Исследование двойного бета распада на спектрометрах TGV-2 и Obelix

TGV-2

Obelix

Н.И.Рухадзе Дубна 2018

Double beta decay

• *two-neutrinos double beta decay (2νββ)*

(Z-2,A) → (Z,A)+2e^-+2υ_e **(2νβ⁻ β⁻)** observables: 2 e^-

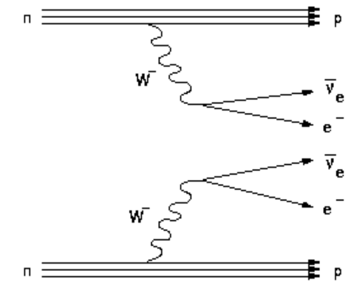
(Z+2,A) → (Z,A)+2e^++2υ_e **(2νβ⁺ β⁺)** observables: 2 e^+, 4×511 keV γ

e^-+(Z+2,A) → (Z,A)+e^++ 2υ_e **(2νβ⁺/EC)** observables: 1 e^+, 2×511 keV γ, X-ray

2e^-+(Z+2,A) → (Z,A)+2υ_e +2X **(2νEC/EC)** observables: 2 X-rays

$(T_{½}^{2\upsilon})^{-1} = G^{2\nu}(Q,Z)\,|M^{2\upsilon}|^2$

$T_{½}^{2\upsilon} \approx 10^{19} - 10^{24}$ *years*



Feynman diagram for 2νββ

• *neutrinoless double beta decay (0νββ)*

(Z-2,A) → (Z,A)+2e^- **(0νβ⁻ β⁻)**

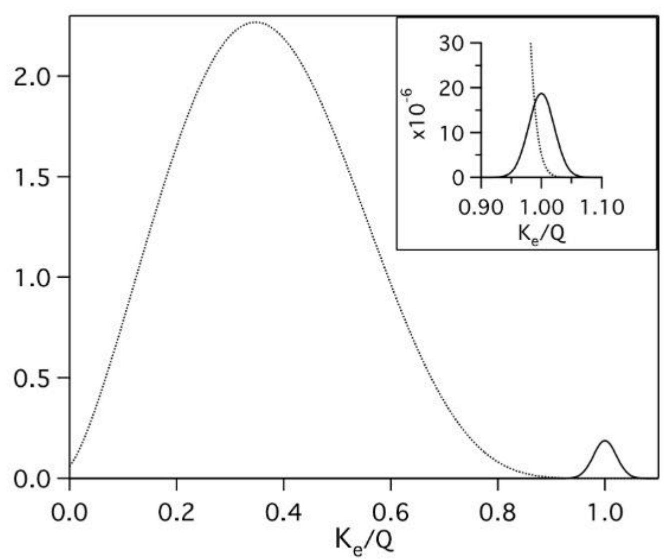
(Z+2,A) → (Z,A)+2e^+ **(0νβ⁺ β⁺)**

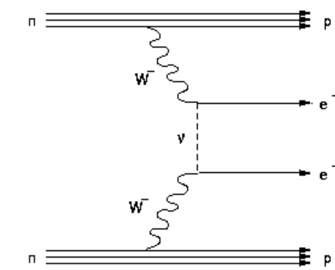
e^-+(Z+2,A) → (Z,A)+e^+ **(0νβ⁺/EC)**

2e^-+(Z+2,A) → (Z,A)* → (Z-2,A)+(γ)+2X **(0νEC/EC)**

$(T_{½}^{0\upsilon})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\upsilon}|^2\,\left|m_{\beta\beta}\right|^2$

$T_{½}^{0\upsilon} \gtrsim 10^{24}$ *years*





Feynman diagram for 0νββ

SEARCH FOR DOUBLE BETA DECAY

At present **$2\nu2\beta^-$** decay was detected in 11 nuclei:

^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U

2νEC/EC in **^{130}Ba** was detected in geochemical experiment (A.P.Meshik et al.. Phys. Rev. C **64**, 2001, 035205) and there is the indication on **2νEC/EC** in **^{78}Kr** (Yu.M.Gavrilyuk et al., Phys. Rev. C **87**, 2013, 035501).

Double beta decay to excited states of daughter nuclei are accompanied by emission of γ-quanta in de-excitation of excited states. These γ-quanta may be detected by low background HPGe detectors with high efficiency and good energy resolution.

$2\nu2\beta^-$ decay to excited states was detected in

^{100}Mo - ^{100}Ru (0^+_1, 1130.3 keV) and **^{150}Nd - ^{150}Sm (0^+_1, 740.4 keV)**.

DOUBLE BETA DECAY OF ^{106}Cd		Experimental signature (TGV-2)
EC/EC	$2e_b^- + {}^{106}Cd \rightarrow {}^{106}Pd + (2\nu_e) + (\gamma)$	2KXPd (+γ for e.s.)
β+/EC	$e_b^- + {}^{106}Cd \rightarrow {}^{106}Pd + e^+ + (2\nu_e) + (\gamma)$	KXPd + 2γ 511 (+ γ for e.s.)
β+β+	${}^{106}Cd \rightarrow {}^{106}Pd + e^+ + e^+ + (2\nu_e) + (\gamma)$	4γ 511 (+ γ for e.s.)

0νEC/EC DECAY to the ground state

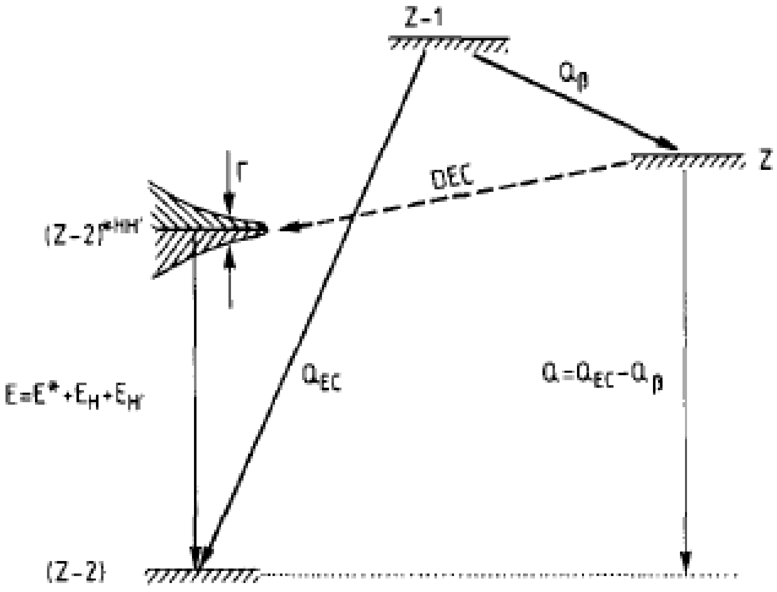
$$2e_b^- + (A,Z) \rightarrow (A,Z-2) + 2X + (\gamma_{brem}, 2\gamma, e^+e^-, e^-_{int})$$

$$E\gamma,.. = \Delta M - \varepsilon_{e1} - \varepsilon_{e2}$$

Suppression factor is **~ 10^4** (in comparison with ECβ+(0ν)) –

M. Doi and T. Kotani, Prog. Theor. Phys. 89 (1993)139.

0νEC/EC Resonance Transitions $(A,Z)\rightarrow(A,Z-2)^{*HH'}$



J. Bernabeu, A. DeRujula, C. Jarlskog, Nucl. Phys. B 223, 15 (1983)

Atom mixing amplitude
ΔM

$$E \simeq E^* + E_H + E_{H'},$$

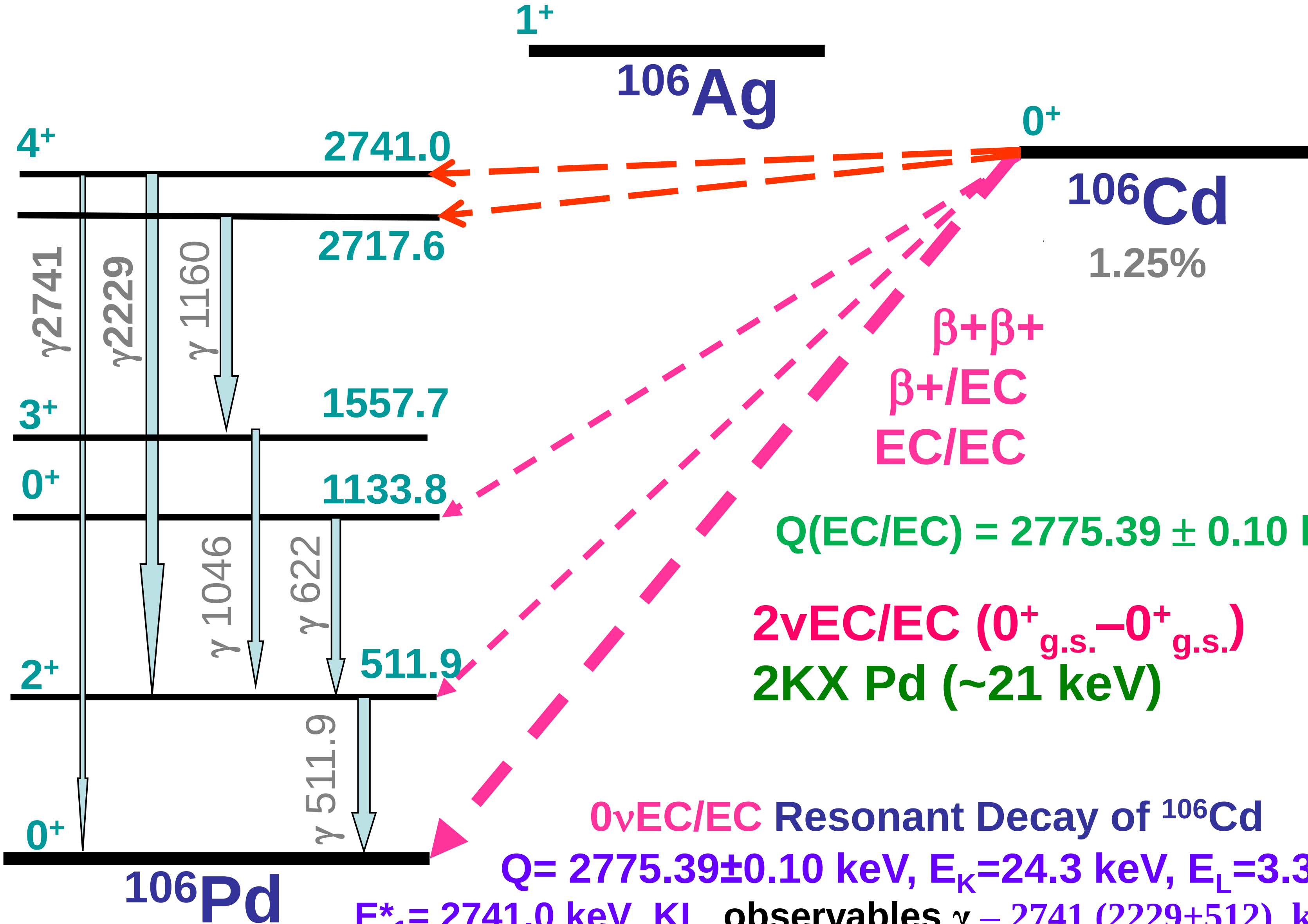
$$\Gamma \simeq \Gamma^* + \Gamma_H + \Gamma_{H'}.$$

Decay rate

$$\frac{1}{\tau} \simeq \frac{(\Delta M)^2}{(Q-E)^2 + \frac{1}{4}\Gamma^2}\Gamma,$$

Enhancement factor on the level of 10^4-10^6 may be obtained for |Q-Q'res| < 1 keV

Z. Sujkowski, S. Wycech,Phys. Rev. C 70 (2004) 052501.



0νEC/EC Resonant Decay of ^{106}Cd

Q= 2775.39±0.10 keV, E_K=24.3 keV, E_L=3.33 keV

E^*_1= 2741.0 keV KL observables γ – 2741 (2229+512) keV

E^*_2= 2717.6 keV KK observables γ – (1160 + 1046 + 512) keV

E^*_3= 2737 keV (?) KL observables γ – ?

Phase III - Search for 0νEC/EC decay of ^{106}Cd → Obelix det.

