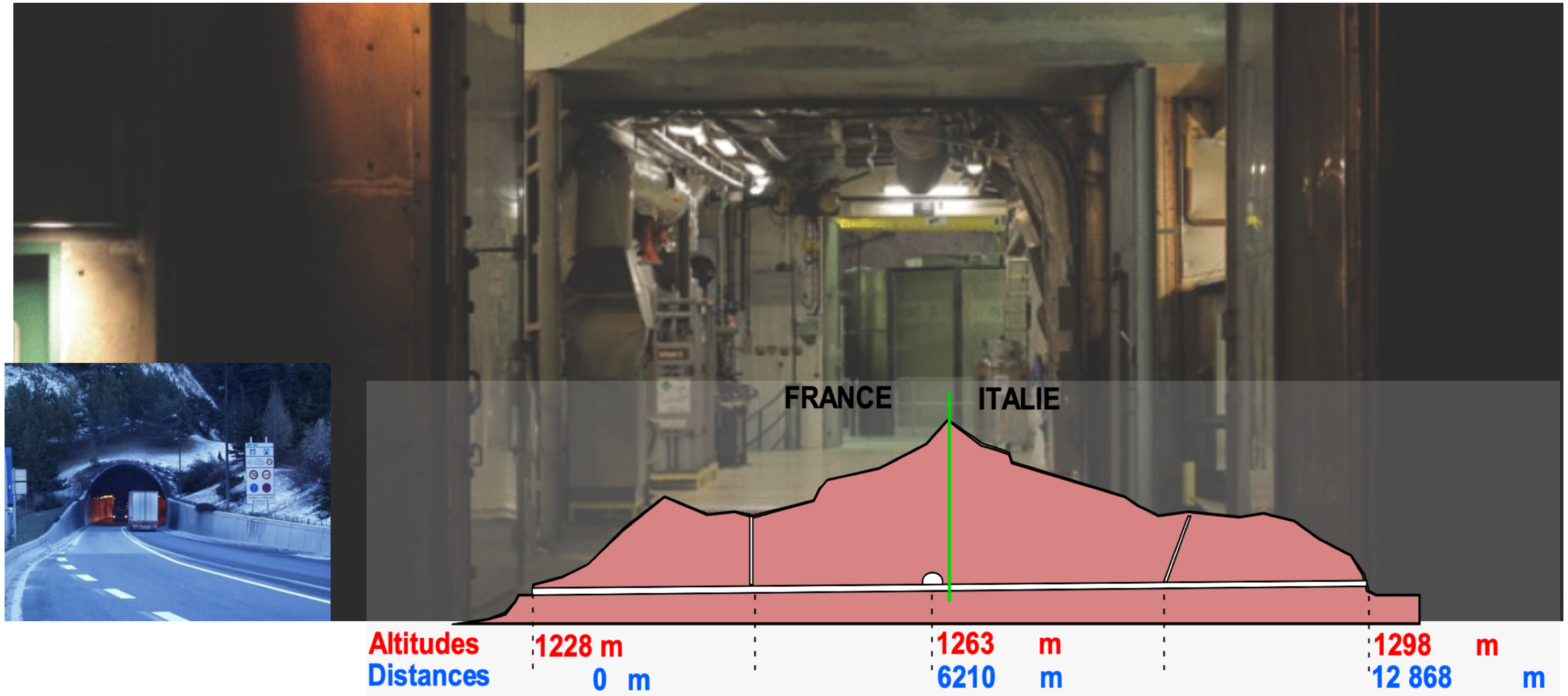
1. Go underground laboratory / reduce neutron flux by 4+ orders
2. Material selection
3. Muon veto system
4. Passive neutron shield
5. Multi-detector assembly
6. Neutron-induced background identification
7. Neutron fluxes measurements and characterization.

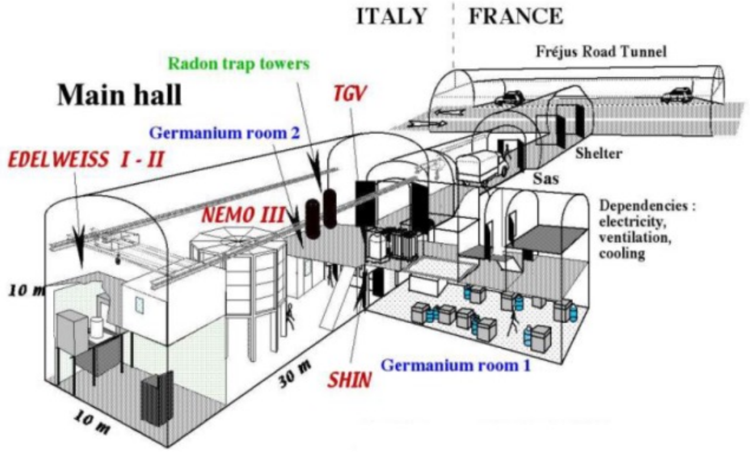


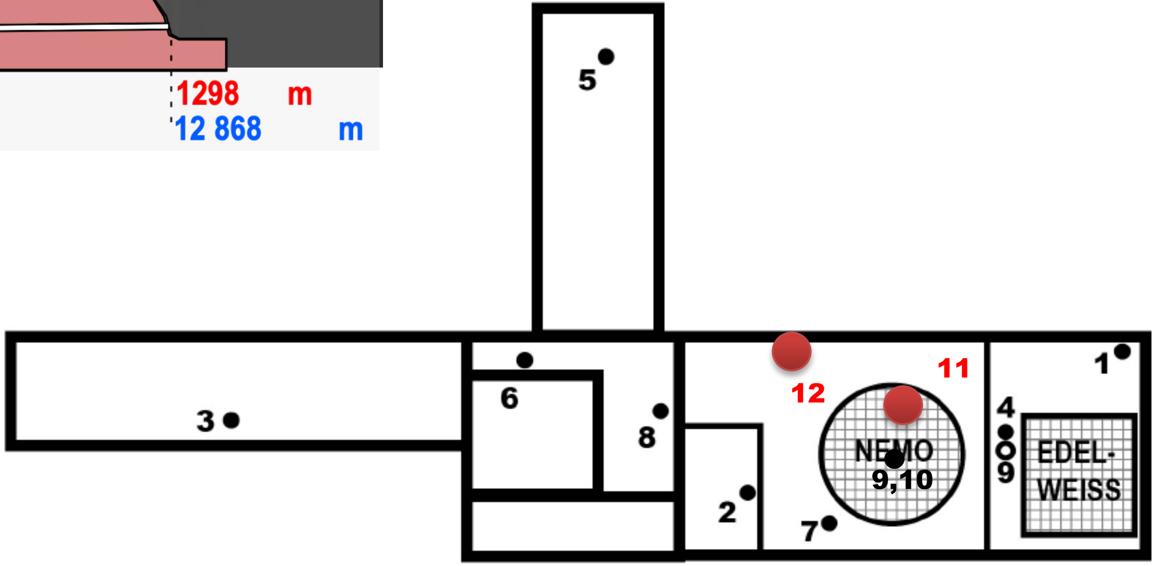
WIMPs
→ nuclear recoils

Sun:
- Neutrinos
- Axions ?
- ???

Neutron flux at LSM

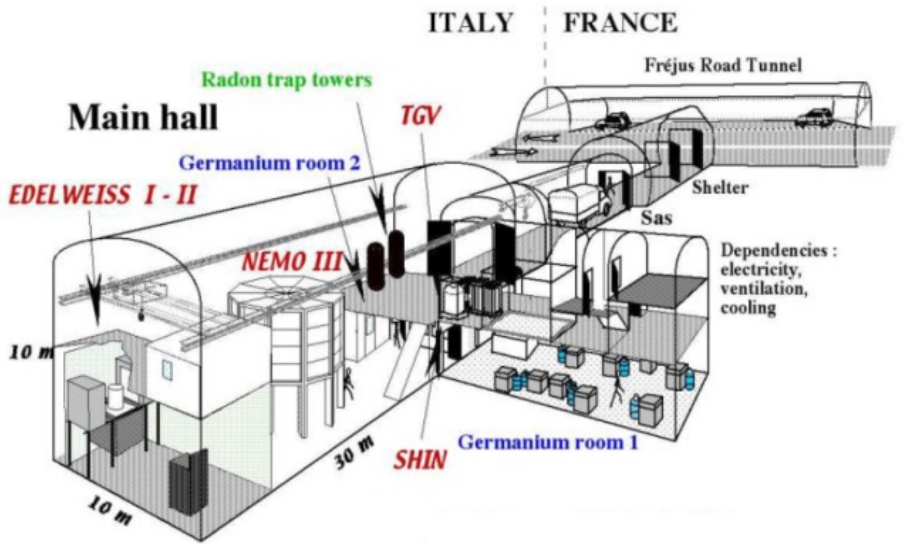




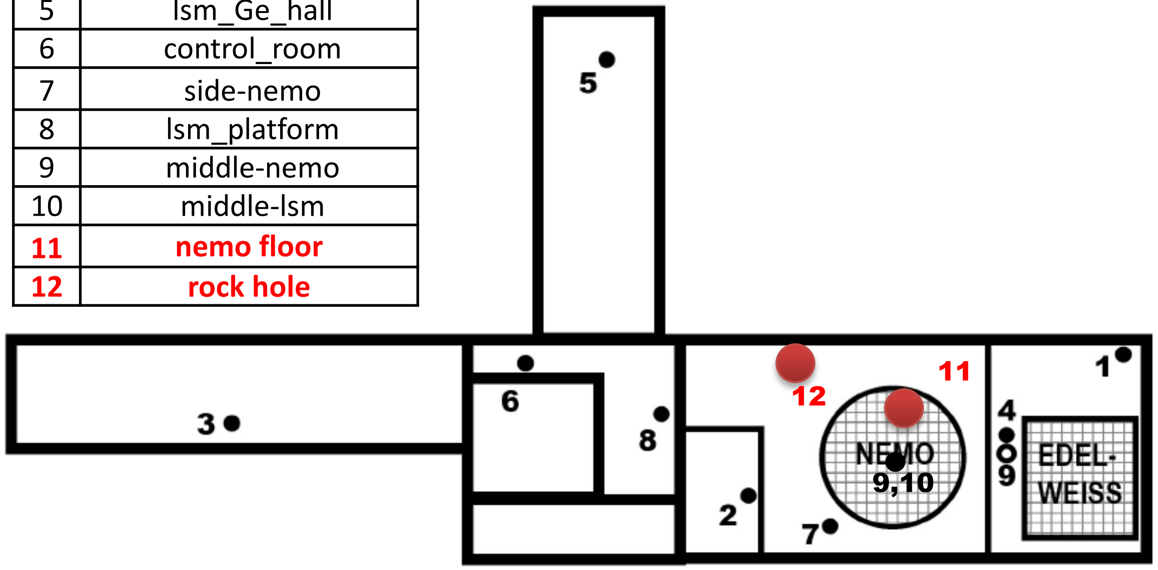


Neutron flux at LSM

Thermal neutron flux, 10^{-6} n/cm^2/sec			
Point	Year	Counting rate at ROI, cpd	Thermal neutron flux, 10^{-6}n/cm^2/sec
1	2008	76.8 ± 1.5	3.64 ± 0.07
	2012	78.2 ± 2.3	3.72 ± 0.11
	2011	74.35 ± 0.6	3.54 ± 0.03
2	2008	97.7 ± 9.3	4.7 ± 0.5
	2012	106.1 ± 7.3	5.1 ± 0.4
3	**2008**	**130.7 ± 12.2**	**6.3 ± 0.6**
	2012	**148.2 ± 12.3**	**7.1 ± 0.6**
4	2008	43.3 ± 4.0	2.1 ± 0.2
	2012	59.7 ± 4.5	2.9 ± 0.2
5	2008	94.7± 9.7	4.5 ± 0.5
	2012	112.1 ± 7.5	5.3 ± 0.4
6	2008	43.3 ± 4.0	2.1 ± 0.2
	2012	59.7 ± 4.5	2.9 ± 0.2
7	2008	43.3 ± 4.0	2.1 ± 0.2
	2012	59.7 ± 4.5	2.9 ± 0.2
8	2008	43.3 ± 4.0	2.1 ± 0.2
	2012	59.7 ± 4.5	2.9 ± 0.2
9	2012	93.3 ± 5.1	4.4 ± 0.3
10	2012	86.1 ± 5.4	4.1 ± 0.3
11	**2013**	**76.13 ± 5.0**	**3.63 ± 0.24**
12	**2013**	**207.09± 7.1**	**9.86 ± 0.34**
	2013+PE	**200.81± 1.6**	**9.56 ± 0.08**



1	Printer room
2	clean_room_nemo
3	**lsm_sas**
4	between EDW-NEMO
5	lsm_Ge_hall
6	control_room
7	side-nemo
8	lsm_platform
9	middle-nemo
10	middle-lsm
11	**nemo floor**
12	**rock hole**



^{3}He-counters and the need for an alternative

- Gas proportional detectors
- Golden standard for neutron measurements
- Thermal neutron cross section of ^{3}He = 5333±7 barns