Experiment TGV-2 (DOUBLE BETA DECAY OF ^{106}Cd)

JINR Dubna, Russia,
IEAP, CTU Prague, Czech Republic,
CU Bratislava, Slovakia,
CSNSM Orsay, France
LSM Modane, France

Laboratoire Souterrain de Modane, France

Phase I ~10g (12 samples) of ^{106}Cd (75%) and ~3.2 g (4 samples) of Cd-nat.
T= 8687h (Feb.2005 –Feb.2006)

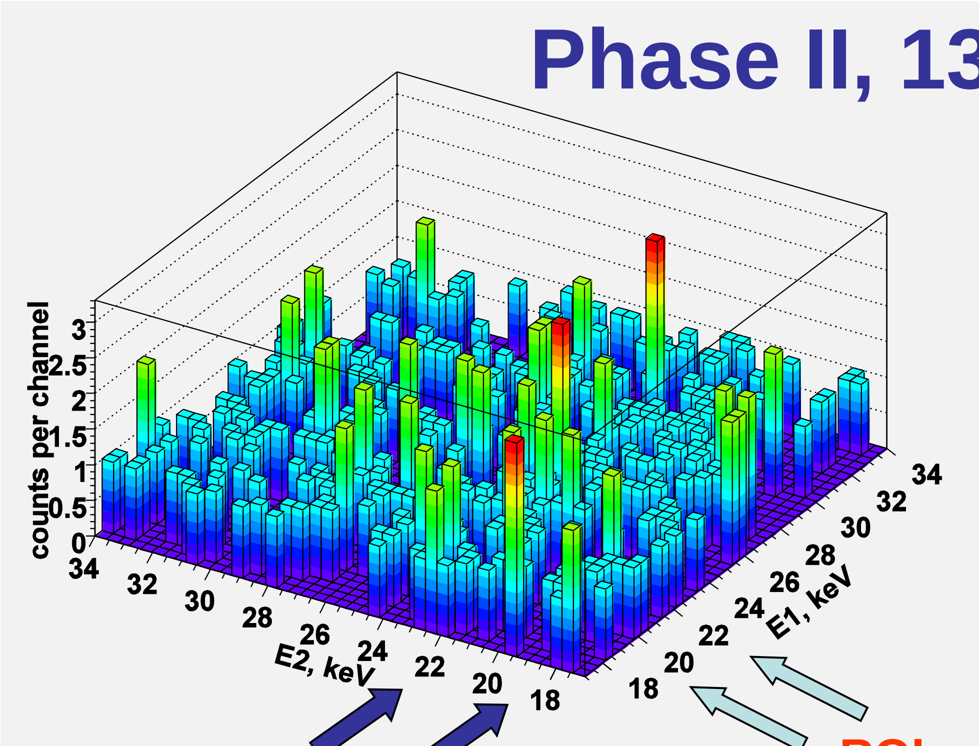
Phase II ~ 13.6 g (16 samples) of ^{106}Cd (75%)
T = 12900h (Dec.2007 – July 2009)

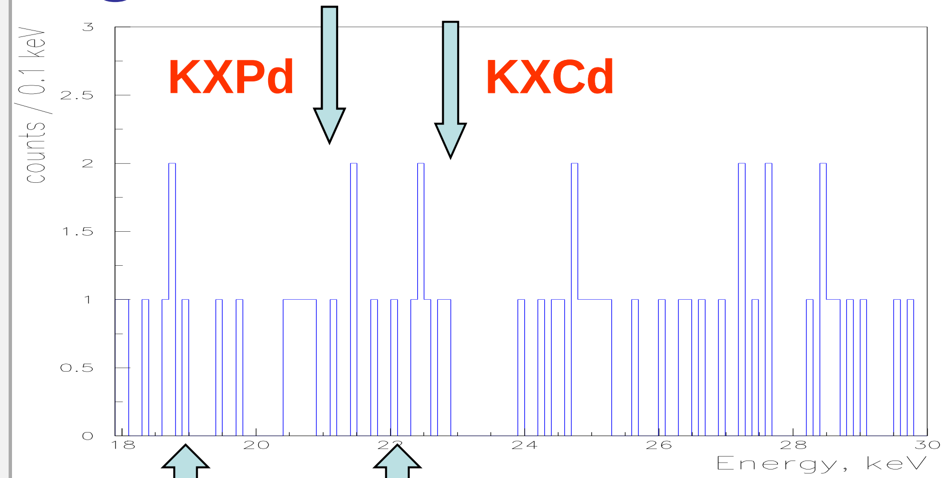
Background I no samples (Aug.2009 – Mar.2010)

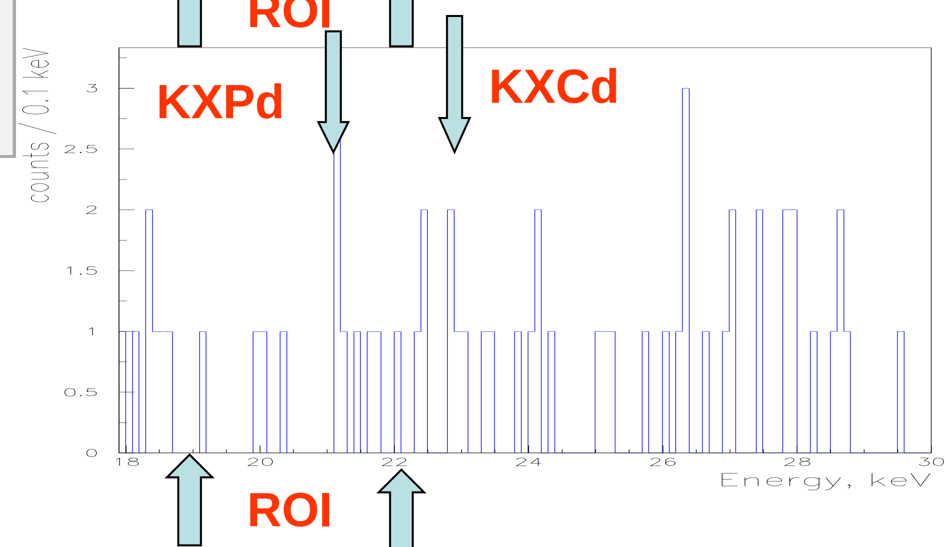
Background II 16 samples of Cd.-nat (April 2010 – Nov. 2013)

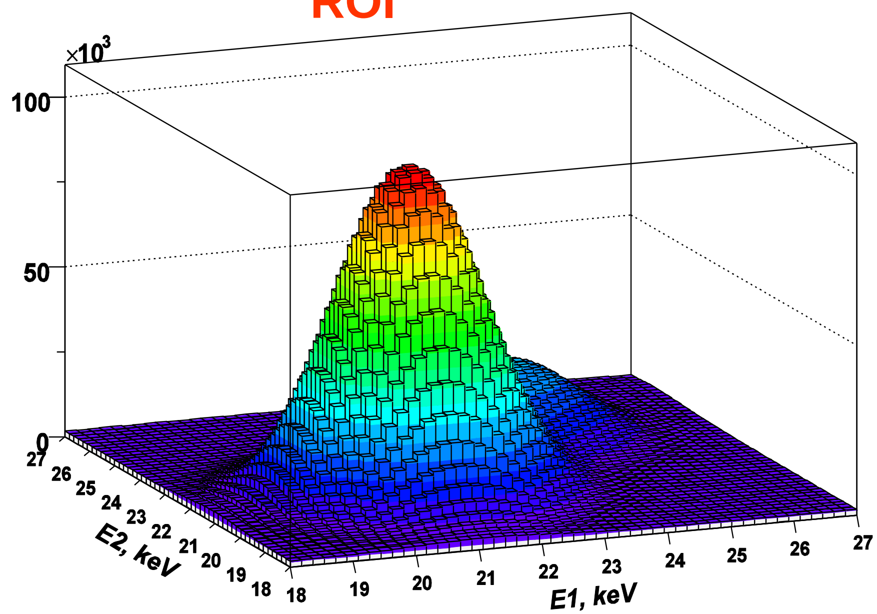
Phase III ~ 23.2 g (16 samples) of ^{106}Cd (99.57%)
(Feb.2014 – Sep.2015, Apr.2016 – ….) T>25000h

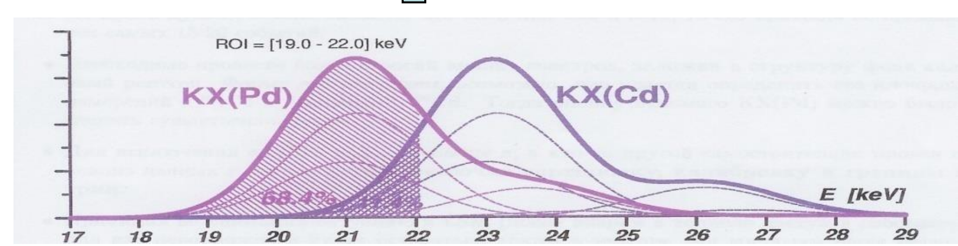
Phase II, 13.6g of ^{106}Cd, T=12900h











Telescope Germanium Vertical (TGV-2)

32 HPGe planar detectors ∅60 mm x 6 mm

with sensitive volume: 20.4 cm^2 x 6 mm

Total sensitive volume: ~400 cm^3

Total mass of detectors: ~3 kg

Total area of samples : 330 cm^2

Total mass of sample(s) : 10 ÷ 25 g

Total efficiency : 50 ÷ 70 %

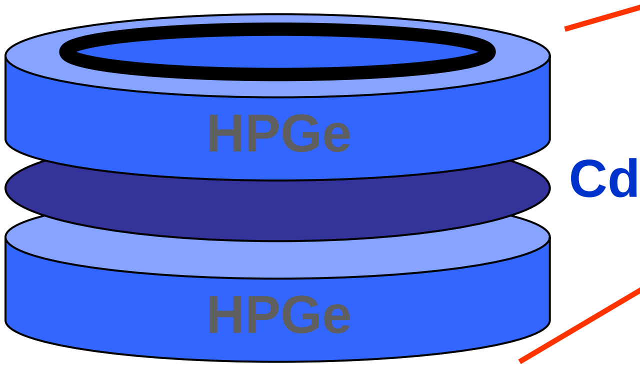
E-resolution : 3 ÷ 4 keV @ ^{60}Co

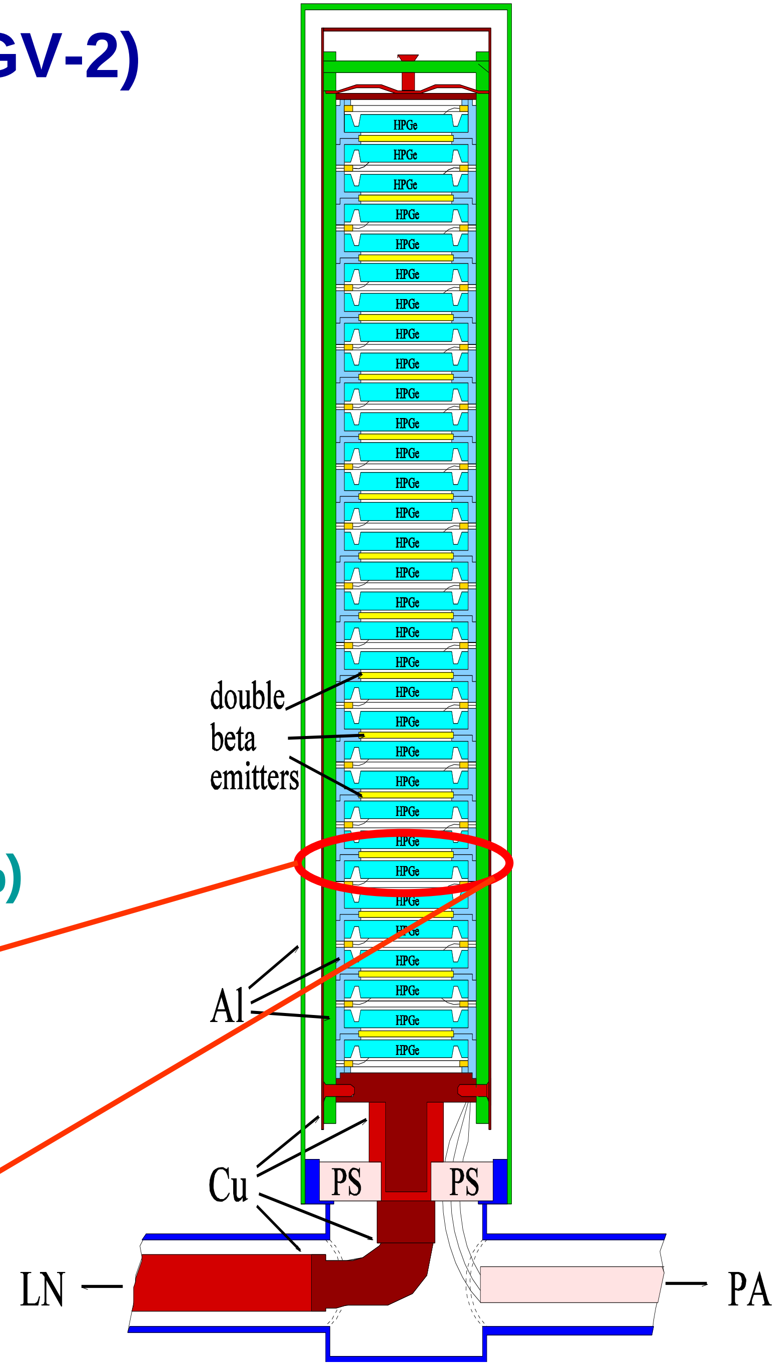
LE-threshold : 5 ÷ 6 keV

Double beta emitters:

16 samples (~70μm) of ^{106}Cd (enrich.99.57%)

~23.2 g (~ 1.3 x 10^{23} atoms) of ^{106}Cd

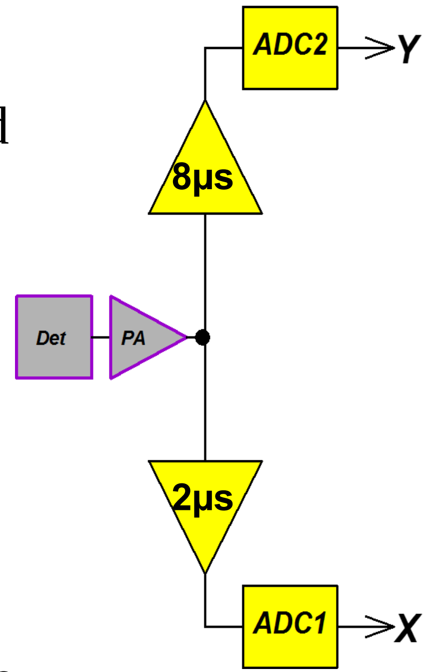


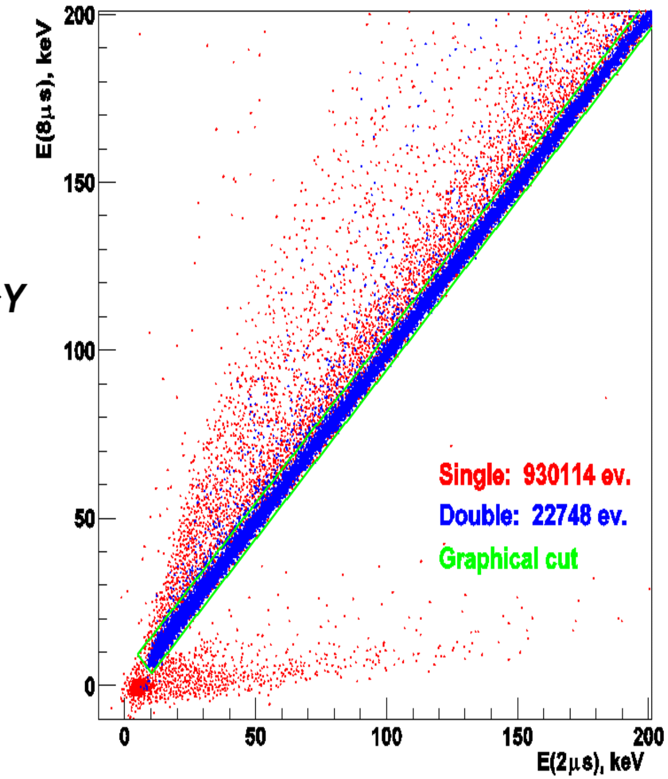


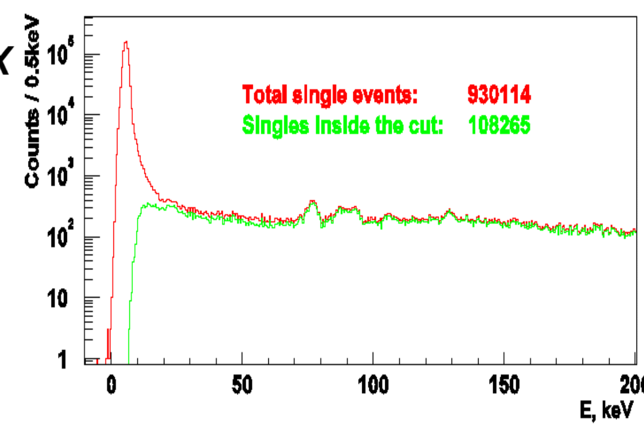
Background suppression

- **Passive shielding**
  - Modane Underground Laboratory
  - Pb + Cu
  - airtight box against radon
  - anti-neutron shielding (borated polyethylene)
- **Construction**
  - Radiopure materials
  - Minimization of amount of construction materials
- **Electronics**
  - telescopic construction (double coincidences from neighboring detectors)
  - double-shaping selection of low energy events

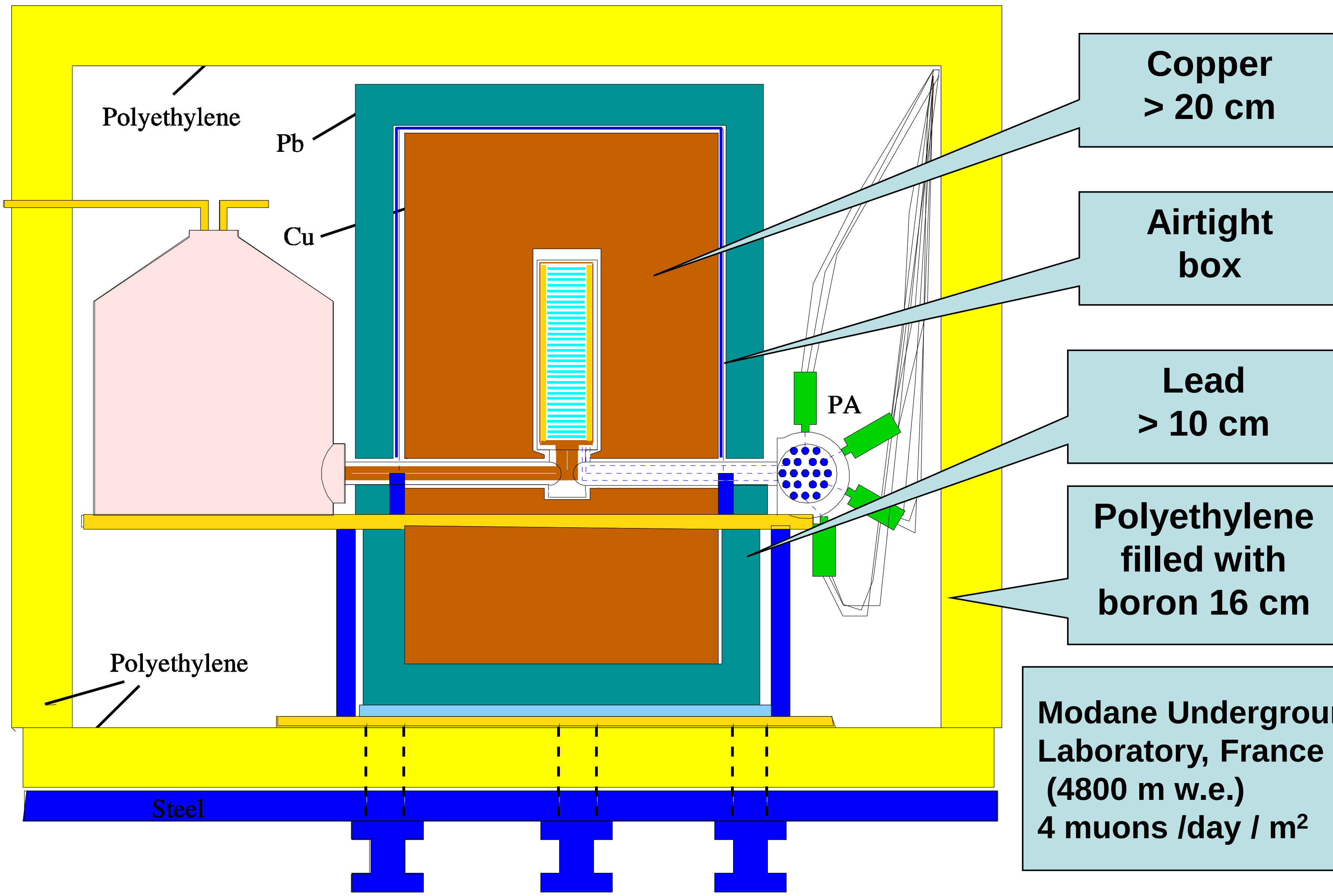
Suppression of microphonic noise



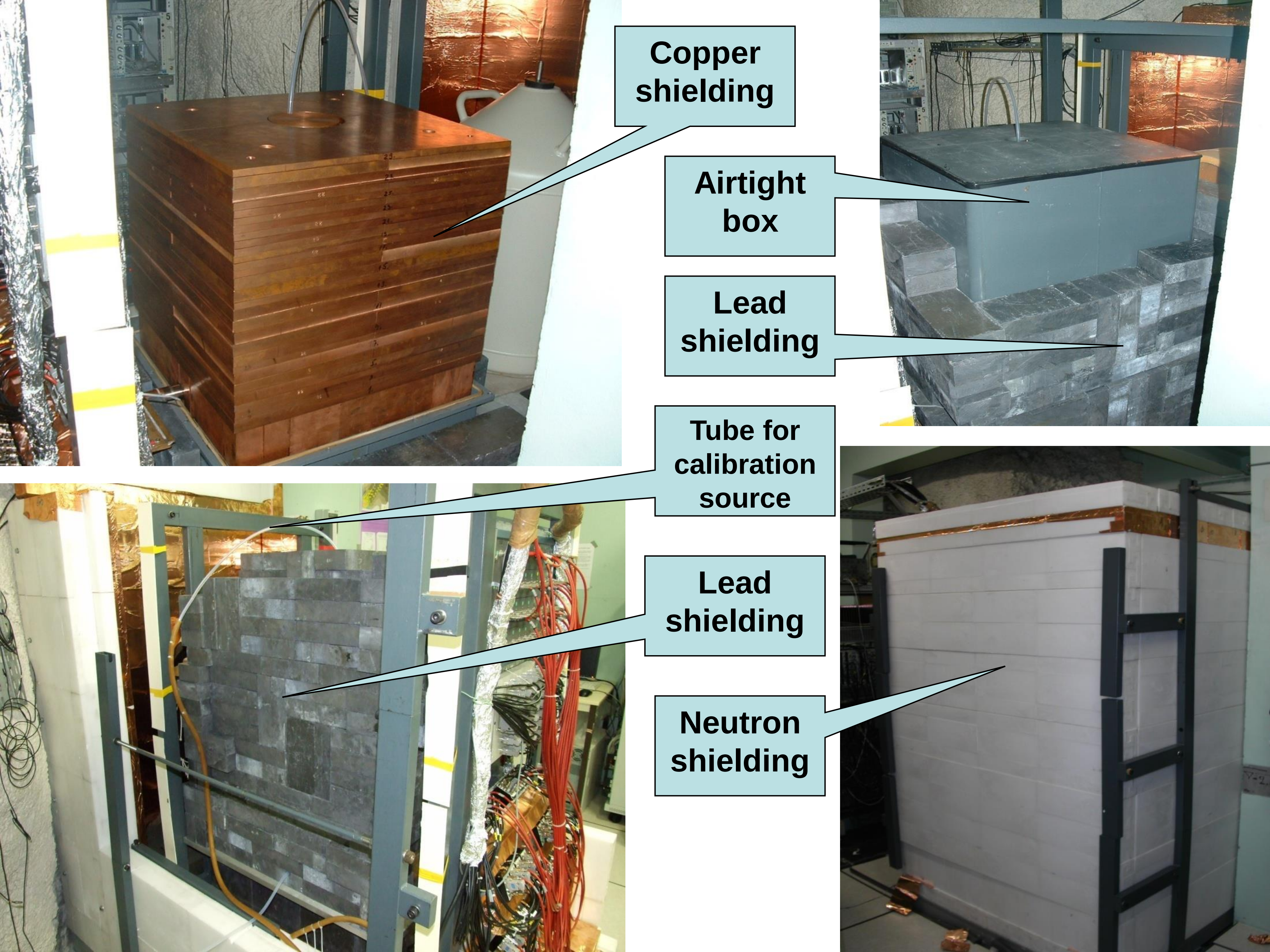




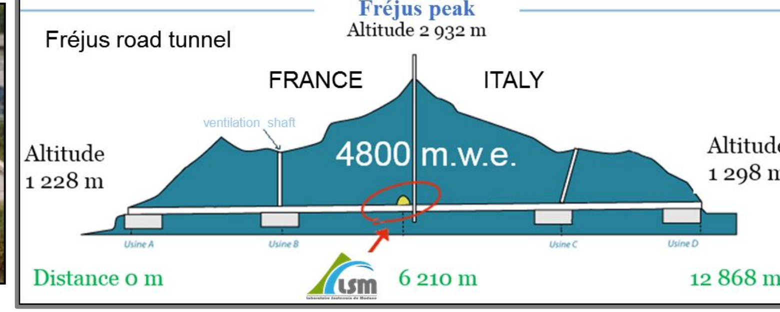
PASSIVE SHIELDING



Modane Underground Laboratory, France (4800 m w.e.)
4 muons /day / m^2

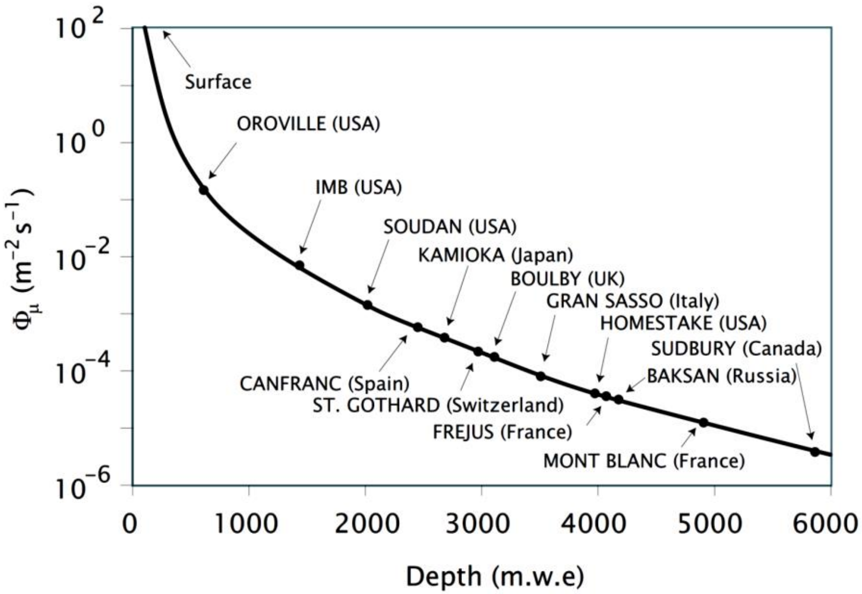

Copper shielding
Airtight box
Lead shielding
Tube for calibration source
Lead shielding
Neutron shielding

Laboratoire Souterrain de Modane



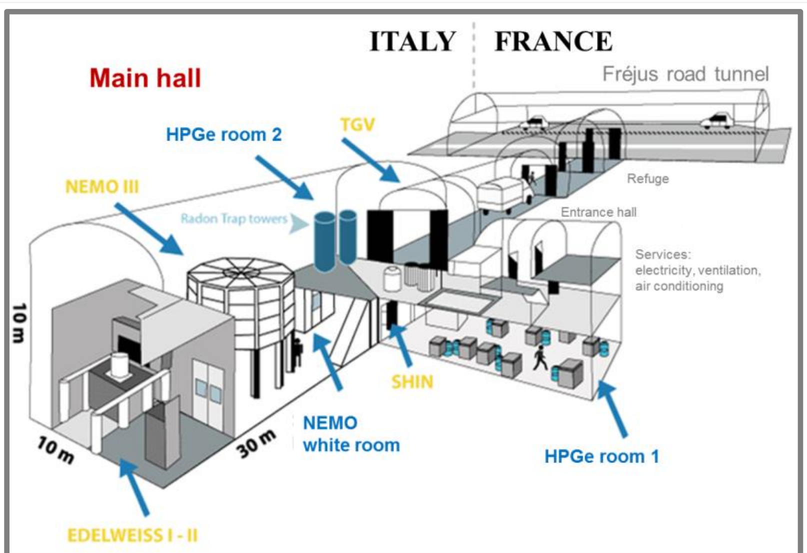
Fréjus Tunnel at the French-Italian border

Depth - 1800 m of rock (4800 mwe)

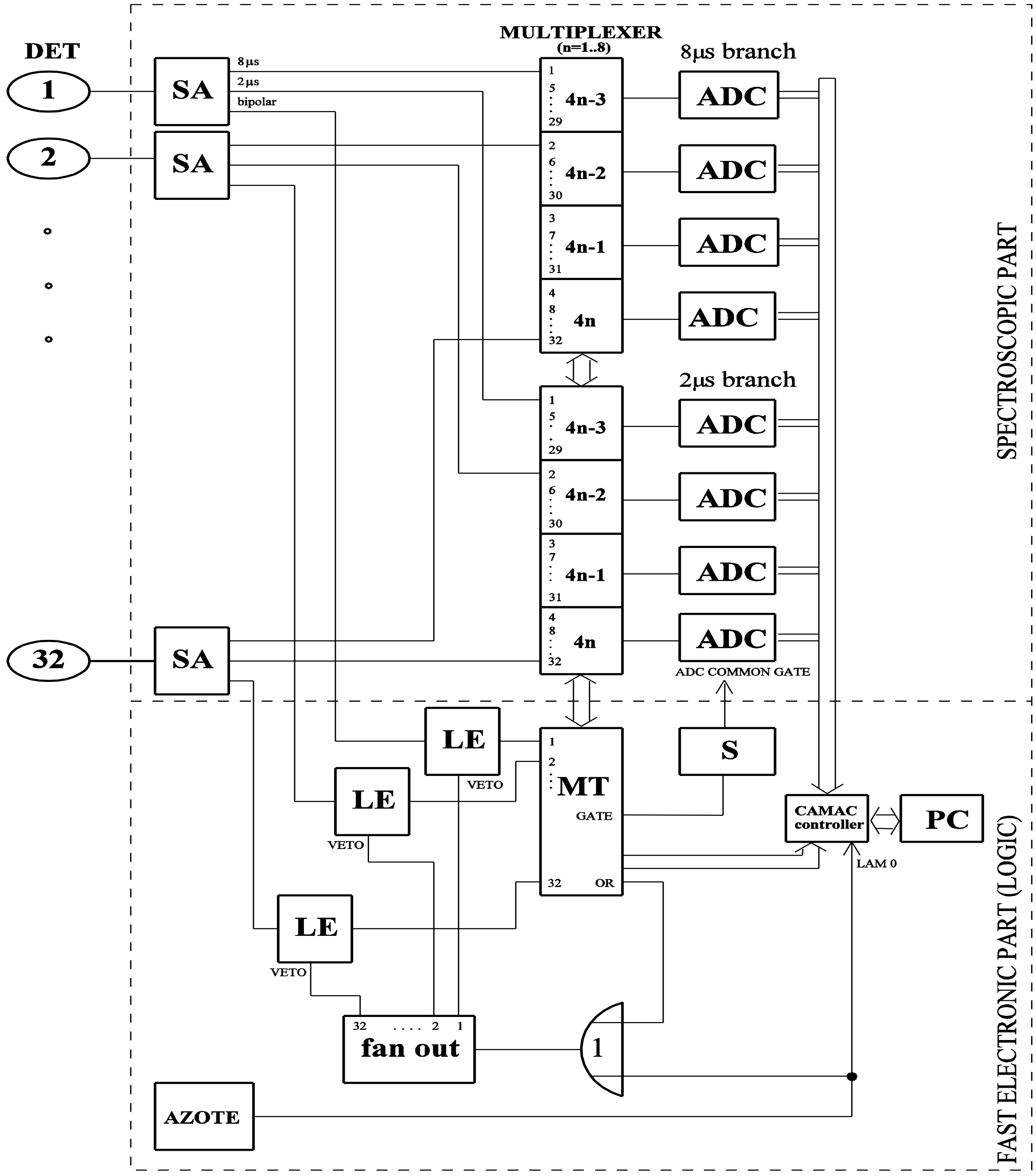


Muons flux - 4 muons / m^2 x day^{-1} ($2x10^6$ reduction factor)

Neutrons flux - 3000 neutrons(fast) /m^2 x day^{-1} (1000 reduction factor)



Блок-схема электронной части TGV-2



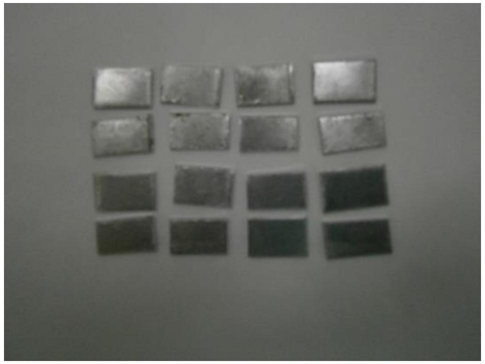
Изменения в электронной схеме с начала 3-й фазы

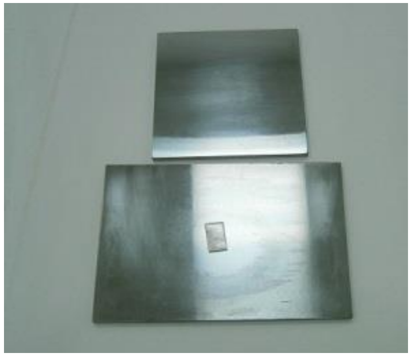
Заменены все блоки LE на PS Octal Discriminators 705

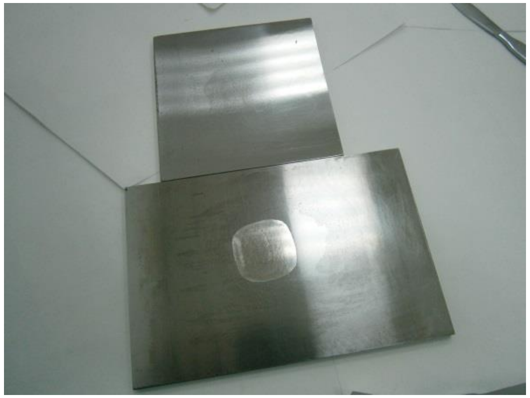
Заменены 28 из 64 спектр. усилителей (Canberra 2022 – 14, и БФУ 314 – 14 каналов)

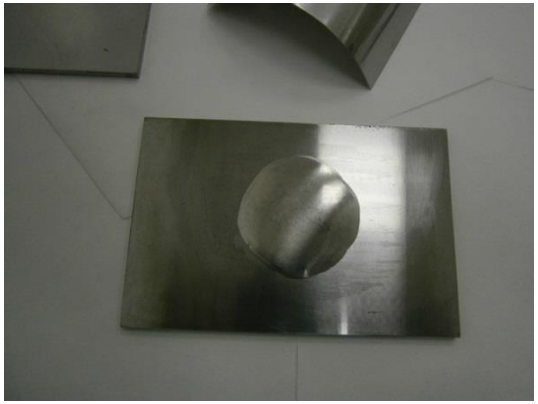
Изготовлен новый модуль управления, объединяющий МТ (годоскоп) и мультиплексеры – он будет установлен в 2018 году

Preparation of ^{106}Cd foiles (Dubna, October 2013)





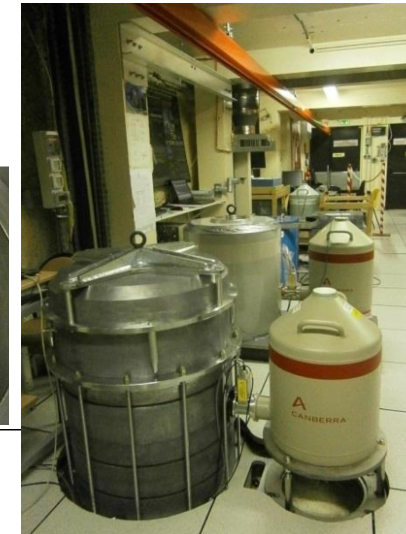


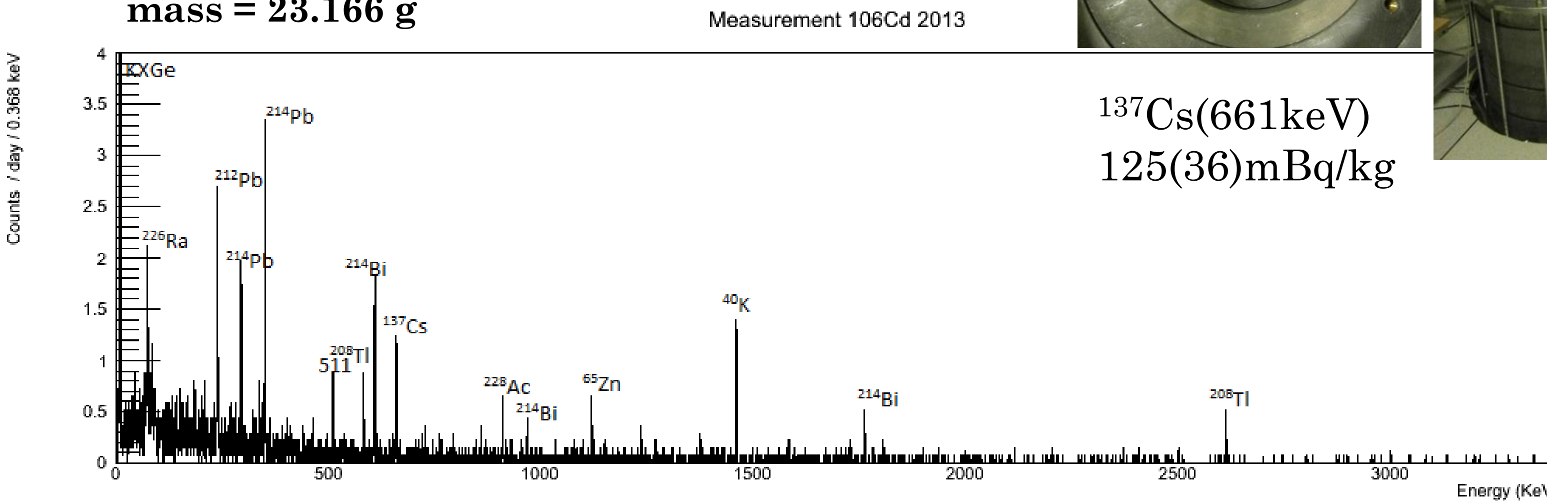


16 circle foils:
thickness = 70±10 mg/cm^2
diameter = 52 mm
mass = 23.166 g
enrichment= 99.57%.