- $n + {}^3He \rightarrow {}^3H + {}^1H + 764 keV$

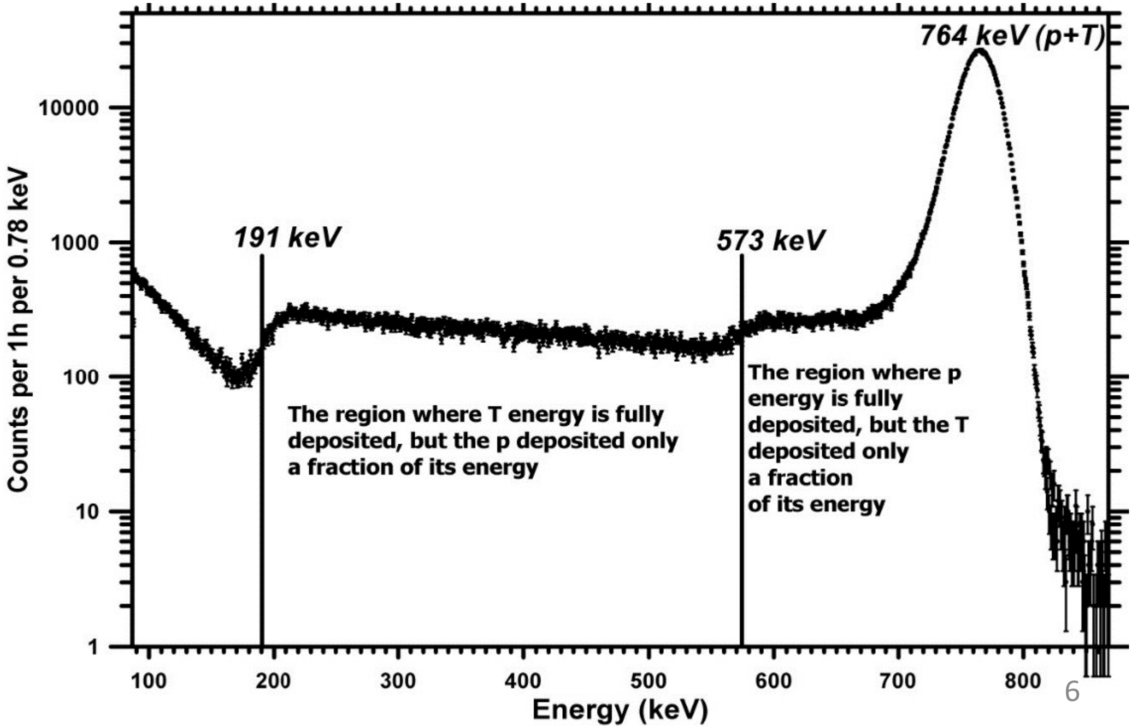
- Negligible sensitivity to gamma rays
- Increased gas pressure per volume → more sensitive detector

Drawbacks:

- ^{3}He proportion in natural He gas=0,000137 %
- Artificially produced from tritium decay in nuclear reactors
- Low availability
- Costs up to $2,000/L
- Not only needed for neutron detection
- Limited export of ^{3}He

^{3}He-counter

^{3}He-counter spectrum



Motivation of neutron measurements with NaI(Tl), CsI(Tl), CsI(Na), CsI scintillation detectors

- widely available,
- simple to use,
- relatively cheap,
- relatively easy to produce,
- can be very radioactive clean,
- highly efficient for γ- detection (multipurpose)

New method:

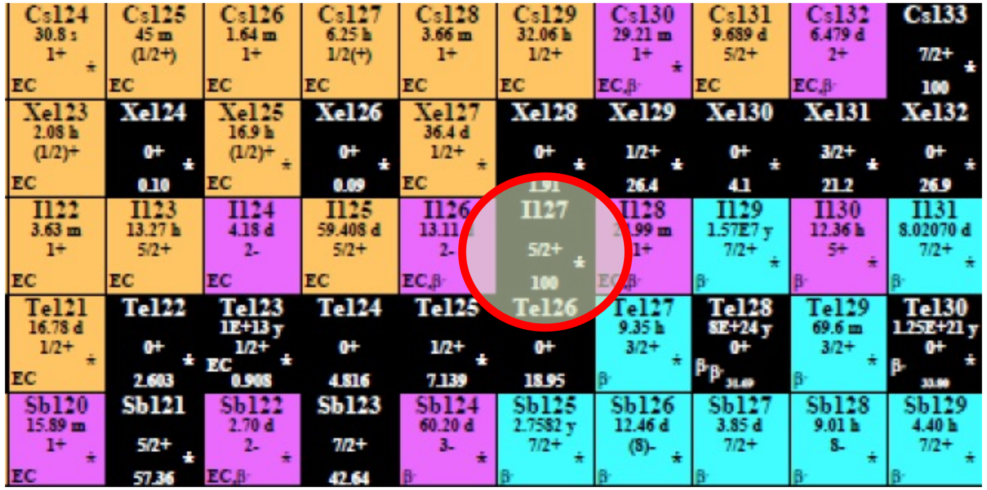
NaI (solid) has **545** times as many moles as an equal volume of ^{3}He (gas, normal pressure)

Iodine has only one stable isotope: $\mathbf{^{127}I}$
$\boldsymbol{\sigma_\gamma}$ **= 6.2(2) barn** (**860** times lower than ^{3}He)

Efficiency of thermal neutron capture in 1 kg NaI detector is ~50% (almost all captures will be on iodine because for ^{23}Na: σ_γ = 0.9(1) barn)

Result of neutron capture is ^{128}I in 6.8 MeV excited state

Detector	Neutrons	Short Description
NaI(Tl)	thermal	boron lining with available NaI detectors
NaI(Tl)	thermal	high-energy photons following (n,γ) reaction on ^{23}Na
NaI(Tl)	thermal	triple β-γ-γ coincidences in two detectors following (n,γ) reaction on ^{23}Na
NaI(Tl)	thermal	activated NaI detector(^{128}I β-decay, $T_{1/2}$ = 25min and ^{24}Na β-decay, $T_{1/2}$ = 15h)
CsI(Na)	fast	57.6 keV signal from ^{127}I(n,n’)inelastic scattering
NaI(Tl), CsI(Tl)	fast	1-200 MeV neutrons, (n,p) and (n,α) reactions, pulse-shape discrimination

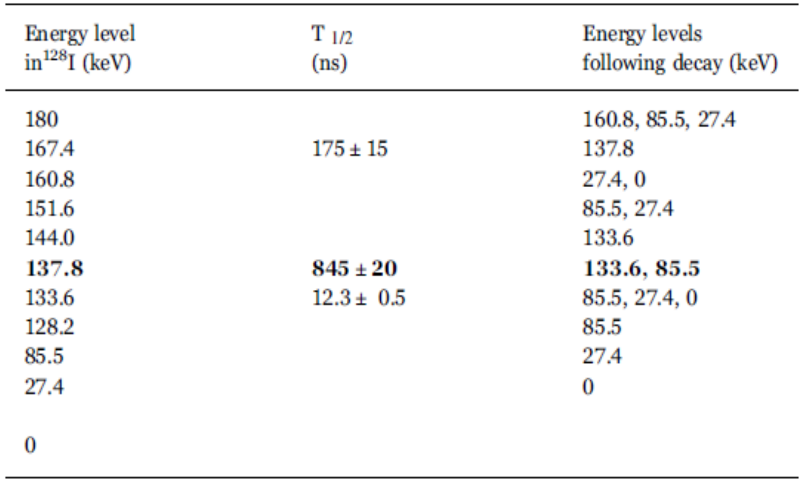


Cs124 30.8 s 1+ ★ EC	Cs125 45 m (1/2+) EC	Cs126 1.64 m 1+ EC	Cs127 6.25 h 1/2(+) EC	Cs128 3.66 m 1+ EC	Cs129 32.06 h 1/2+ EC	Cs130 29.21 m 1+ ★ EC,β^-	Cs131 9.689 d 5/2+ EC	Cs132 6.479 d 2+ EC,β^-	Cs133 7/2+ ★ 100
Xe123 2.08 h (1/2)+ EC	Xe124 0+ ★ 0.10	Xe125 16.9 h (1/2)+ ★ EC	Xe126 0+ ★ 0.09	Xe127 36.4 d 1/2+ ★ EC	Xe128 0+ ★ 1.91	Xe129 1/2+ ★ 26.4	Xe130 0+ ★ 4.1	Xe131 3/2+ ★ 21.2	Xe132 0+ ★ 26.9
I122 3.63 m 1+ EC	I123 13.27 h 5/2+ EC	I124 4.18 d 2- EC	I125 59.408 d 5/2+ EC	I126 13.11 2- EC,β^-	I127 5/2+ ★ 100	I128 99 m 1+ EC,β^-	I129 1.57E7 y 7/2+ ★ β^-	I130 12.36 h 5+ ★ β^-	I131 8.02070 d 7/2+ ★ β^-
Te121 16.78 d 1/2+ ★ EC	Te122 0+ ★ 2.603	Te123 1E+13 y 1/2+ ★ EC 0.908	Te124 0+ 4.816	Te125 1/2+ ★ 7.139	Te126 0+ 18.95	Te127 9.35 h 3/2+ ★ β^-	Te128 8E+24 y 0+ $\beta^-\beta^-$ 31.69	Te129 69.6 m 3/2+ ★ β^-	Te130 1.25E+21 y 0+ ★ β^- 33.80
Sb120 15.89 m 1+ ★ EC	Sb121 5/2+ ★ 57.36	Sb122 2.70 d 2- ★ EC,β^-	Sb123 7/2+ 42.64	Sb124 60.20 d 3- ★ β^-	Sb125 2.7582 y 7/2+ ★ β^-	Sb126 12.46 d (8)- ★ β^-	Sb127 3.85 d 7/2+ ★ β^-	Sb128 9.01 h 8- ★ β^-	Sb129 4.40 h 7/2+ ★ β^-

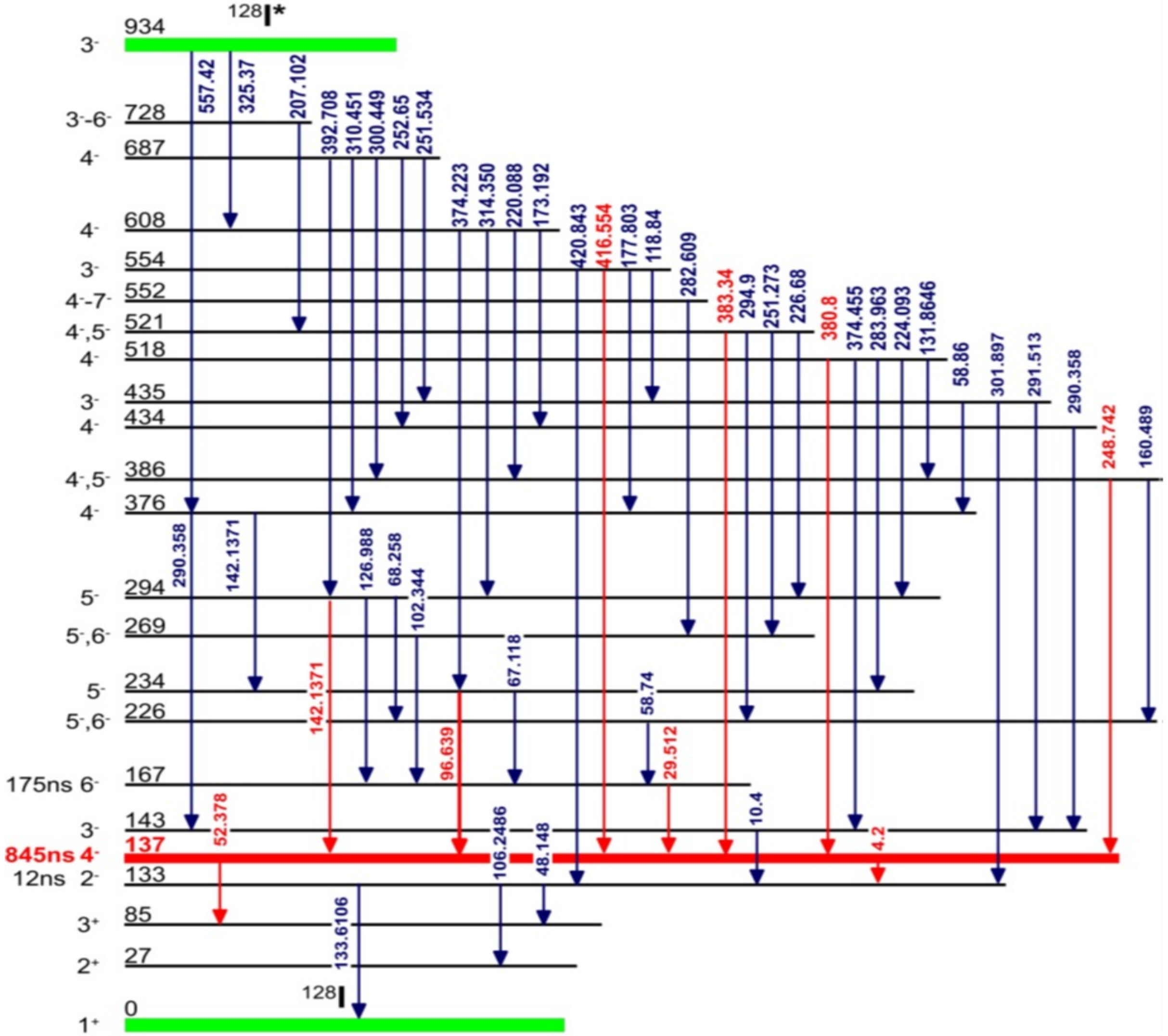
Description of the method

- ^{128}I decay to the ground state proceeds through a series of low-energy levels
- ^{128}I has 137.8 keV isomeric state
- $T_{1/2}$ = 0.845(20) μsec
- ~40% de-excitations pass through the 137.8 keV level
- Delayed coincidences to identify neutrons

^{128}I excited energy levels below 200 keV and their decay transitions



Energy level in ^{128}I (keV)	$T_{1/2}$ (ns)	Energy levels following decay (keV)
180		160.8, 85.5, 27.4
167.4	175 ± 15	137.8
160.8		27.4, 0
151.6		85.5, 27.4
144.0		133.6
137.8	**845 ± 20**	**133.6, 85.5**
133.6	12.3 ± 0.5	85.5, 27.4, 0
128.2		85.5
85.5		27.4
27.4		0
0		



Yakushev E. et al. **Sensitive neutron detection method using delayed coincidence transitions in existing iodine-containing detectors** // Nucl. Instrum. Methods Phys. Res.,Sect. A. 2017. Vol. 848. P. 162–165. https://doi.org/10.1016/j.nima.2016.12.022

The results of measurements of the ambient neutron flux in LSM (Modane, France)