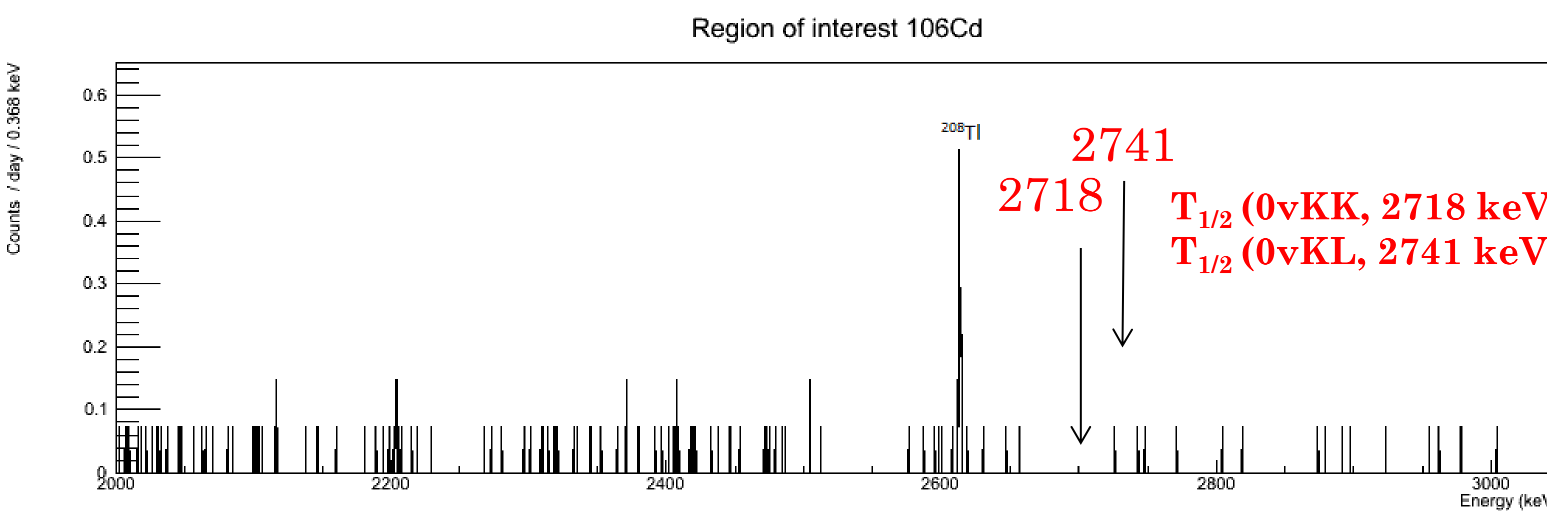
Measurement of ^{106}Cd with 600 cm^3 HPGe detector Obelix, November 2013, T=395 h

16 circle foils of ^{106}Cd
with enrich. 99.57%
Ø = 52 mm
thick. 70(10) mg/cm^2
mass = 23.166 g





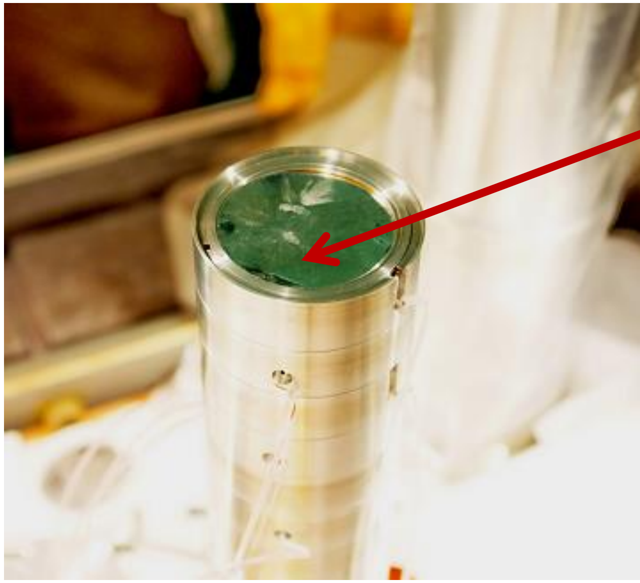
^{137}Cs(661keV)
125(36)mBq/kg

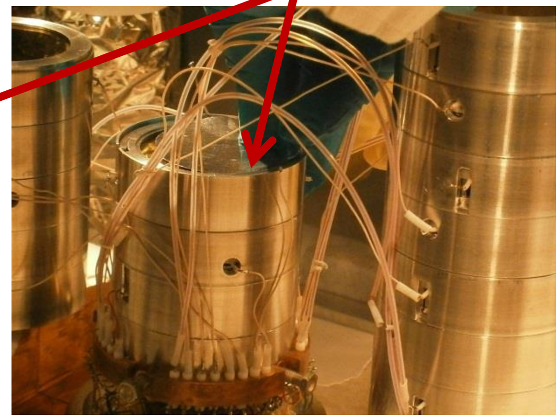


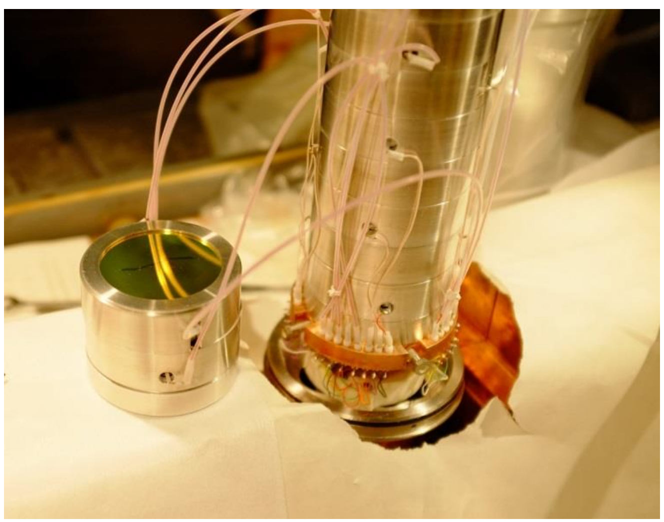
$T_{1/2}$ (0vKK, 2718 keV) > 1.4×10^{20} y,
$T_{1/2}$ (0vKL, 2741 keV) > 0.9×10^{20} y