NaI(Tl)
Diameter 63 mm
Length 63 mm
~720 grams

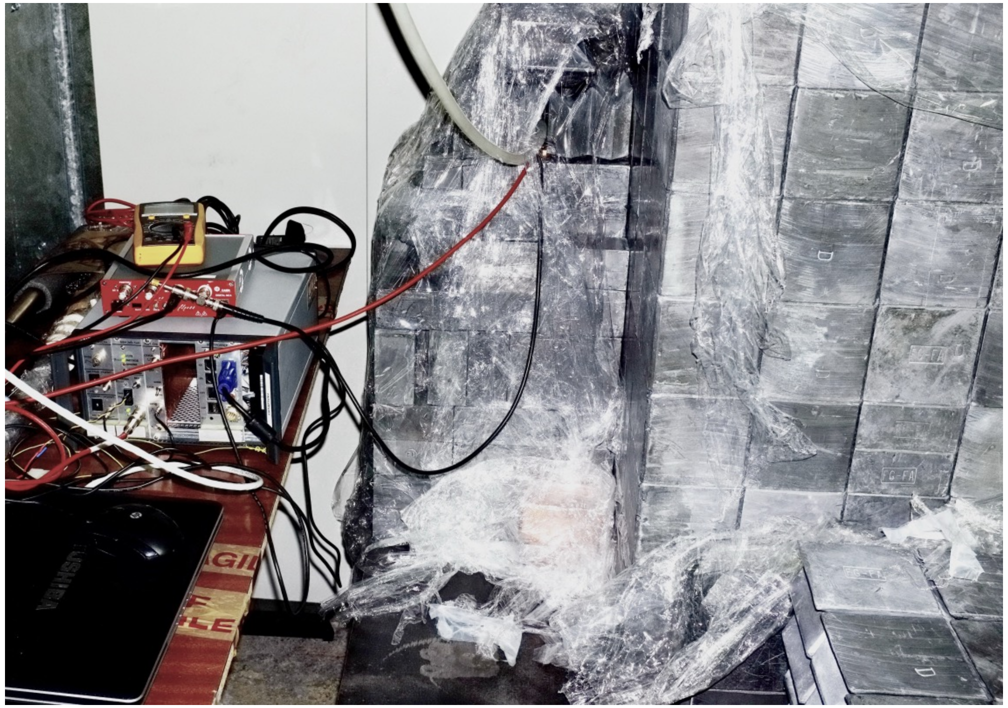
PMT
Hamamatsu R6091

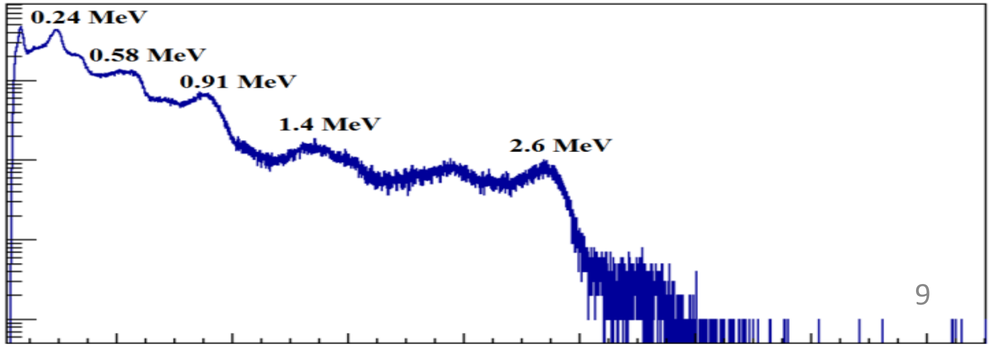
CAEN
Multi channel analyzer DT5780

Shield
Simple Cu+Pb shield near EDW-I

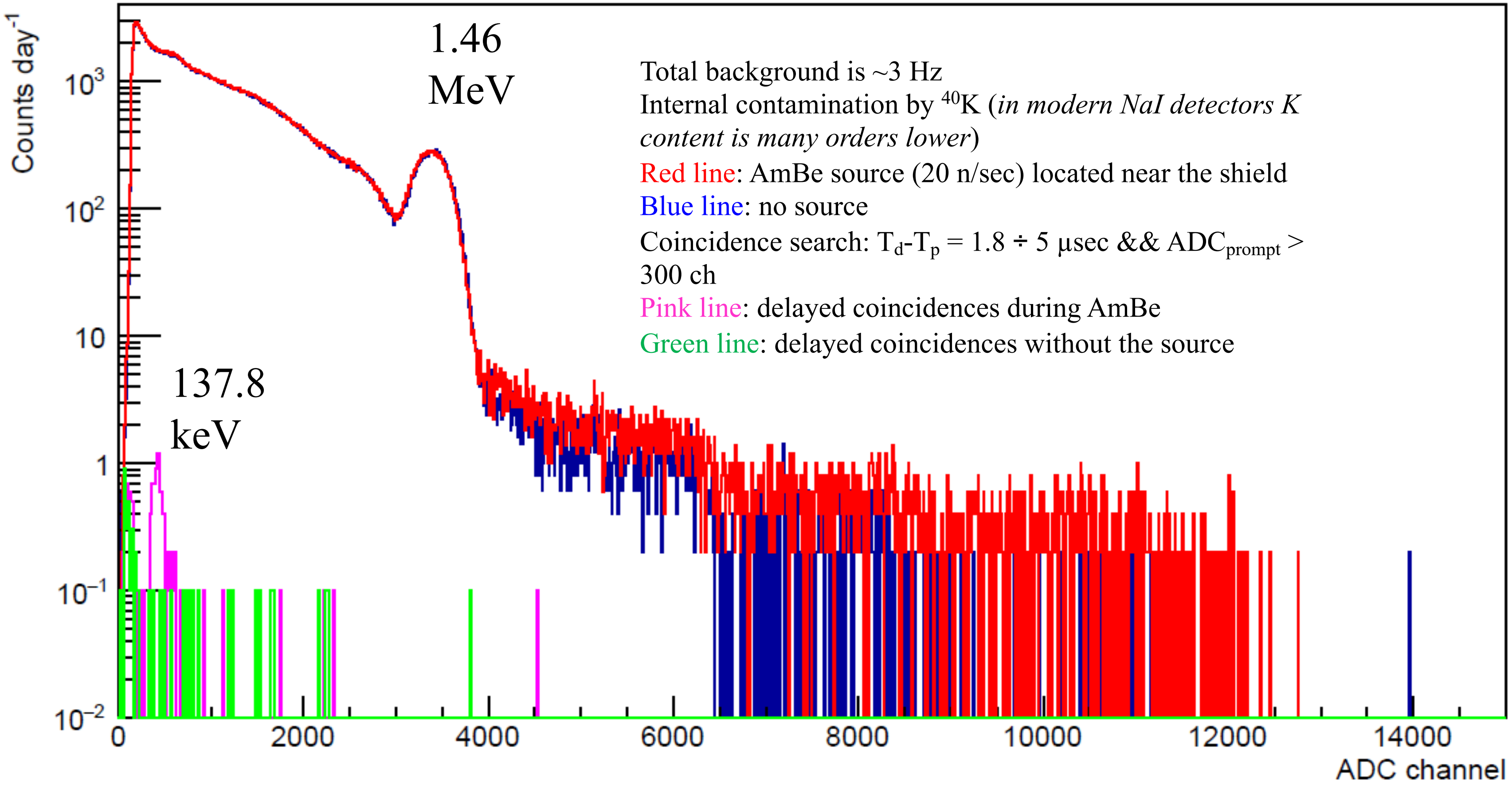
Calibrations
γ : Th + K(internal)
Neutron : AmBe (20 n/sec)

Simultaneous measurement with low-background ^{3}He detector CHM-57





The results of measurements with AmBe source in LSM (Modane, France)



Total background is ~3 Hz
Internal contamination by ^{40}K (*in modern NaI detectors K content is many orders lower*)
Red line: AmBe source (20 n/sec) located near the shield
Blue line: no source
Coincidence search: T_d-T_p = 1.8 ÷ 5 μsec && ADC_{prompt} > 300 ch
Pink line: delayed coincidences during AmBe
Green line: delayed coincidences without the source

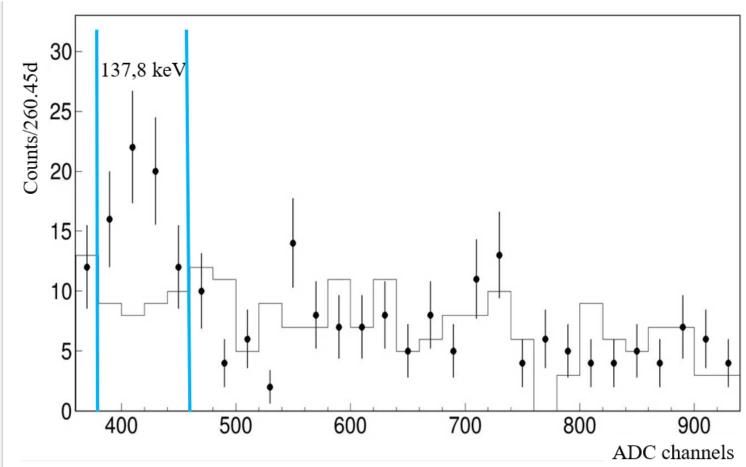
Cut:
$T_{prompt} - T_{delay}$ = 1.8-5 μsec

Results:
Neutron events: 1.8 - 5 μsec: 70 events

Background: 11.8 -15 μsec: 37 events

Flux = 2.1 ± 0.5 × 10^{-6} n cm^{-2} sec^{-1}

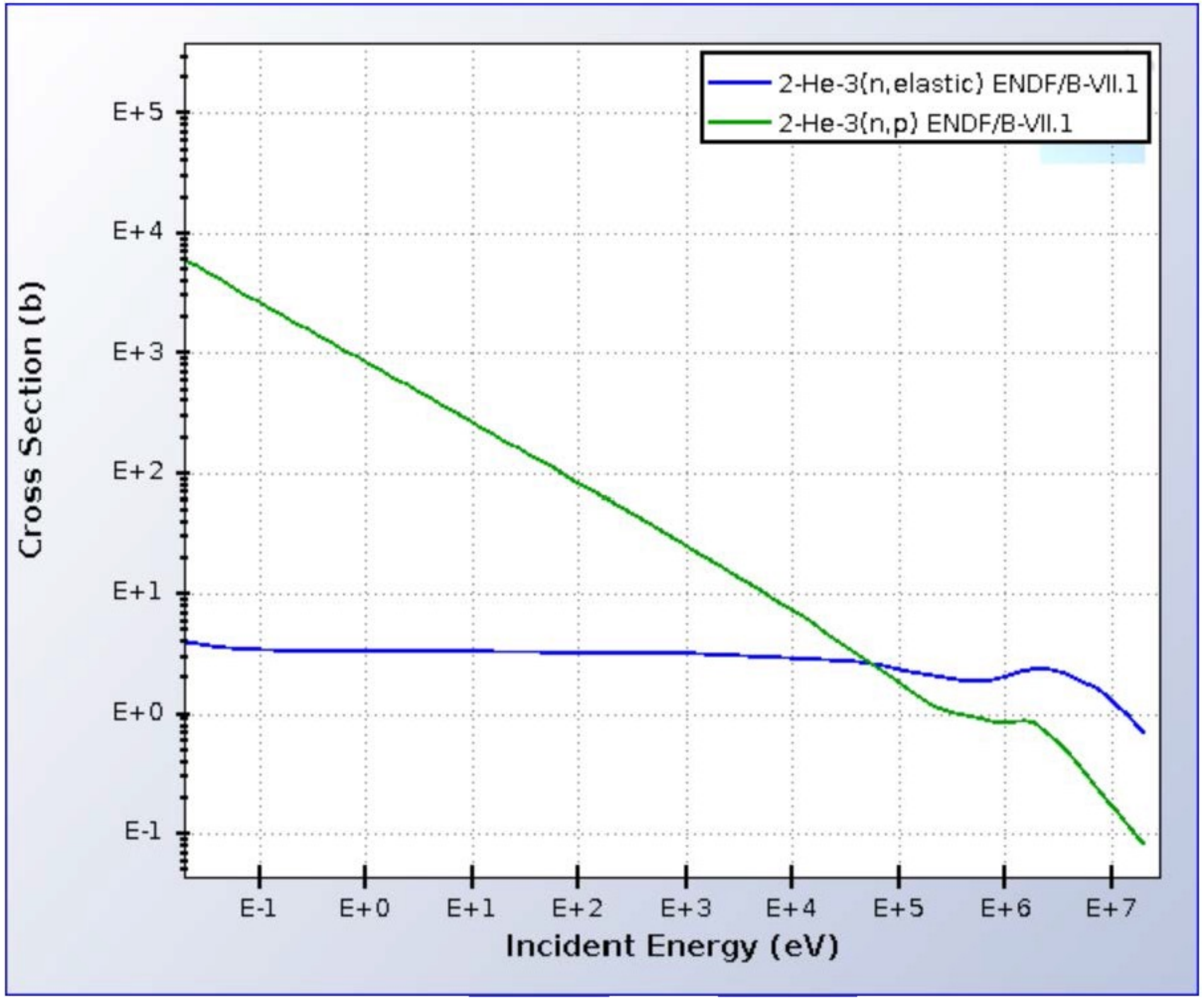
same as ^{3}He detector - 2.3 × 10^{-6} n cm^{-2} sec^{-1}



Ponomarev, D.V. et al. **Measuring Low Neutron Fluxes at the Modane Underground Laboratory Using Iodine-Containing Scintillators//** Instrum Exp Tech 62, 309–311 (2019). https://doi.org/10.1134/S0020441219030084

Fast neutron detection with bare ^{3}He counter

Cross sections of neutron capture and elastic scattering of ^{3}He

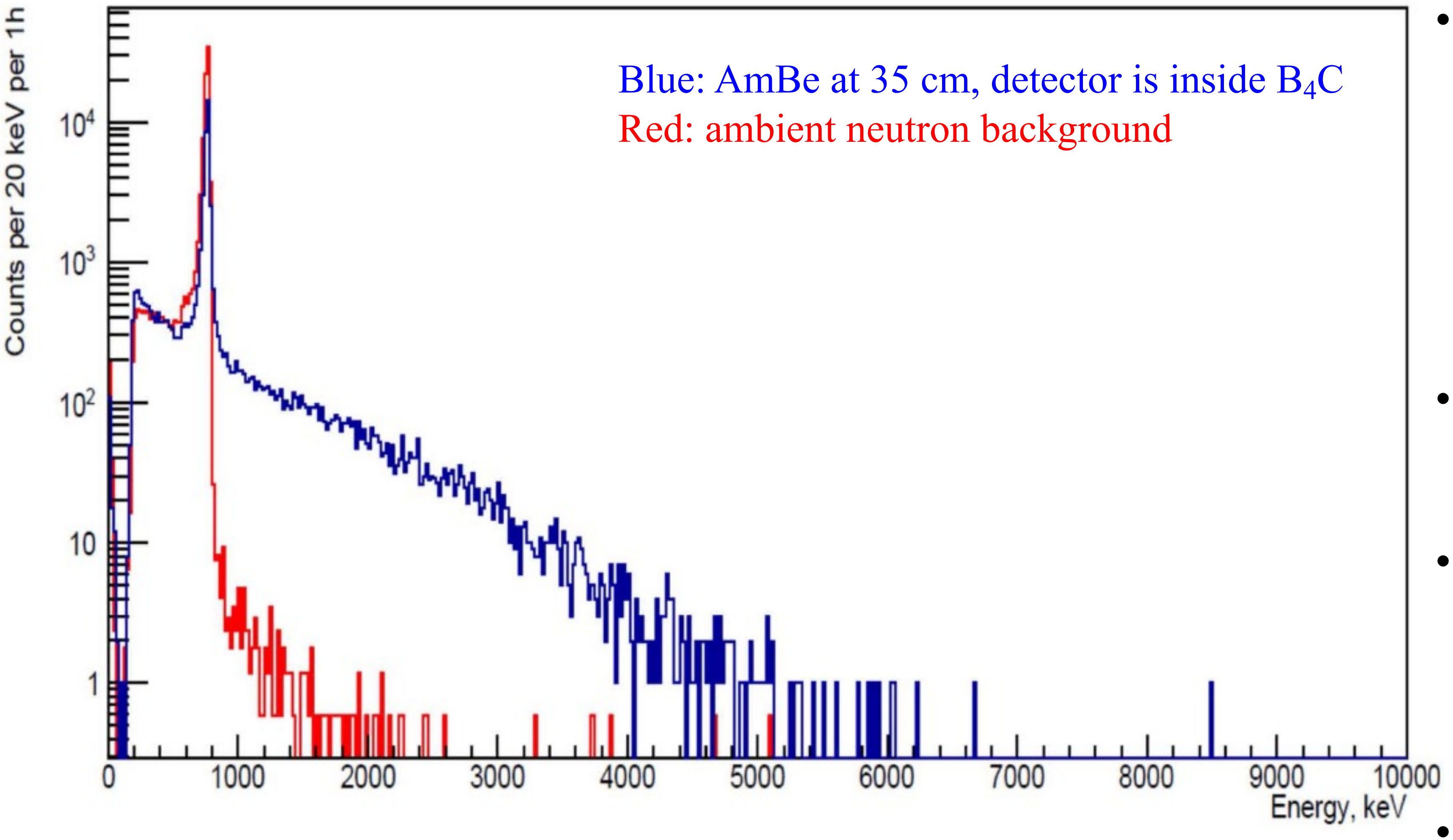


$$n + {}^3He \rightarrow t + p + (764\ keV + E_n)$$

- ^{3}He(n,p) cross section for the neutrons with energies 100 keV to 10 MeV is ~1 barn.
- The ability to detect fast neutrons with a ^{3}He counter whose intrinsic background close to 0.

Augier C. et al. **Fast neutron background characterization of the future Ricochet experiment at the ILL research nuclear reactor** // The European Physical Journal C. 2023. Vol. 83. P. 20. https://doi.org/10.1140/epjc/s10052-022-11150-x

Fast neutron measurements with AmBe source



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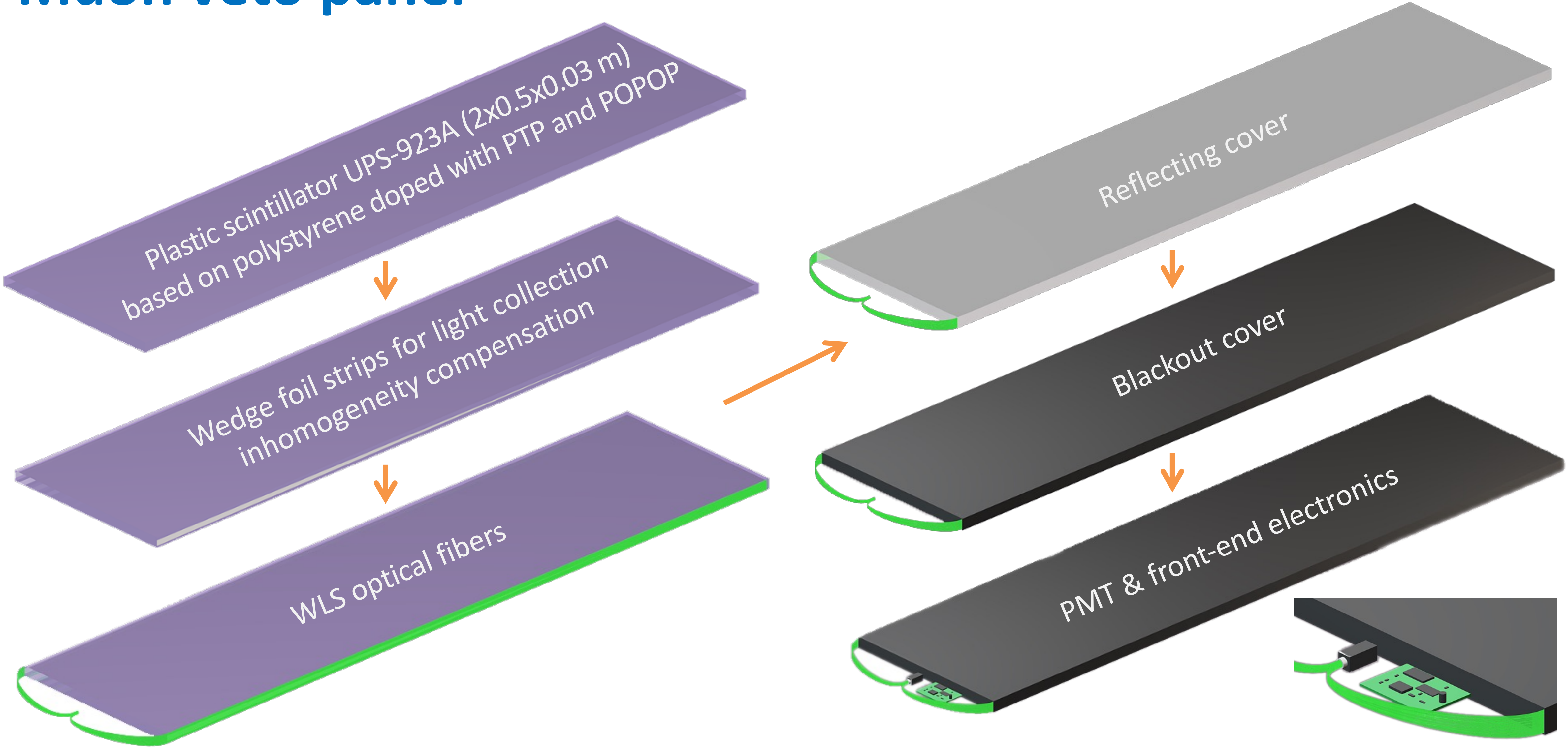
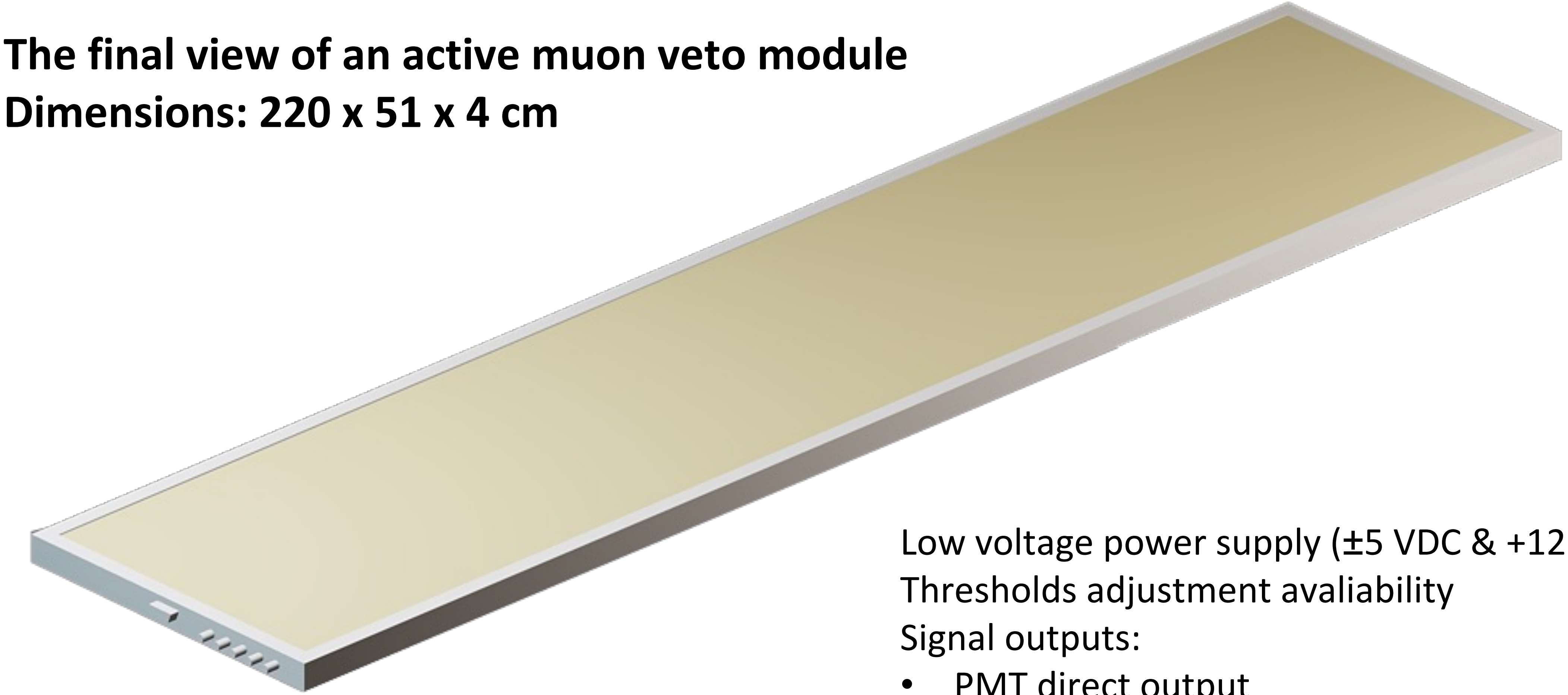
- The neutron detector is created at JINR and based on low-background ^{3}He counter CHM-57[1]. Diameter = 31 mm, l = 860 mm. The gas mixture is 400 kPa of ^{3}He and 500 kPa of ^{40}Ar.
- α-particle background ~2 events day^{-1} MeV^{-1}.
- Count rate in background measurements ~ 40 events day^{-1} in energy range 1 – 3 MeV, the same as expected.
- Multi channel analyzer DT5780.

Muon veto panel



Muon veto panel

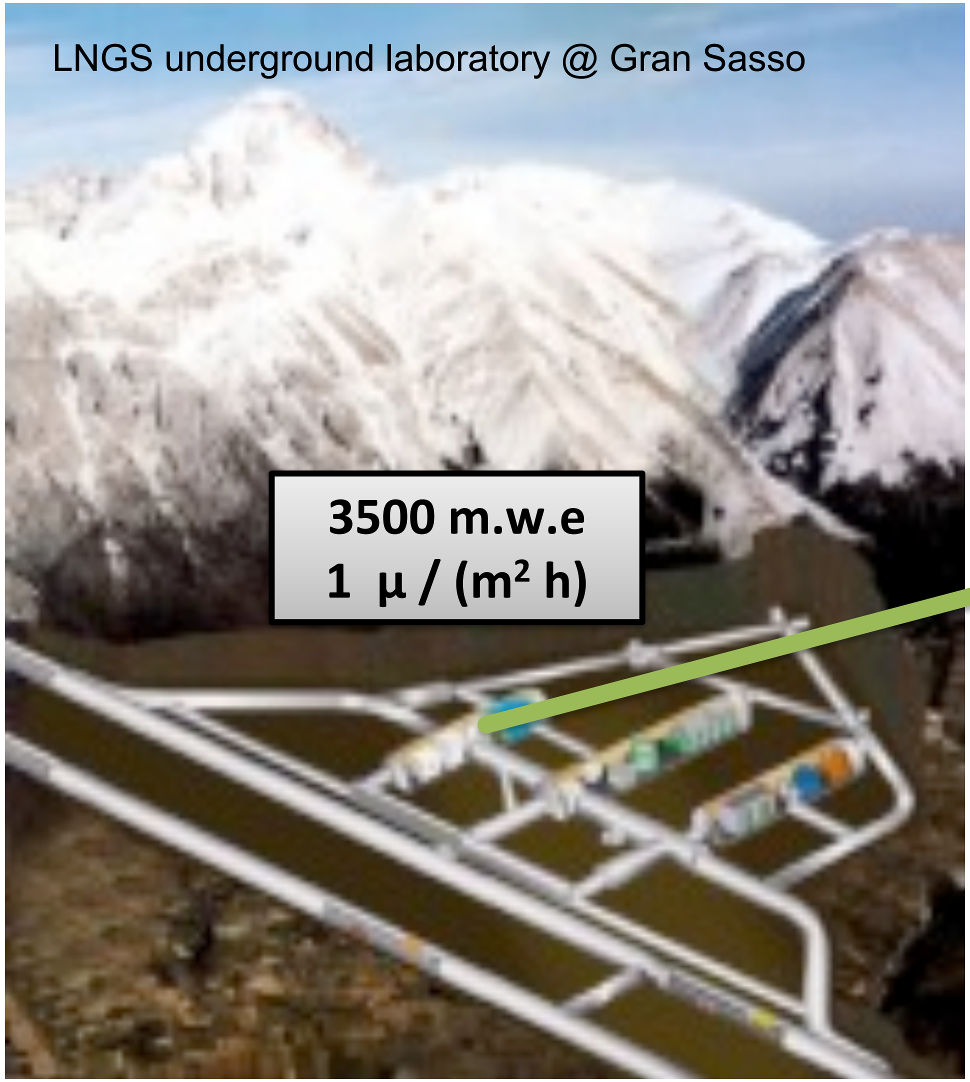
The final view of an active muon veto module
Dimensions: 220 x 51 x 4 cm