Detectors and foils of TGV-2

^{106}Cd

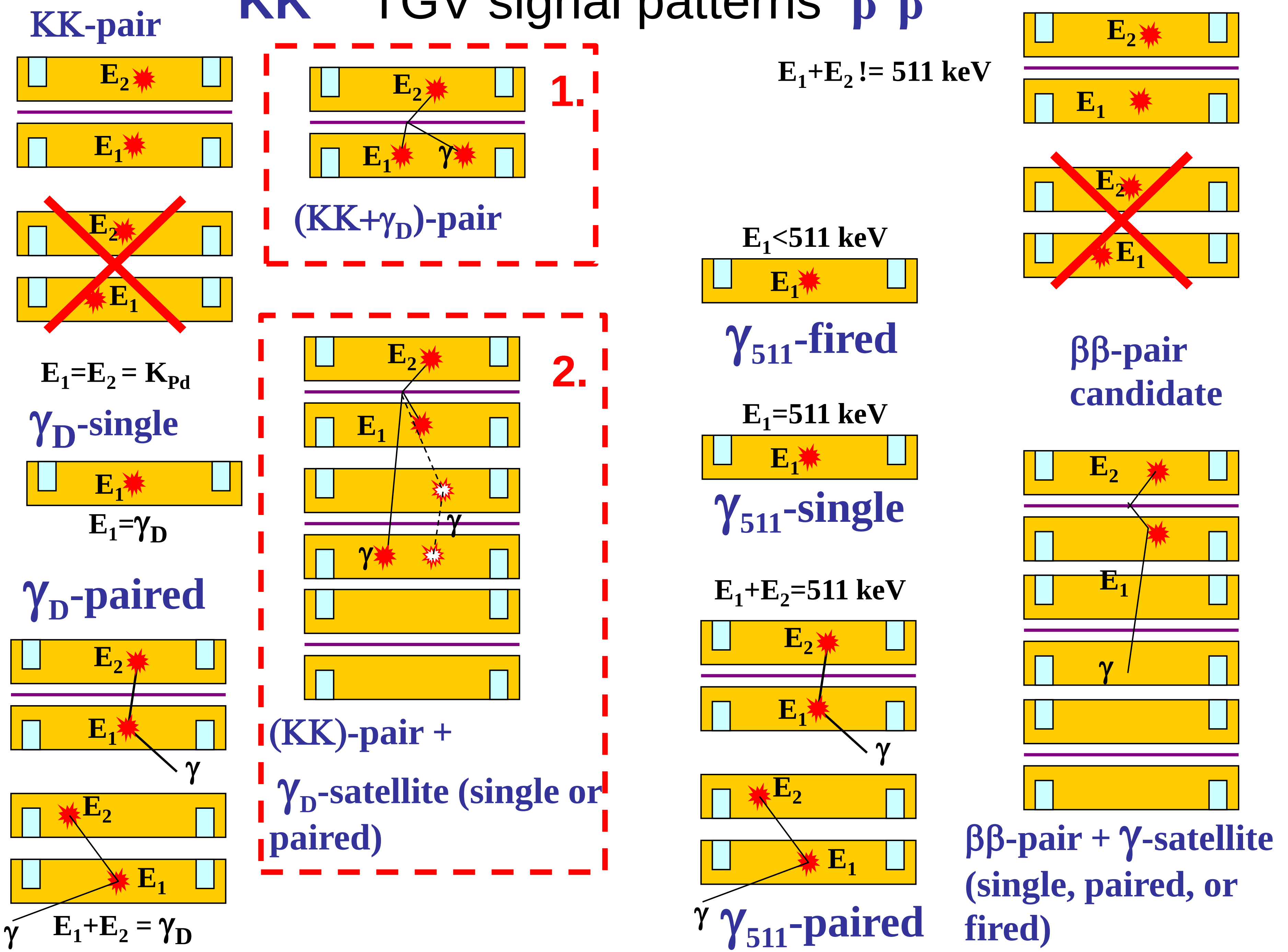




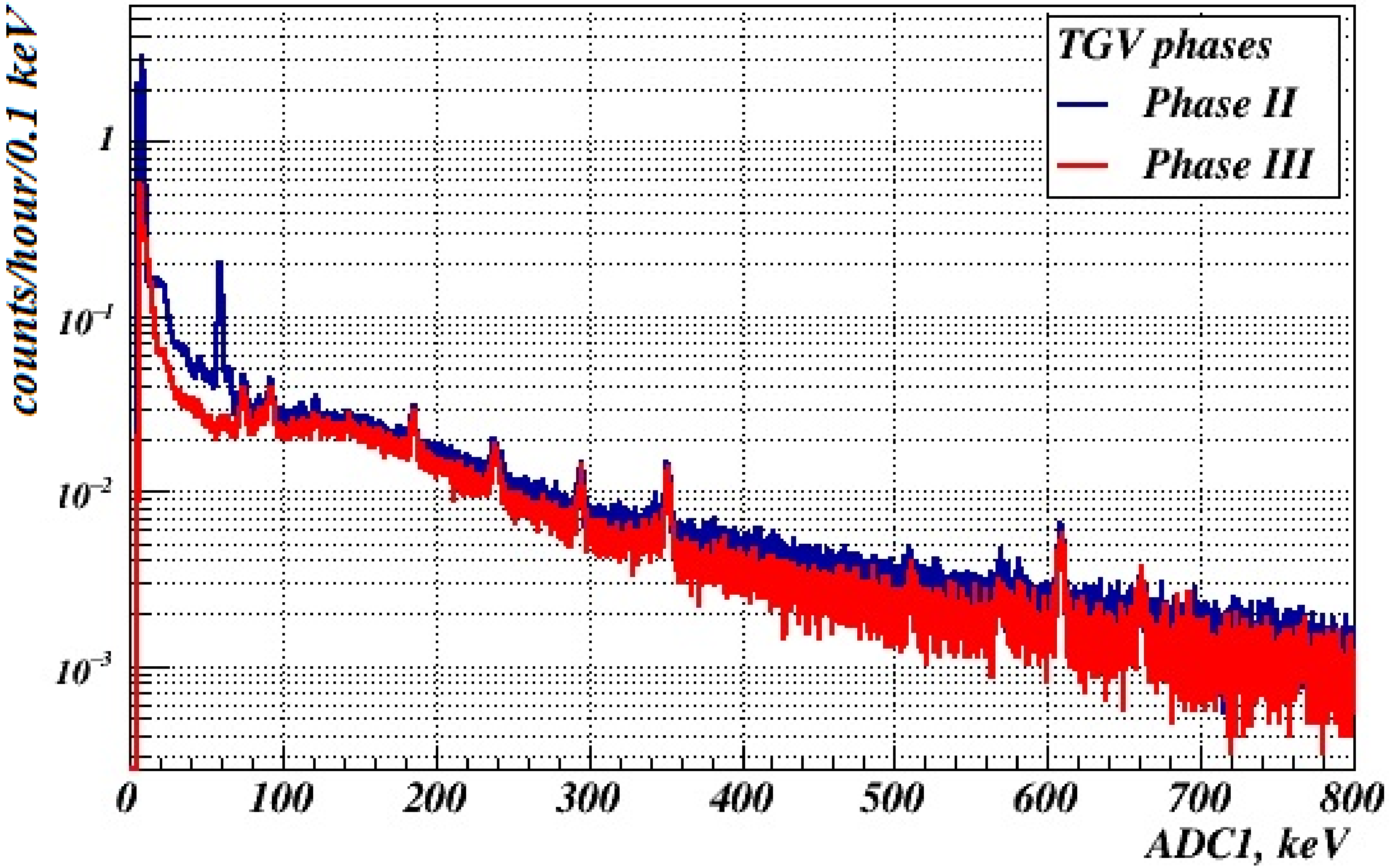


16 circle foils:
thickness = 70±10 mg/cm^2
diameter = 52 mm
mass = 23.166 g
enrichment= 99.57%.

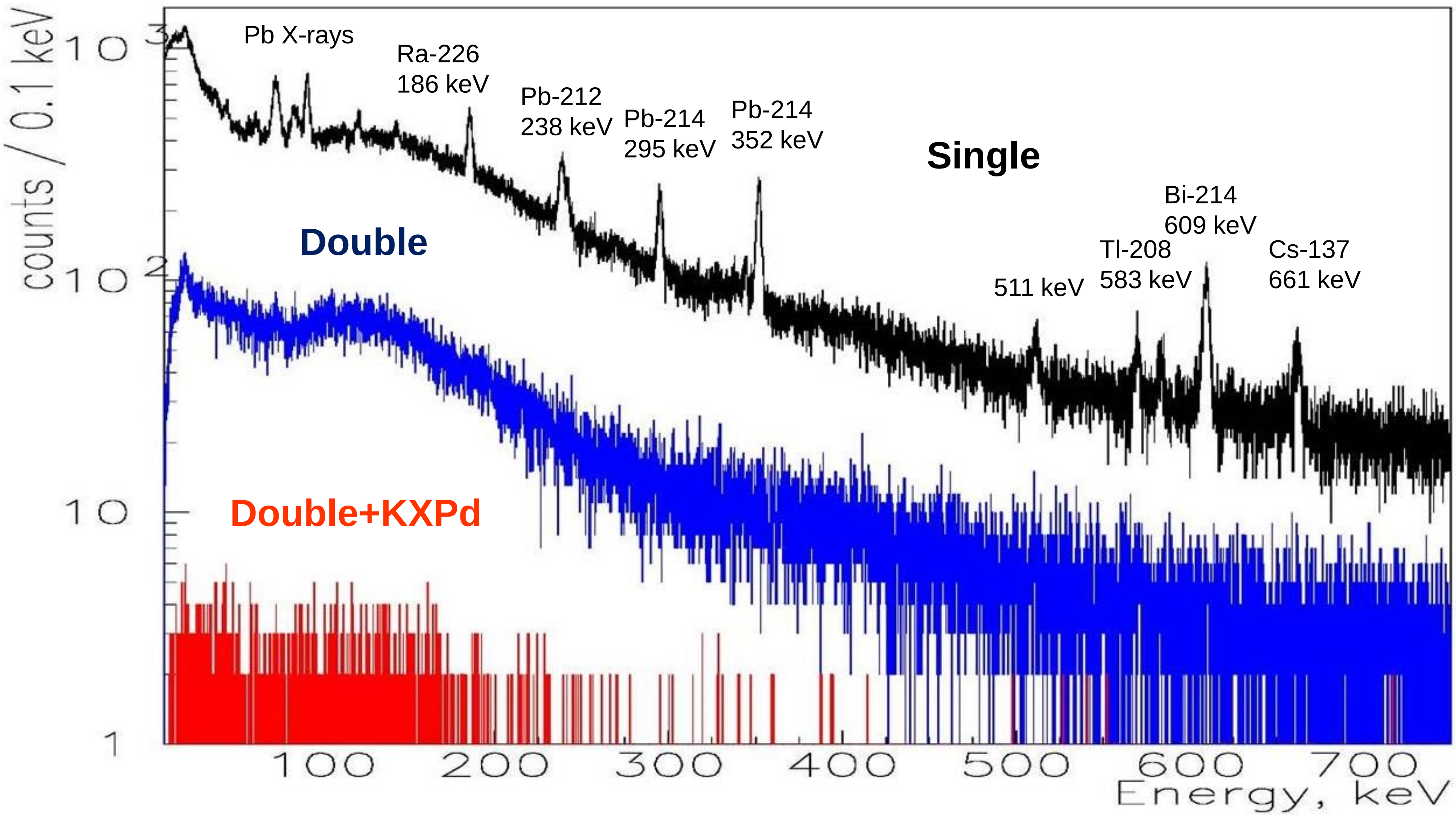
KK TGV signal patterns $\beta^+\beta^+$



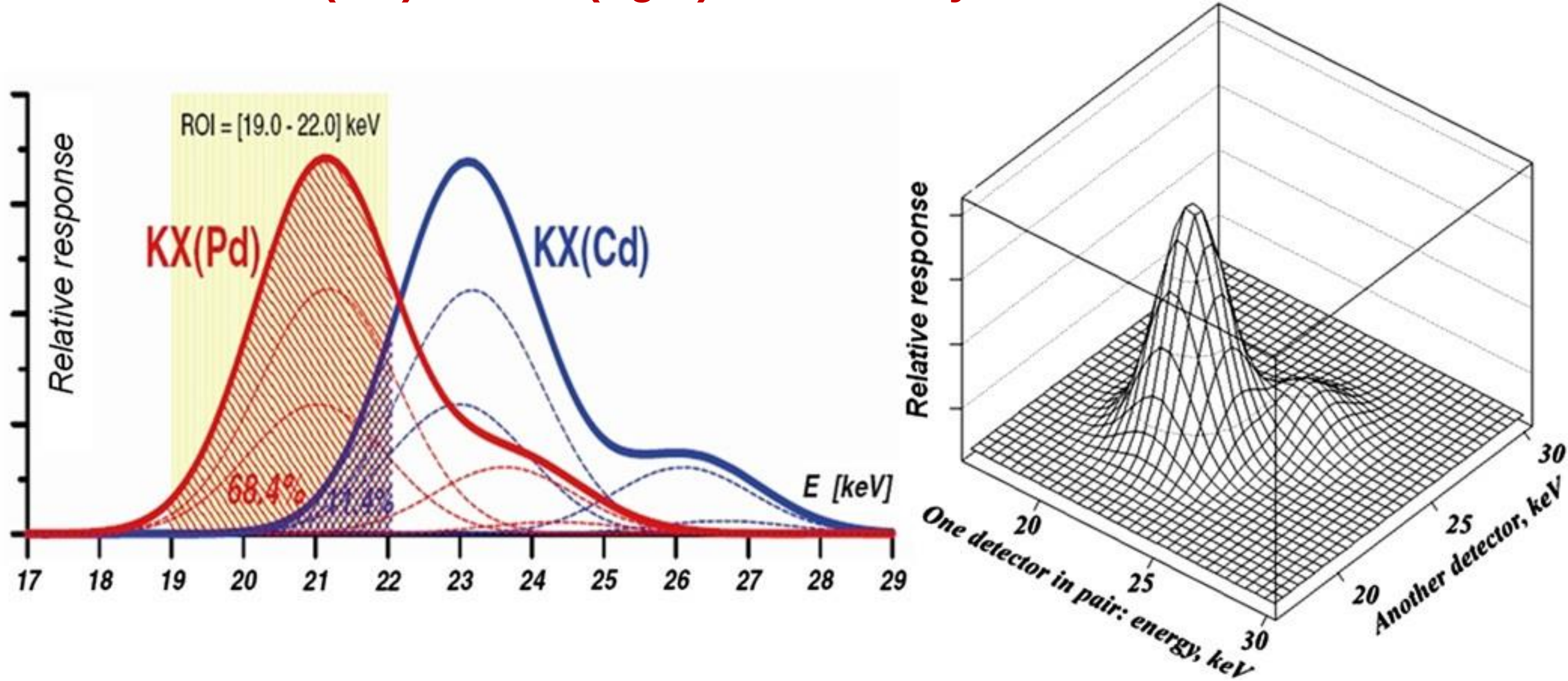
Одиночные события в фазе 2 и фазе 3



Single, Double and Double+KXPd energy spectra of TGV-2



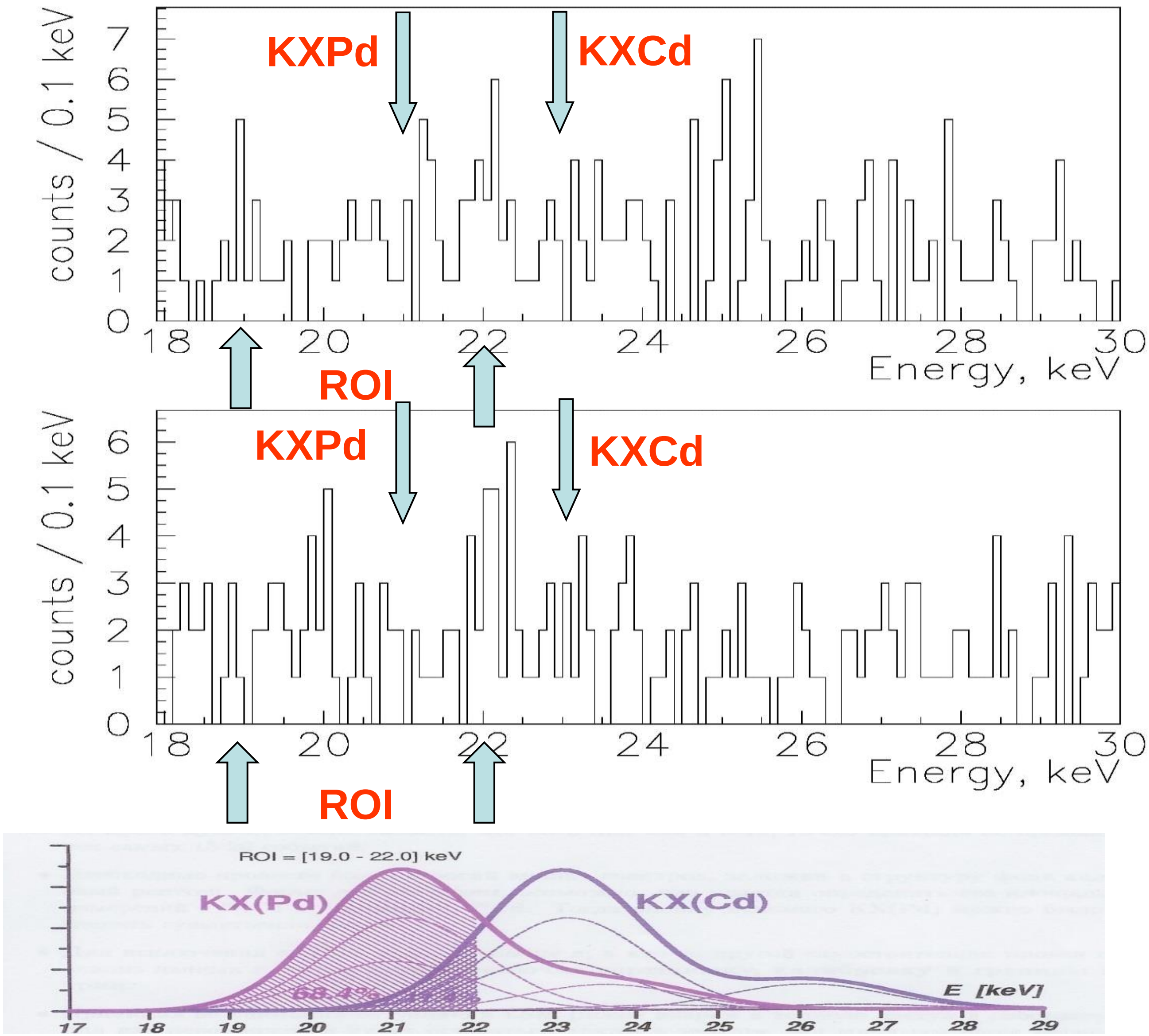
1D (left) and 2D (right) TGV-2 analysis methods



In 1D fit approach, a signal in the 19–22 keV energy window was required in one detector, while a signal from another face-to-face neighbor detector was collected in a 1D-histogram. The final accumulated spectrum was fitted with a 1D-model which included the KXPd multiplet as signal, and the Cadmium KX-ray (KXCd) multiplet with linear underlay as background. The energy window boundaries, 19 and 22 keV, were selected as a compromise between signal efficiency and background reduction of KXCd-rays generated by any charged particle crossing the source foils.