Low voltage power supply (±5 VDC & +12 VDC)
Thresholds adjustment avaliability
Signal outputs:

- PMT direct output
- Preamp output
- 2 × logical (NIM) outputs

GERDA setup location



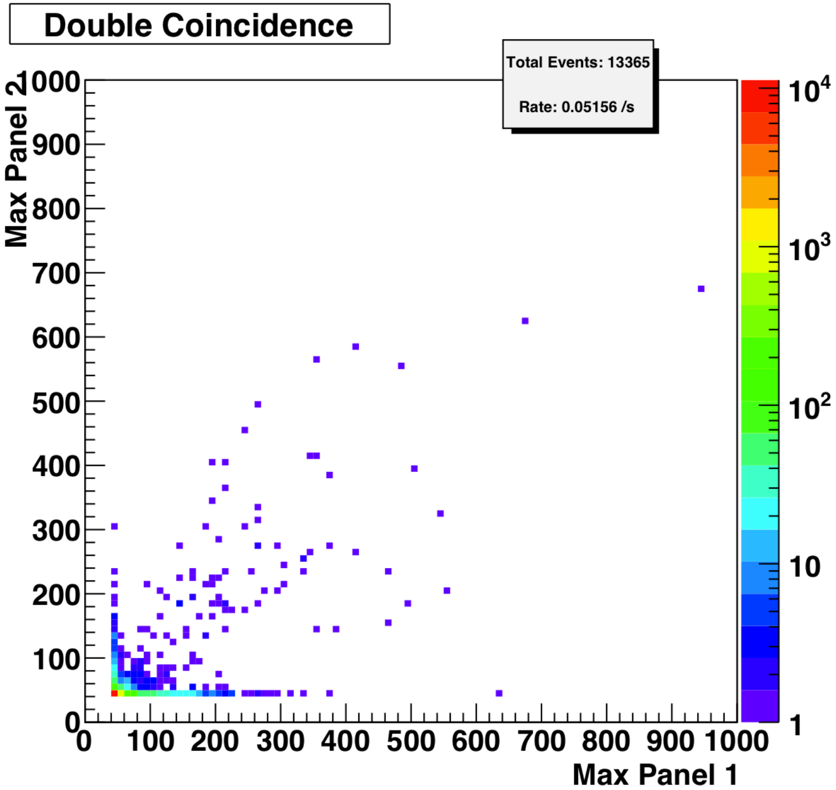
LNGS underground laboratory @ Gran Sasso

3500 m.w.e

$1\ \mu / (m^2\ h)$

Muon veto panels layout

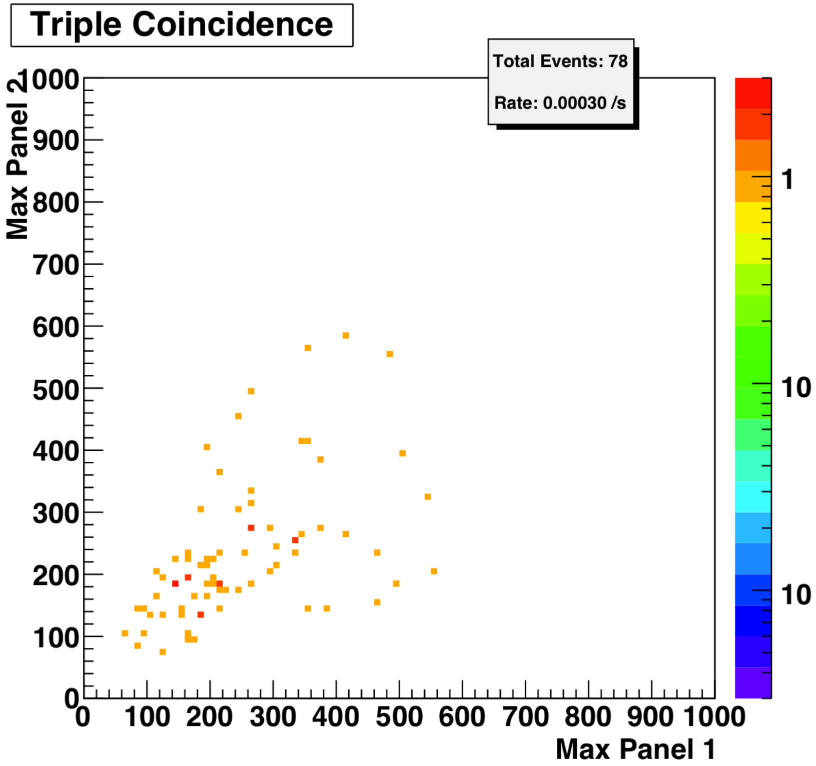
Count rates & performance



Double Coincidence

Total Events: 13365

Rate: 0.05156 /s



Triple Coincidence

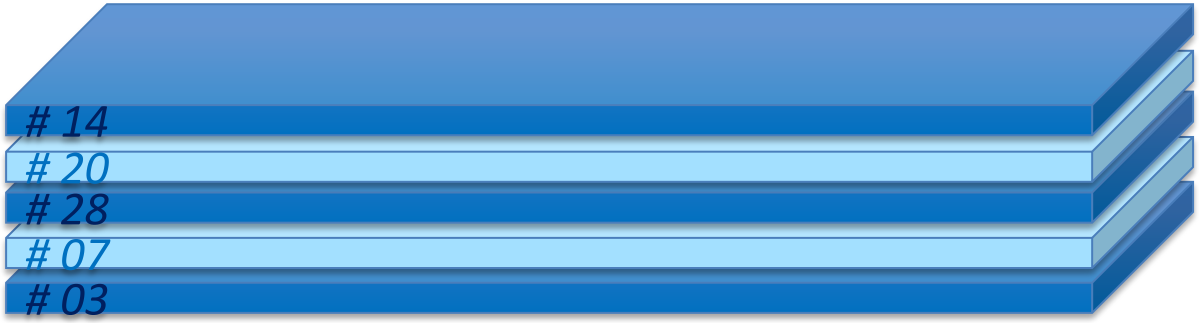
Total Events: 78

Rate: 0.00030 /s

Coincidence modes crosscheck

№	Single, Cnt/s	Double, Cnt/s			Triple, Cnt/s		
		Coinc.	Anticoinc.	Sum	Coinc.	Anticoinc.	Sum
18	**262.3**	164.6	96.3	**260.9**	147.2	113.7	**260.9**
19	**225.5**	162.3	63.2	**225.5**	147.6	79.5	**227.1**
20	**274.2**	162.6	109.9	**272.5**	147.9	125.1	**272.9**
21	**207.9**	163.4	44.8	**208.2**	147.1	60.9	**208.1**

Count rates & performance

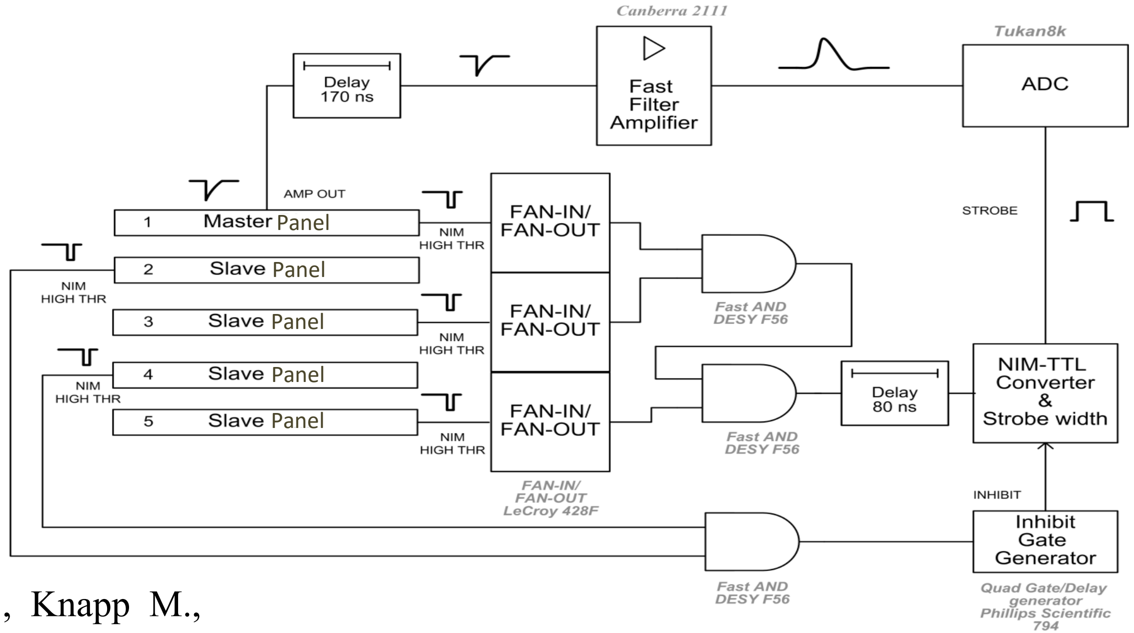


Efficiency measurements

Efficiency of muon detection for a panel corresponds to **99,75 ± 0,18 %**

Efficiency of registration for the double coincidence mode is **99.50 ± 0,25 %**

Efficiency of registration for the triple coincidence mode is **99.25 ± 0,31 %**



Freund F K., Falkenstein R., Grabmayr P., Hegai A., Jochum J., Knapp M., Lubsandorzhiev B., Ritter F., Schmitt C., Schütz A.-K., Zhitnikov I., Shevchik E., Shirchenko M., Zinatulina D. The performance of the Muon Veto of the GERDA experiment // **Eur. Phys. J. C. 2016. V. 76. P. 298.**

Conclusions:

- The new method of neutron detection with existing iodine containing scintillators allow to measure low flux of thermal neutrons;

- For low background environment 10^{-8} n cm^{-2} sec^{-1} neutron flux could be possible to measure with a bigger detector (~100kg);

- NaIL detector is a promising detector for background measurements. Such the detectors together with their usual implementation for γ– measurements, can be highly efficiently applied for detection of neutrons with different energies. The three main reactions are $^{6}Li(n,t)^{4}He$ (thermal neutrons), $^{127}I(n,\gamma)^{128}I$ (epithermal neutrons), $^{127}I(n,n')^{127}I^{*}$ (fast neutrons).

- The low-background ^{3}He proportional counter can be used to characterize the fast neutron fluxes if it's own BKG is low enough.

- Active muon veto system is very important for the low-backgournd experiments, not only shielding from cosmic muons but also as a veto for neutrons indused inside the experimental setup.

Joint Institute for Nuclear Research

SCIENCE BRINGING NATIONS TOGETHER

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Symposium on Science @ PAUL
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Articles

1. Yakushev E. et al. **Sensitive neutron detection method using delayed coincidence transitions in existing iodine-containing detectors** // Nucl. Instrum. Methods Phys. Res.,Sect. A. 2017. Vol. 848. P. 162–165. https://doi.org/10.1016/j.nima.2016.12.022

2. Ponomarev, D.V. et al. **Measuring Low Neutron Fluxes at the Modane Underground Laboratory Using Iodine-Containing Scintillators//** Instrum Exp Tech 62, 309–311 (2019). https://doi.org/10.1134/S0020441219030084

3. Ponomarev D., et al. **NaI(Tl+Li) scintillator as multirange energies neutron detector** // Journal of Instrumentation. 2021. Vol. 16, no. 12. P. 12011. https://doi.org/10.1088/1748-0221/16/12/P12011

4. Augier C. et al. **Fast neutron background characterization of the future Ricochet experiment at the ILL research nuclear reactor** // The European Physical Journal C. 2023. Vol. 83. P. 20. https://doi.org/10.1140/epjc/s10052-022-11150-x

5. Freund F K., Falkenstein R., Grabmayr P., Hegai A., Jochum J., Knapp M., Lubsandorzhiev B., Ritter F., Schmitt C., Schütz A.-K., Zhitnikov I., Shevchik E., Shirchenko M., Zinatulina D. The performance of the Muon Veto of the GERDA experiment // Eur. Phys. J. C. 2016. V. 76. P. 298.

Dark Matter Detectors in UG Laboratories

WIMPs scatter off atoms in a detector → **detect the signal…**

- **event rate is ultra small;**
- **and (or) energy deposition is tiny**

2 tasks for any modern experiment:

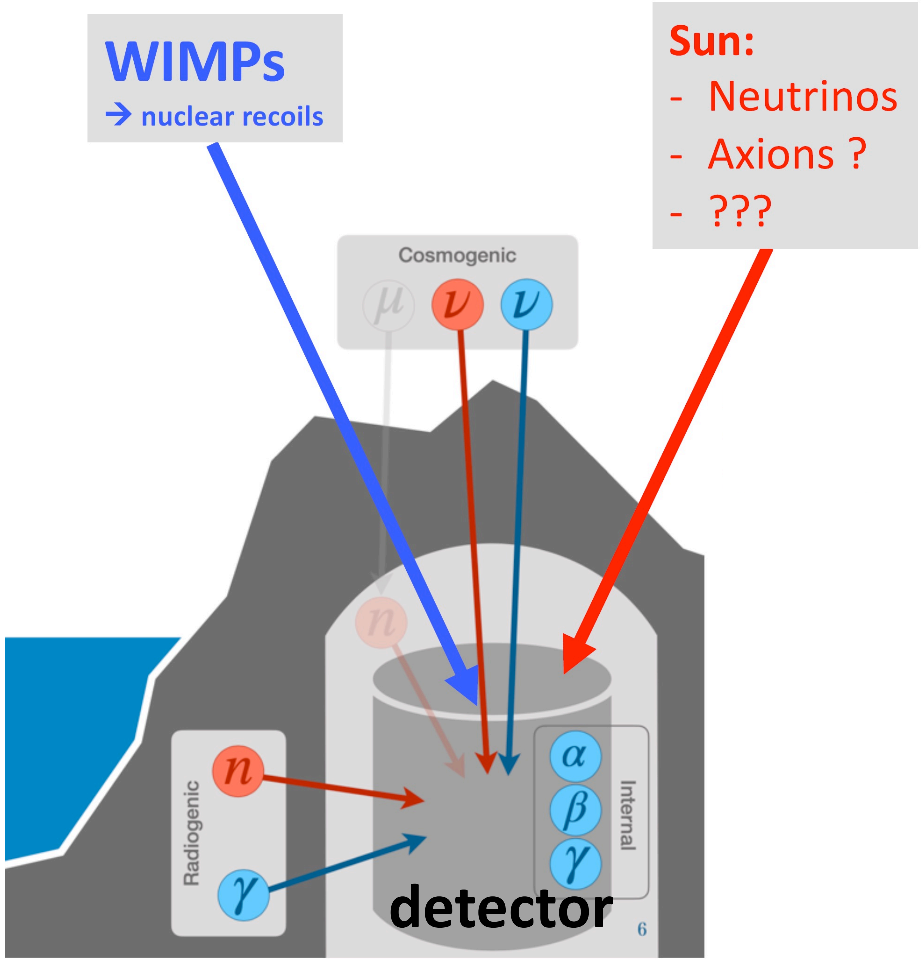
1) Maximize signal

→ big target (detector)

2) Minimize background

→ extreme low radioactive background requirements

→ Reduction and understanding of backgrounds



WIMPs

→ nuclear recoils

Sun:

- Neutrinos
- Axions ?
- ???

2 tasks for any modern experiment:

- Target (detectors) mass (i.e. expected number of “good” events)
- Reduction and understanding of backgrounds

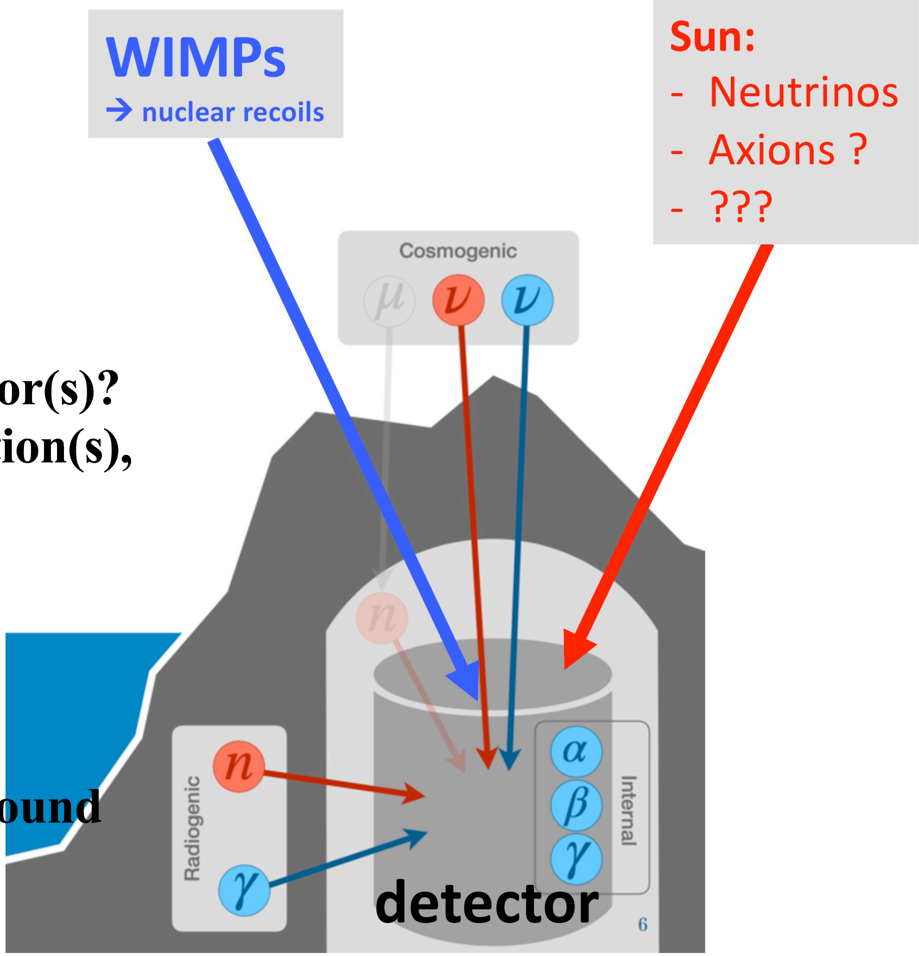
backgrounds

- Cosmic rays and cosmic activation
- Ambient natural radioactivity
  - Radioactivity of materials
  - Radioactive dust
  - Radioactive gases
- Exotic (neutrino induced background, etc)

…

detector(s)

- What parameters of a detector(s)? Energy threshold, good resolution(s), selection power
- Large volume 10 kg – 1 ton
- Efficient shielding, Underground lab, material selection, …



Traditional methods for reduction of backgrounds

- Underground laboratory

- Low radioactive materials
  - Material selection
  - Clean rooms
  - Clean conditions, (include air) during all phases of the experiment
- Veto systems

- Multi layer passive and active shields (include shields from radioactive gases in air, from dust, etc)
  - New bigger detectors provides effective self-shielding

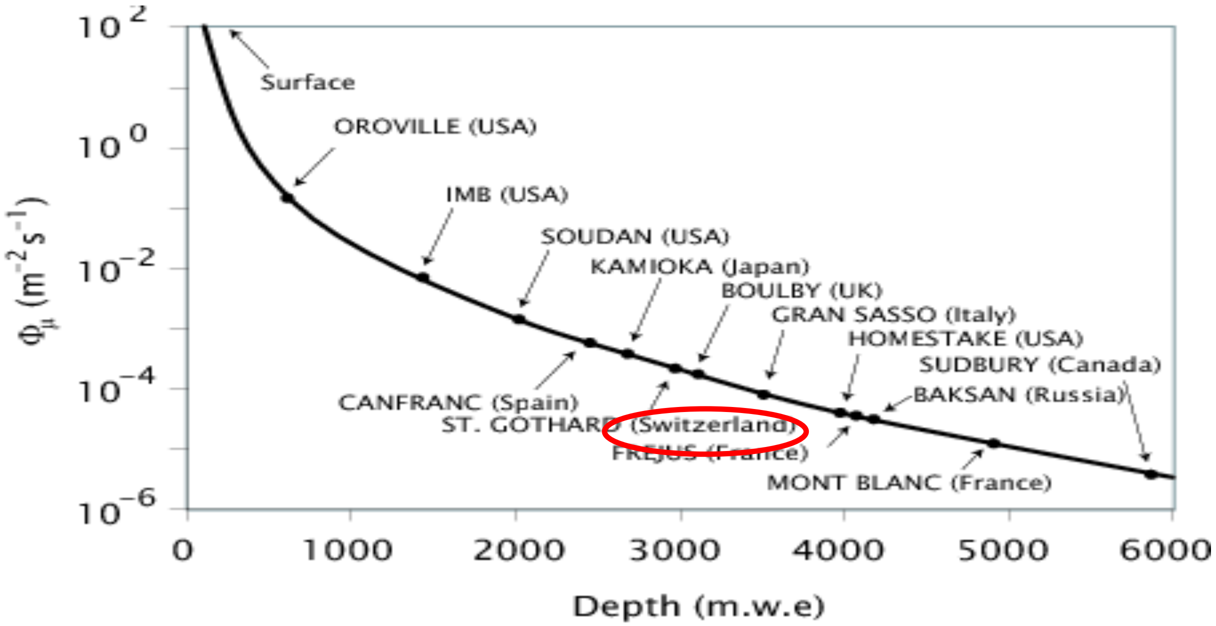
Shield/ underground

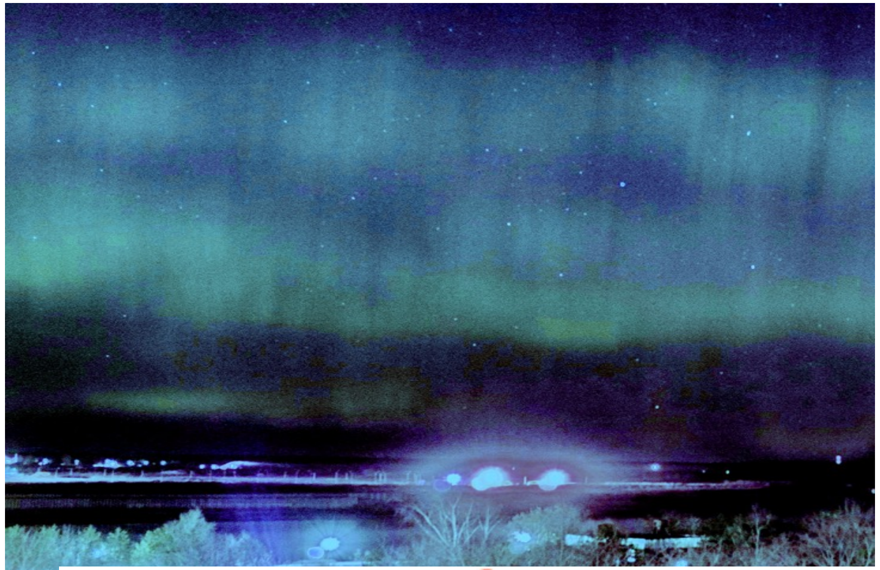
Primary cosmic rays composed essentially of all periodic elements:

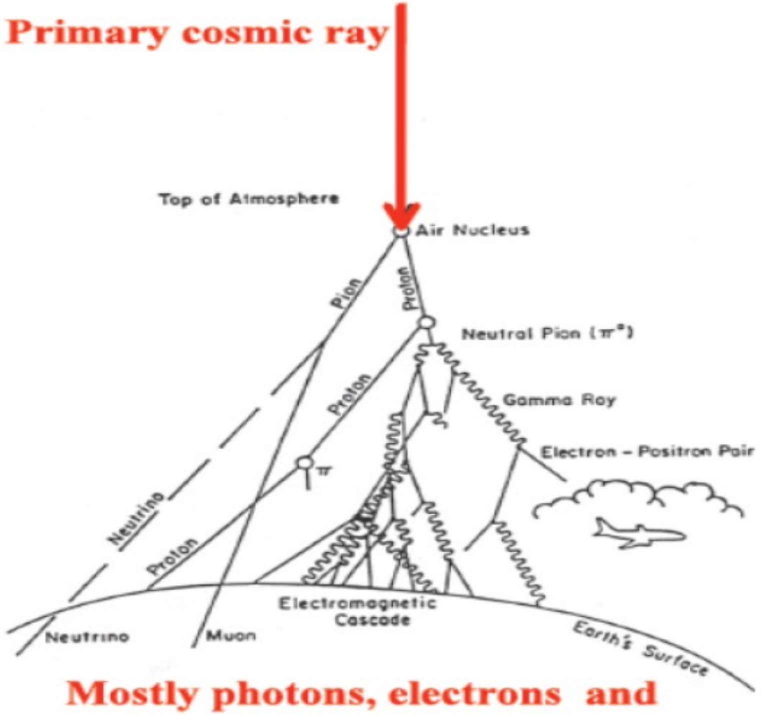
~ 89% protons, ~ 10% helium nuclei

~1% heavy elements (C, O, Si, …)

- At sea level, most are muons with mean energy at 4 GeV, but there are also much higher energies
- Also, about 20% are fast neutrons
- Only deep underground laboratories can provide effective shield from the cosmic







Mostly photons, electrons and muons at Earth's surface

Background / neutrons

Neutron background sources underground:

Low energy neutrons induced by U/Th activities

- fission and (α,n) reactions in the surrounding rock/concrete
- fission reactions in detector shield

High energy neutrons induced by muons

Fight with neutron background:

1) Go underground laboratory / reduce neutron flux by 4+ orders
2) Material selection
3) Muon veto system
4) Passive neutron shield
5) Multi-detector assembly / neutron background identification