In 2D fit approach, the double coincidence events from neighboring face-to-face detectors, both in the 16–30 keV energy range, were collected in a 2Dhistogram. The final 2D-spectrum was fitted by a 2D-model consisting of the 2D-Gaussian KXPd multiplet as signal, and the KXCd 2D-Gaussian multiplet together with the 2D-background slope as background.

2νEC/EC decay of ^{106}Cd



Preliminary: 2.0×10^{20} y < $T_{1/2}$ (2ν*EC/EC*)> 3.5×10^{21} y

Last TGV-2 results on double beta decay of ^{106}Cd

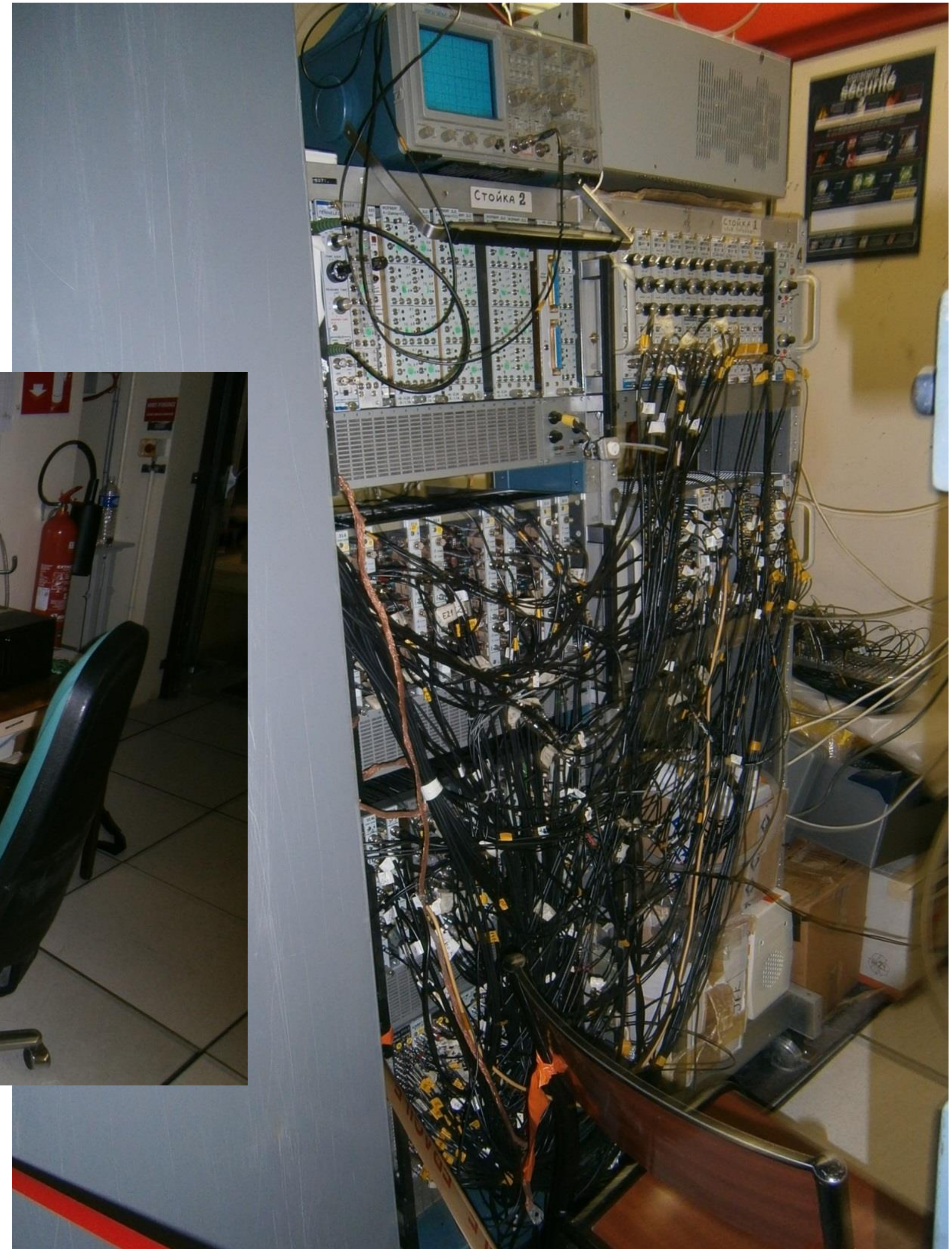
Decay mode	Final level of ^{106}Pd	$T_{1/2}$, y (90%CL) Phase II*	$T_{1/2}$, y (90%CL) Phase III
2ν*EC/EC*	0^+g.s.	4.2×10^{20}	$2.0\times10^{20} < T_{1/2} > 3.5\times10^{21}$ preliminary
	2^+, 511.9 keV	1.2×10^{20}	1.7×10^{20}
	0^+_1, 1134 keV	1.0×10^{20}	1.5×10^{20}
0ν*EC/EC*	2717.6 keV	1.6×10^{20}	1.4×10^{20}
0ν*EC/EC*	4^+, 2741 keV	1.8×10^{20}	0.9×10^{20}
2νβ^+/*EC*	0^+g.s.	1.1×10^{20}	3.0×10^{20}
	2^+, 511.9 keV	1.1×10^{20}	3.0×10^{20}
	0^+_1, 1134 keV	1.6×10^{20}	4.5×10^{20}
2ν$\beta^+\beta^+$	0^+g.s.	1.4×10^{20}	3.9×10^{20}
	2^+, 511.9 keV	1.7×10^{20}	4.7×10^{20}

$T_{1/2}$theor. (2ν*EC/EC*) ~ $10^{20} - 10^{22}$

*N.I.Rukhadze et al., *Journal of Physics: Conference Series* 375 (2012) 042020

TGV-2 on the new place

TGV-2 on the new place



Detector Obelix*

P type coaxial HPGe detector Canberra in U-type ultra low background cryostat located at LSM, France (4800 m w.e.)

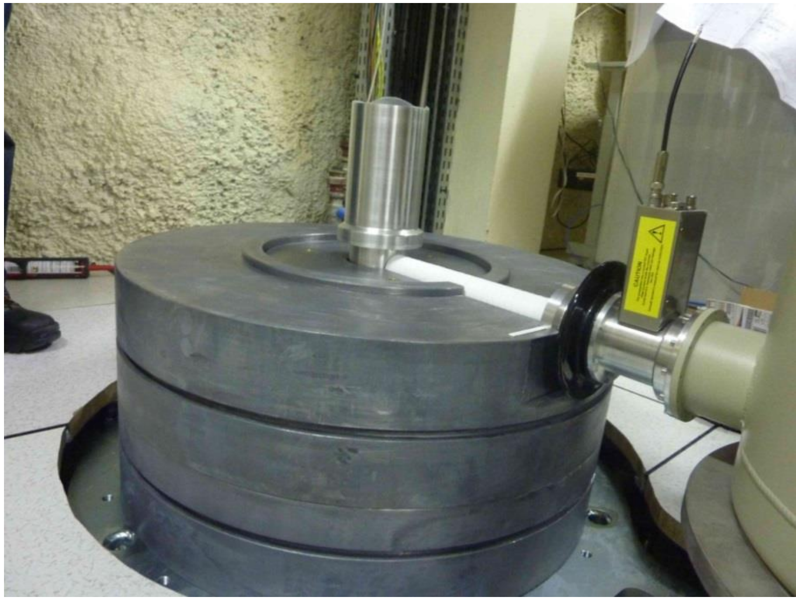
JINR Dubna, Russia,
IEAP, CTU Prague, Czech Republic,
LSM Modane, France

Sensitive volume	600 cm^3
Efficiency	~160%
Peak / Compton	83
Energy resolution	~1.2 keV at 122 keV (^{57}Co), ~2 keV at 1332 keV (^{60}Co)
Distance from cap	4 mm
Entrance window	Al, 1.6 mm

~12 cm arch. Pb

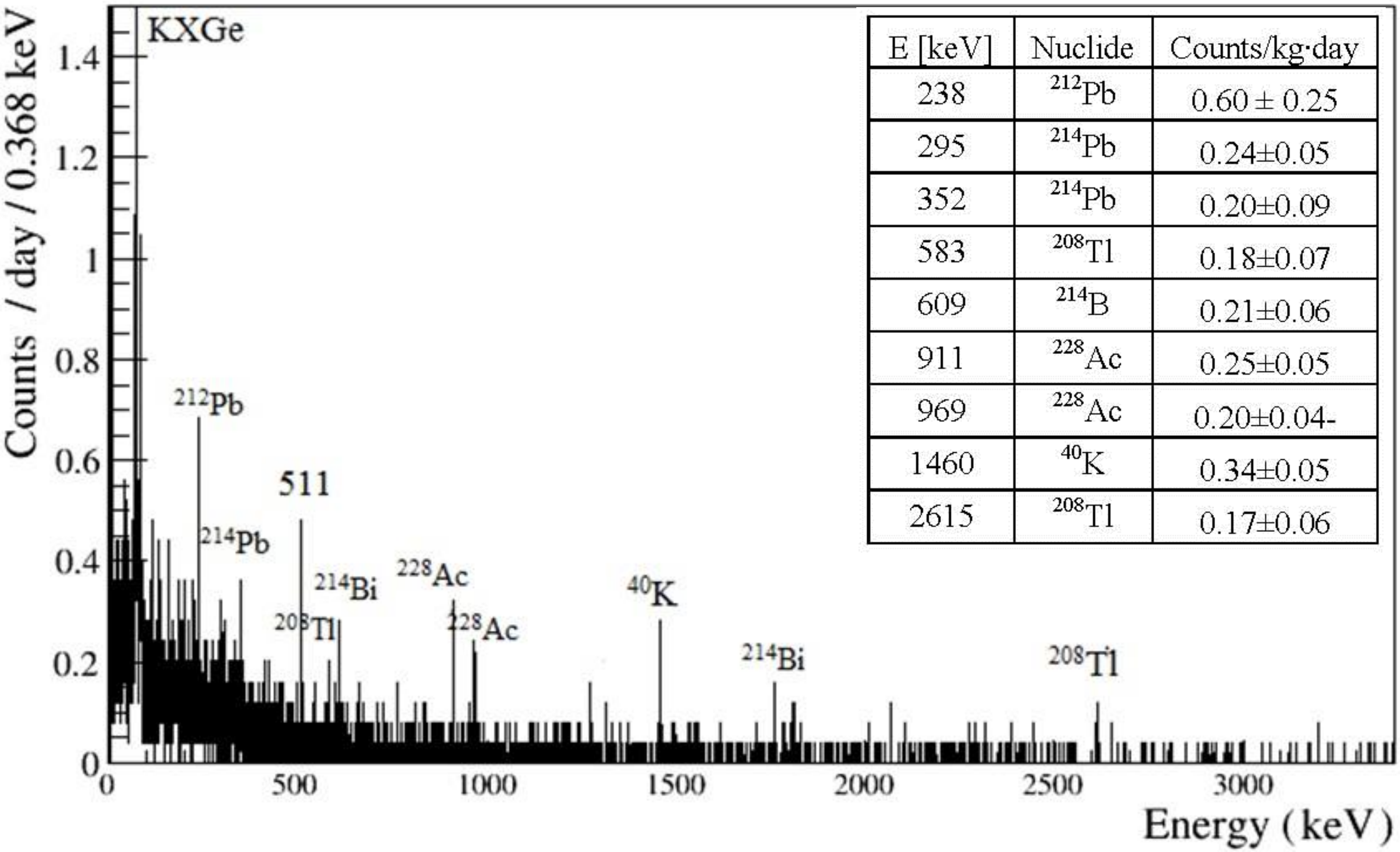
~20 cm low active Pb

Radon free air



*JINST 12 (2017) P02004.