Test in Dubna

NaI(Tl) Ø63 mm x 63 mm
PMT Hamamatsu R6091
CAEN Multi channel analyzer DT5780

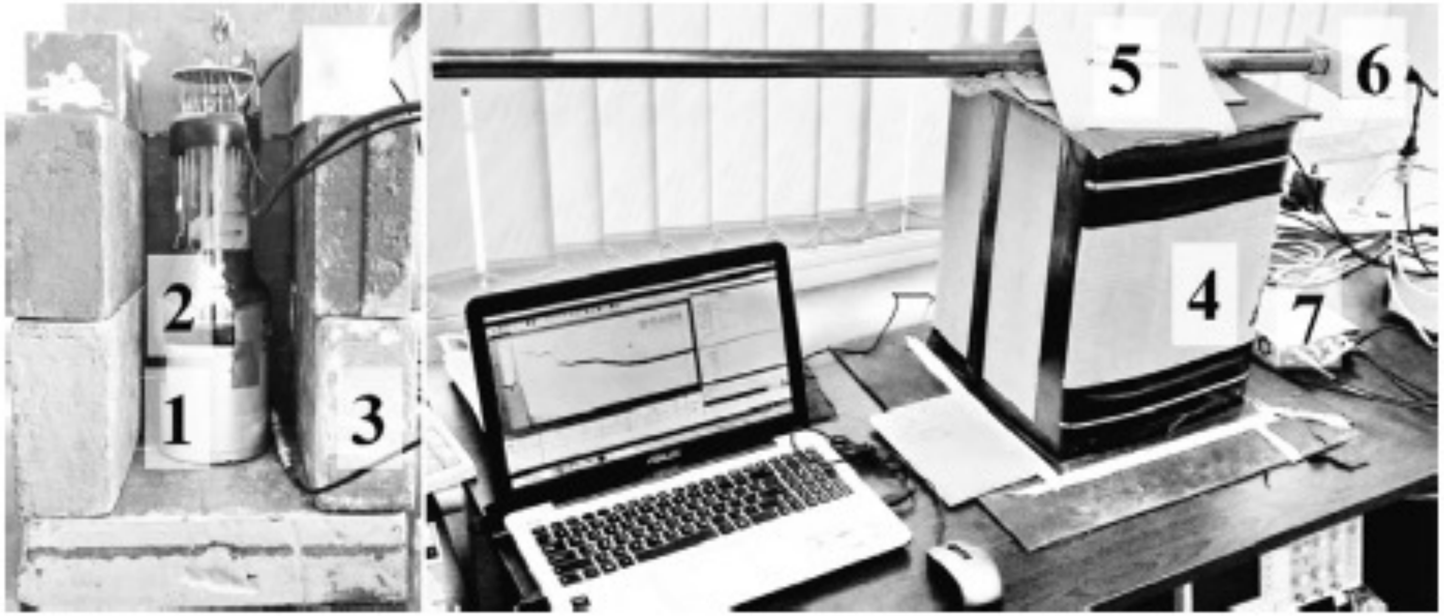
Data acquisition in list mode

Simultaneous measurement with low-background ^{3}He detector CHM-57

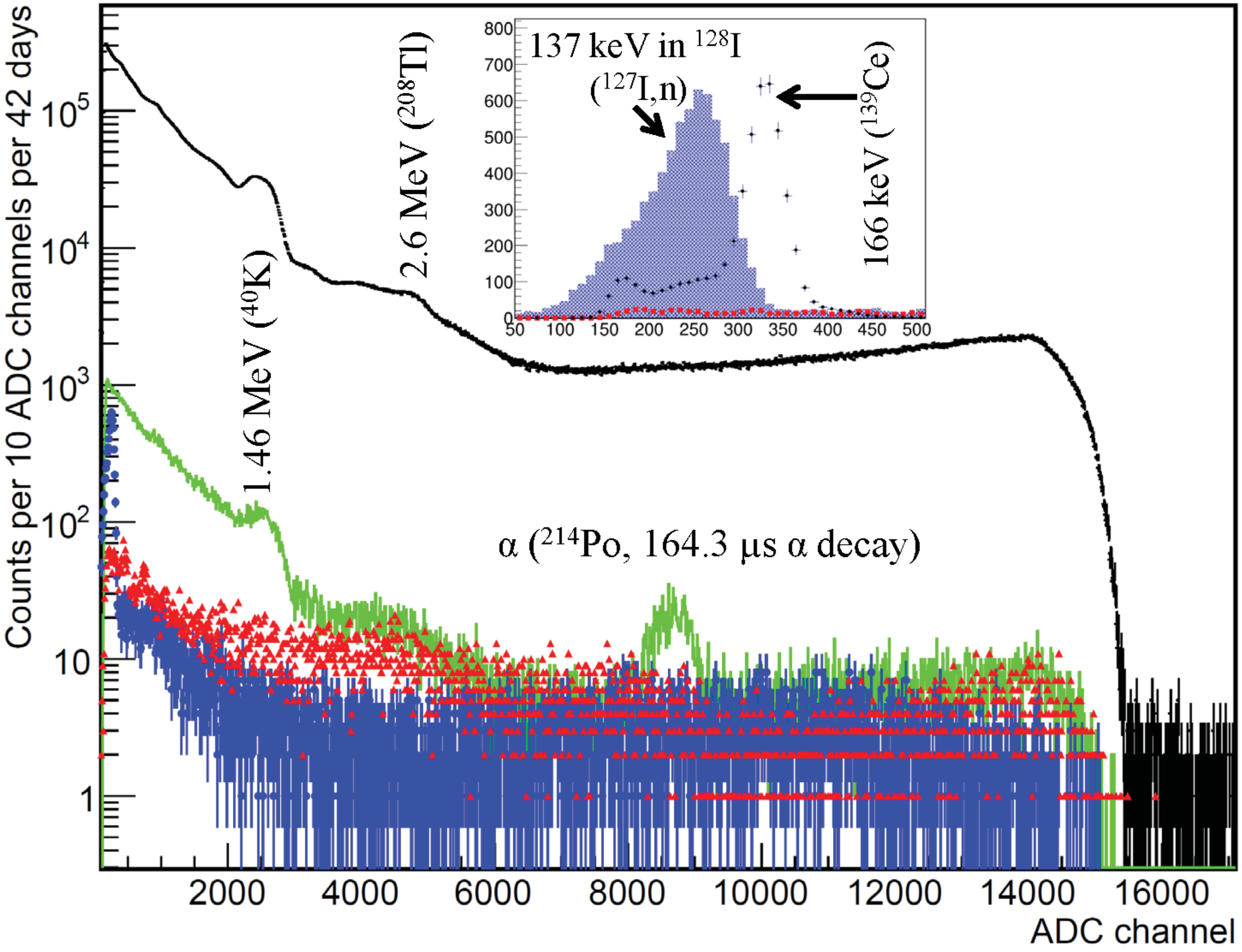
Energy scale calibration near 137 keV with ^{139}Ce (166 keV γ-line)

Strong PuBe neutron source (10^4 n/sec) to verify the effect

Measurements of ambient neutrons



Ambient neutron flux in JINR

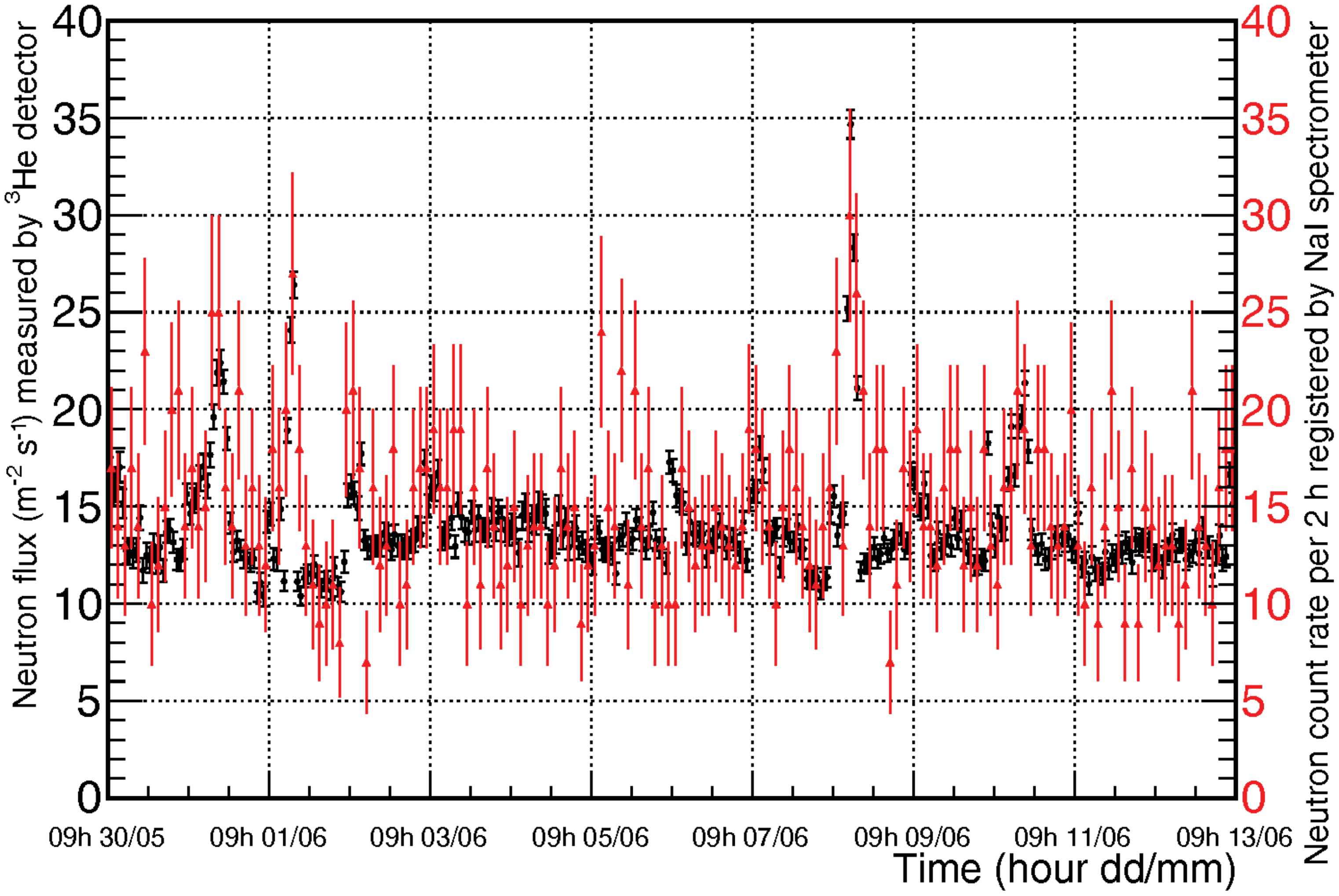


Black — total spectrum.

Red and **Blue** — prompt and delayed signals ($\Delta t = 1.8 - 10$ μs).

Green — delayed signals with $\Delta t = 10 - 500$ μs

Ambient neutron flux in JINR



Red dots – neutron events in the NaI(Tl) detector

Black dots – neutron flux measured by the ^{3}He counter

Absolute sensitivity to thermal neutrons is **6.5 ± 1.0 counts sec^{-1}** for thermal 4π neutron flux **1 n cm^{-2} sec^{-1}**

Accidental background for this detector and shield is **0.8 events day^{-1}** for any delay time window at **1 μsec**

NaIL detector and experimental setup

Size: 127x152мм

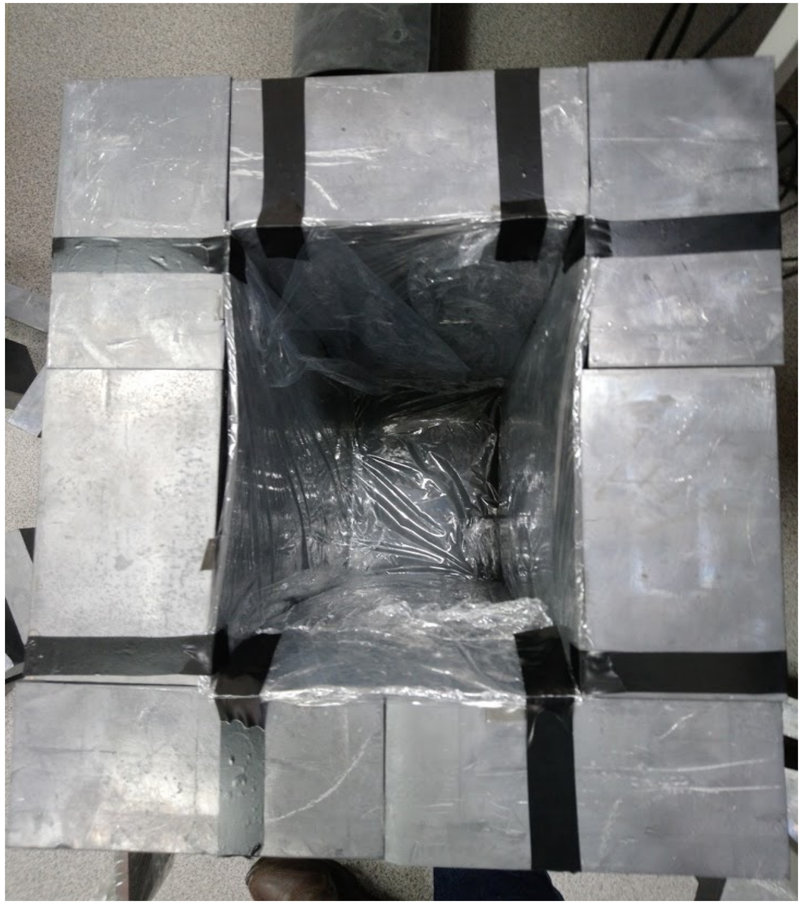
Resolution at 662keV of ^{137}Cs: ≈ 6.7%

Natural Li concentration: ≈ 1% of the number of atoms in the crystal

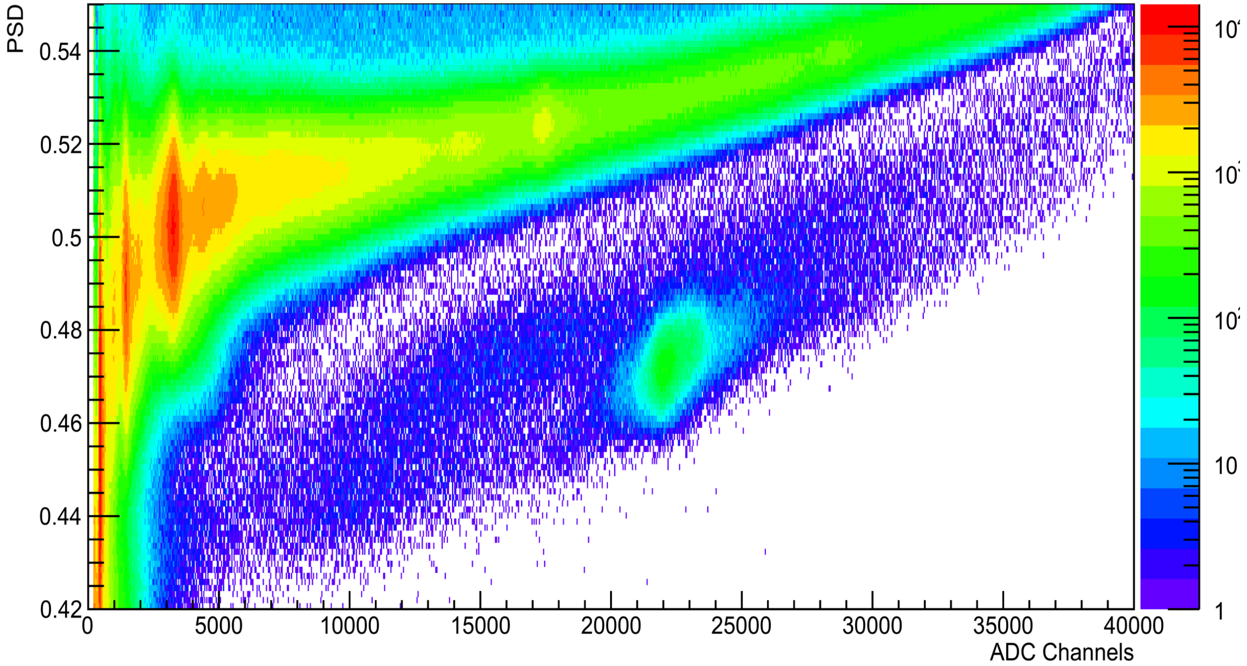
Density: 3.66 g/cm^3

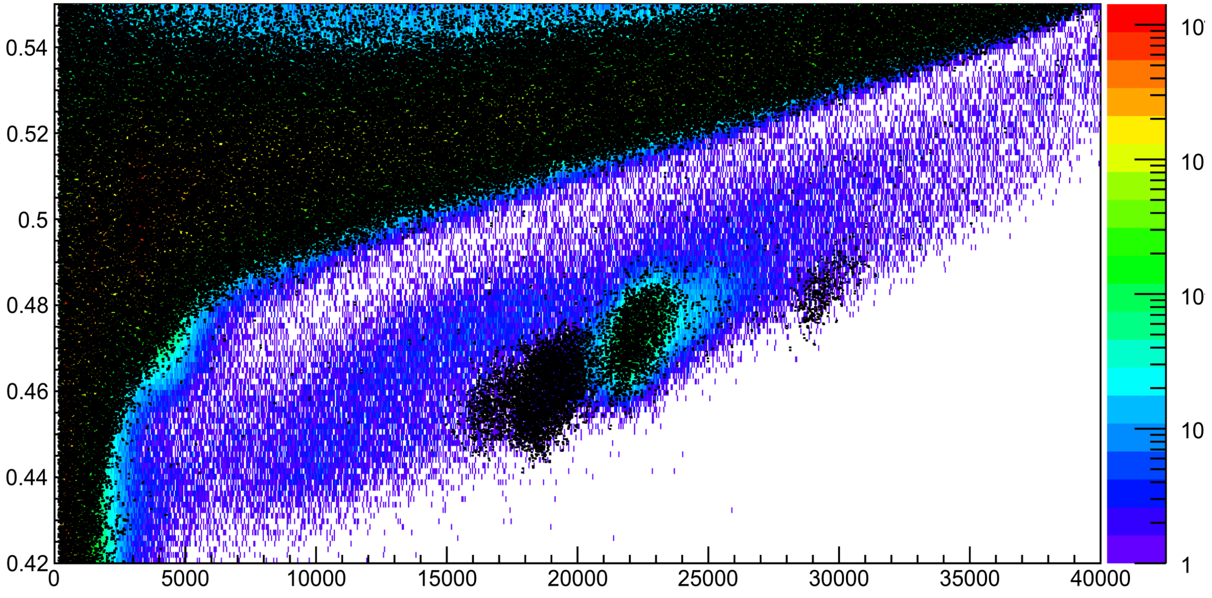
Shield: borated rubber + cm of lead

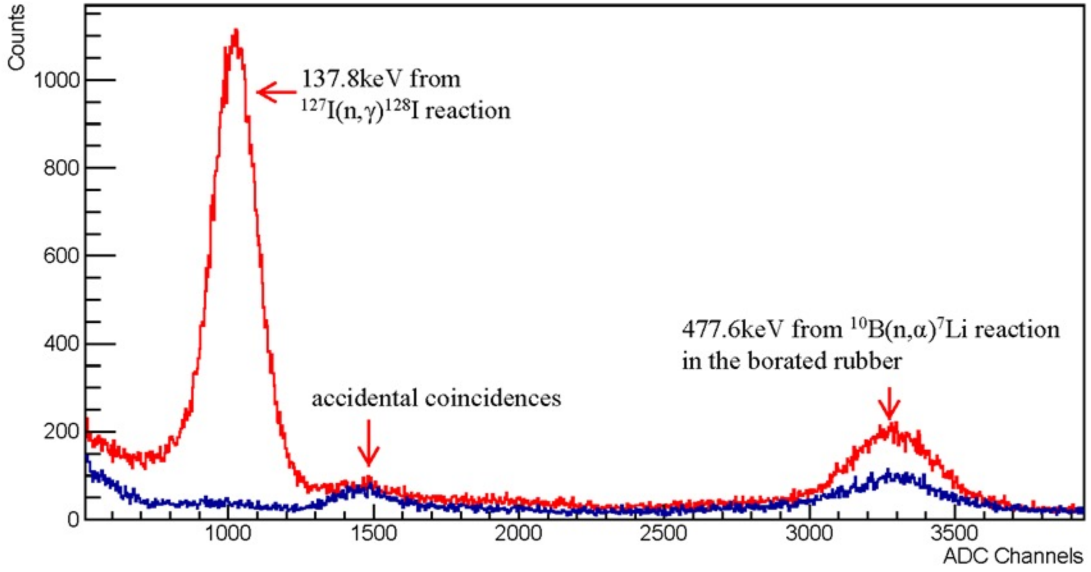
MCA: CAEN DT5725 with PSD firmware



Measurements with NaIL detector



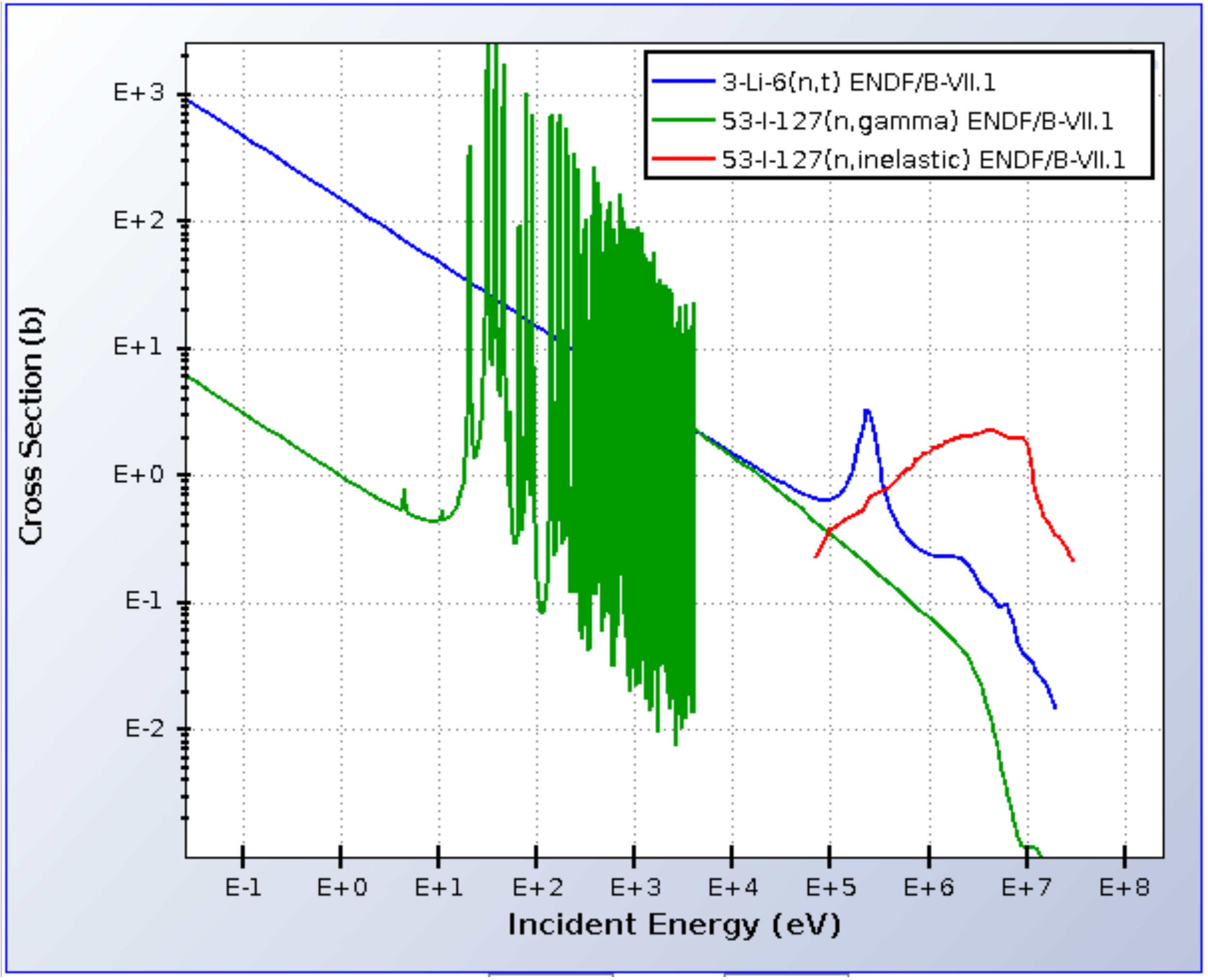




^{6}Li(n,t)^{4}He:
For PSD two gates was used :
Short gate- 350ns
Long gate- 700ns
α-background: Contamination by 238U chain,
Approx. 170 events per day from ^{214}Po

^{127}I(n,γ)^{128}I:
Delay time window 0.9-10µs for neutron events
Shifted delay window 10.9-20µs for background determination

Three ways to neutron detection with NaI(Tl+Li)



Ponomarev D., et al. **NaI(Tl+Li) scintillator as multirange energies neutron detector** // Journal of Instrumentation. 2021. Vol. 16, no. 12. P. 12011. https://doi.org/10.1088/1748-0221/16/12/P12011

- Thermal neutron capture on Li-6:

  $^{6}Li+n_{th}\rightarrow{}^{4}He+{}^{3}H+4.79$ MeV, $\sigma=940$ b;

- Epithermal neutron capture on I-127:

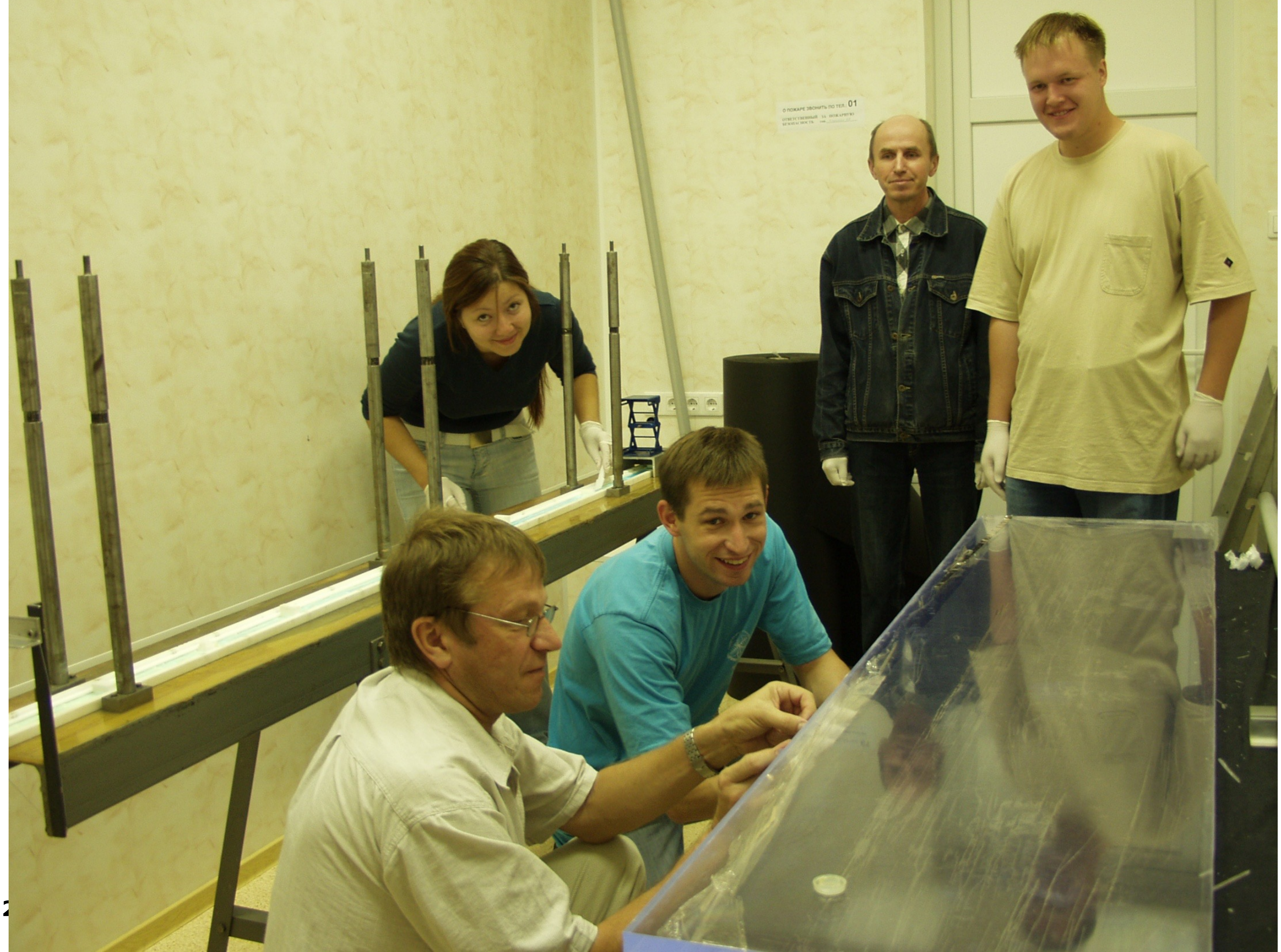
  $^{127}I+n_{th}\rightarrow{}^{128}I^{*}+6.8$ MeV $\sigma_{th}=6.2$ b,

  For the neutrons with the energies from 50 eV to 10 keV the integral of the resonances is 153.9 b;

- Inelastic scattering of fast neutrons on I-127 with excitation of 57.6 keV and 202.86 keV.

  E_n= 2.8MeV: $\sigma_{57}=0.43$ b, $\sigma_{202}=0.16$ b,
  E_n= 14.1MeV: $\sigma_{57}=0.28$ b, $\sigma_{202}=0.11$ b,

Panels of the active muon veto system


О ПОЖАРЕ ЗВОНИТЬ ПО ТЕЛ. 01
ОТВЕТСТВЕННЫЙ ЗА ПОЖАРНУЮ БЕЗОПАСНОСТЬ