Background of the Obelix spectrometer



E [keV]	Nuclide	Counts/kg·day
238	^{212}Pb	0.60 ± 0.25
295	^{214}Pb	0.24±0.05
352	^{214}Pb	0.20±0.09
583	^{208}Tl	0.18±0.07
609	^{214}B	0.21±0.06
911	^{228}Ac	0.25±0.05
969	^{228}Ac	0.20±0.04-
1460	^{40}K	0.34±0.05
2615	^{208}Tl	0.17±0.06

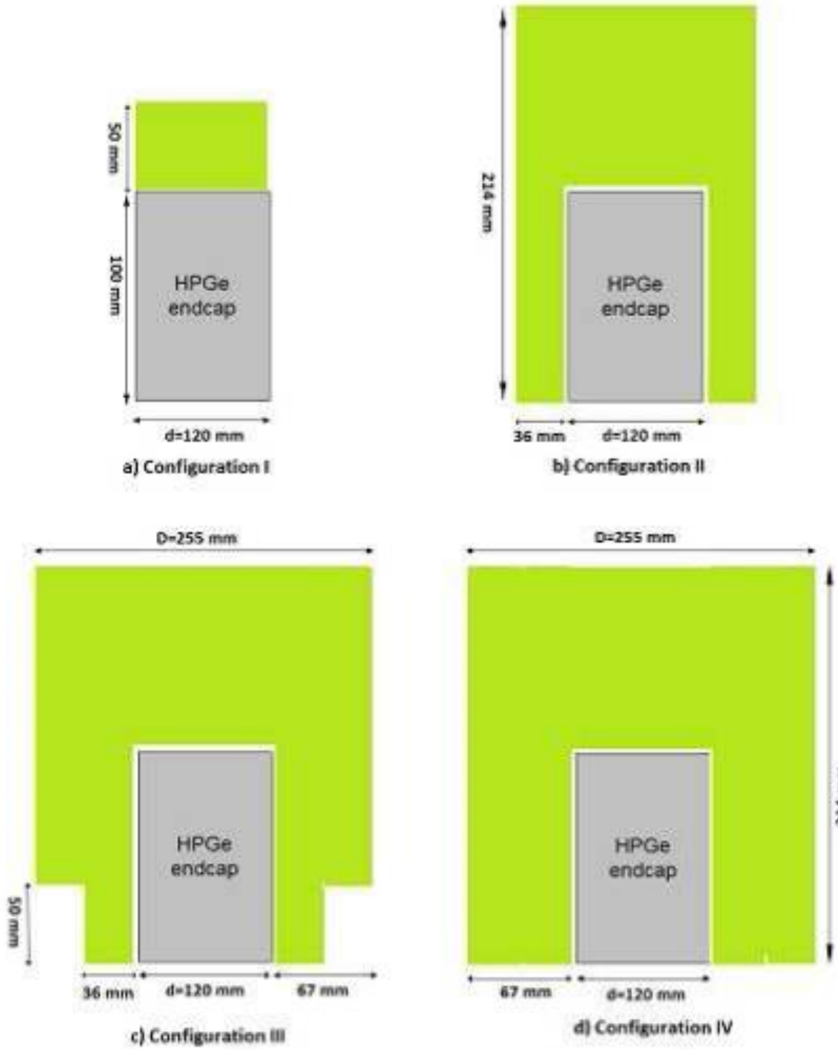
Integral count rate [30-3000 keV]:

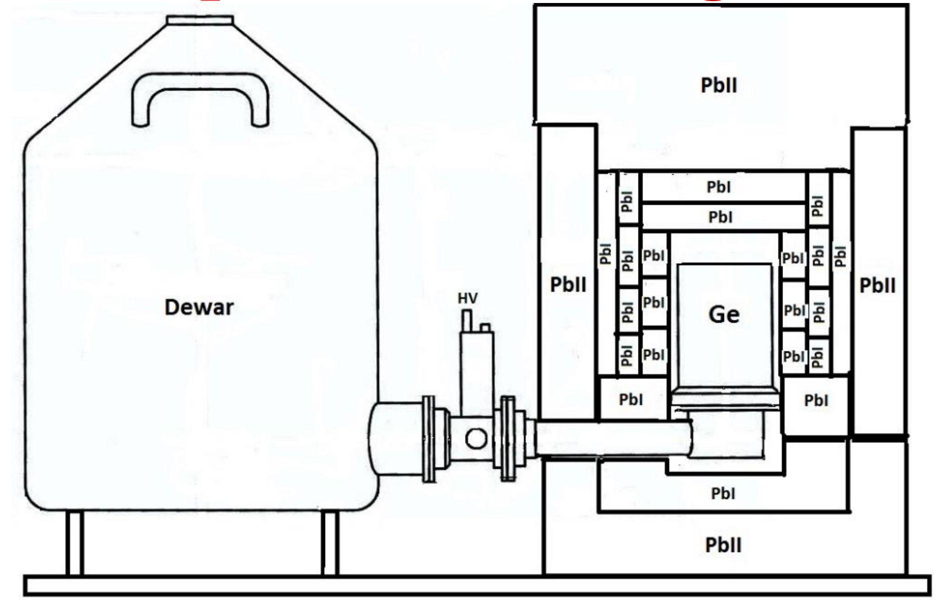
2011 – **173 counts/kg · d**

2014 – **73 counts/kg · d**

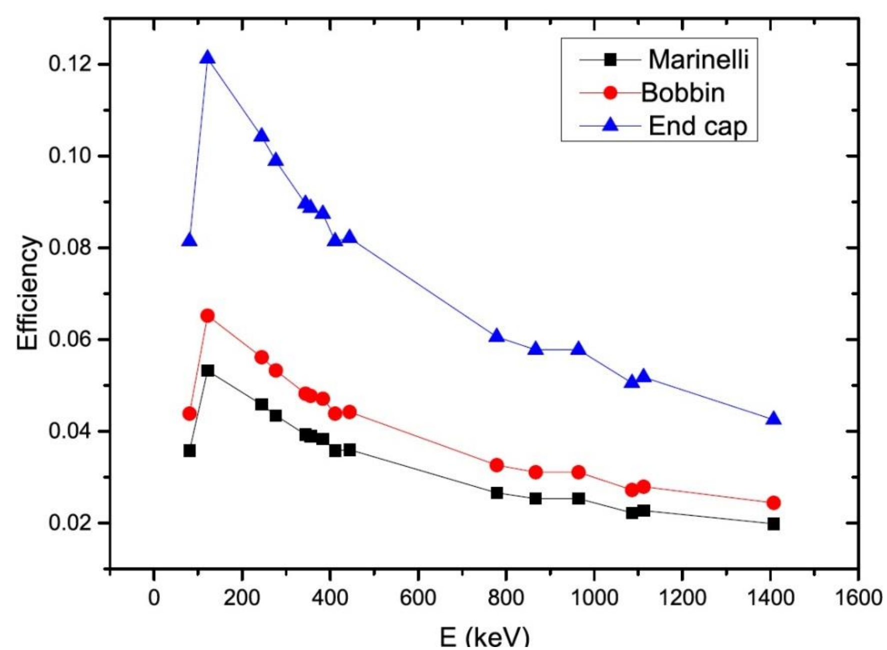
2017 - **95 counts/ kg·d** (after the detector was repaired by Canberra)

Configurations of the Obelix passive shielding





Efficiencies of the Obelix for some geometries



PbI ~ 12 cm of archeological lead (activity of < 60 mBq/kg) (~7 cm can be removed)

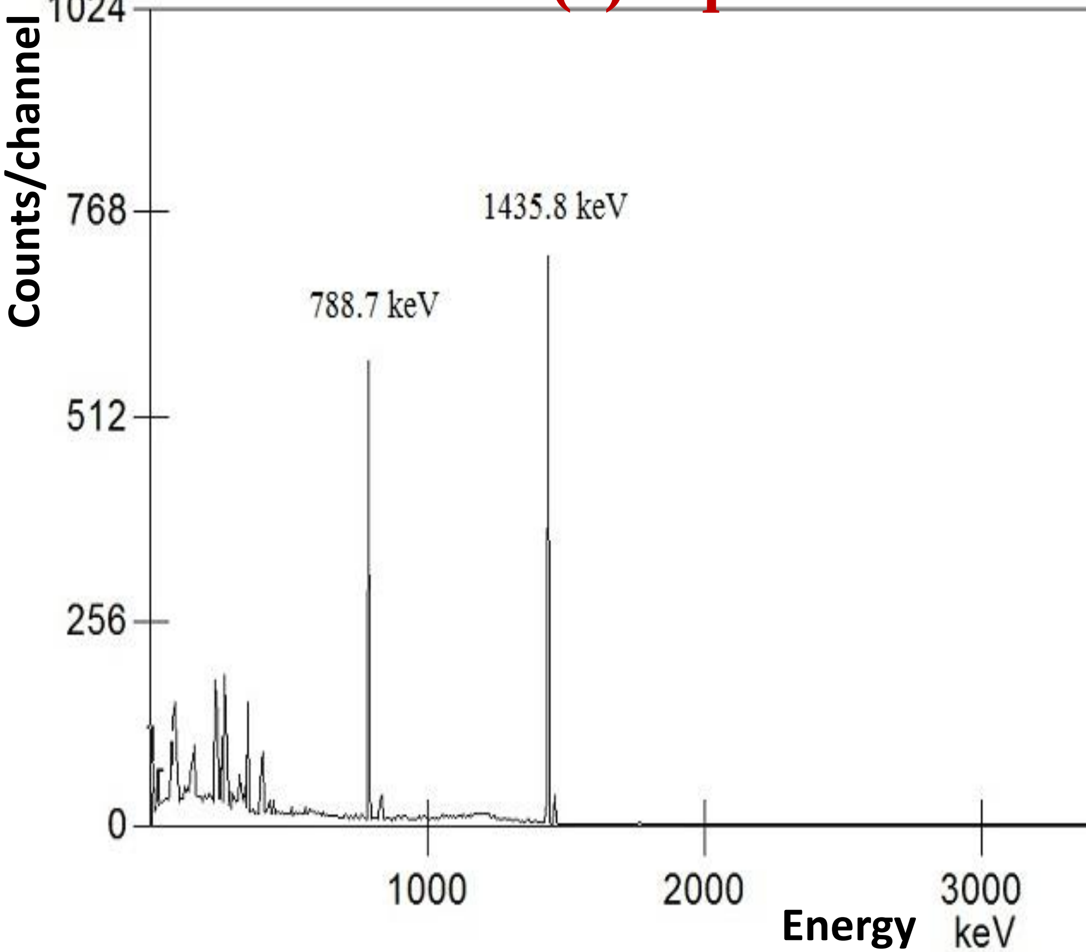
PbII ~ 20 cm of low-active lead (activity of 5 - 20 Bq/kg)

Measurement of La source in Marinelli bobbin

La_2O_3(238g)+flour(954g),T=1800s

~0.09% ^{138}La ($T_{1/2}$~1×10^{11}y)

A = 168 (2) Bq



S (788keV) = 3488±60 ε = 3.4%

S (1435keV) = 4821±70 ε = 2.3%

Double beta decay to the excited states

Motivations:

- Nuclear spectroscopy (to know decay scheme of nuclei)
- NME problem - **NME(g.s.) ≈ NME(0_1^+)**
- $2\nu\beta\beta(0^+ \to 0_1^+)$ decay (one has a very nice signature for the decay)

Experimental search can be distinguish by 2 approaches:

- With gamma spectroscopy using HPGe detector (observations of ^{100}Mo and ^{150}Nd have been accomplished)
- Secondary analysis in large scale ββ decay experiments (^{100}Mo in NEMO-3)

^{100}Mo - ^{100}Ru (0^+_1, 1130.3 keV) decay was detected in several experiments, including measurements performed at LSM, Modane with the **Obelix** HPGe spectrometer
(**R. Arnold et al. Nucl. Phys. A 925 (2014) 25**)

Present "positive" results on 2νββ decay of ^{100}Mo to the 0_1^+ excited state of ^{100}Ru.

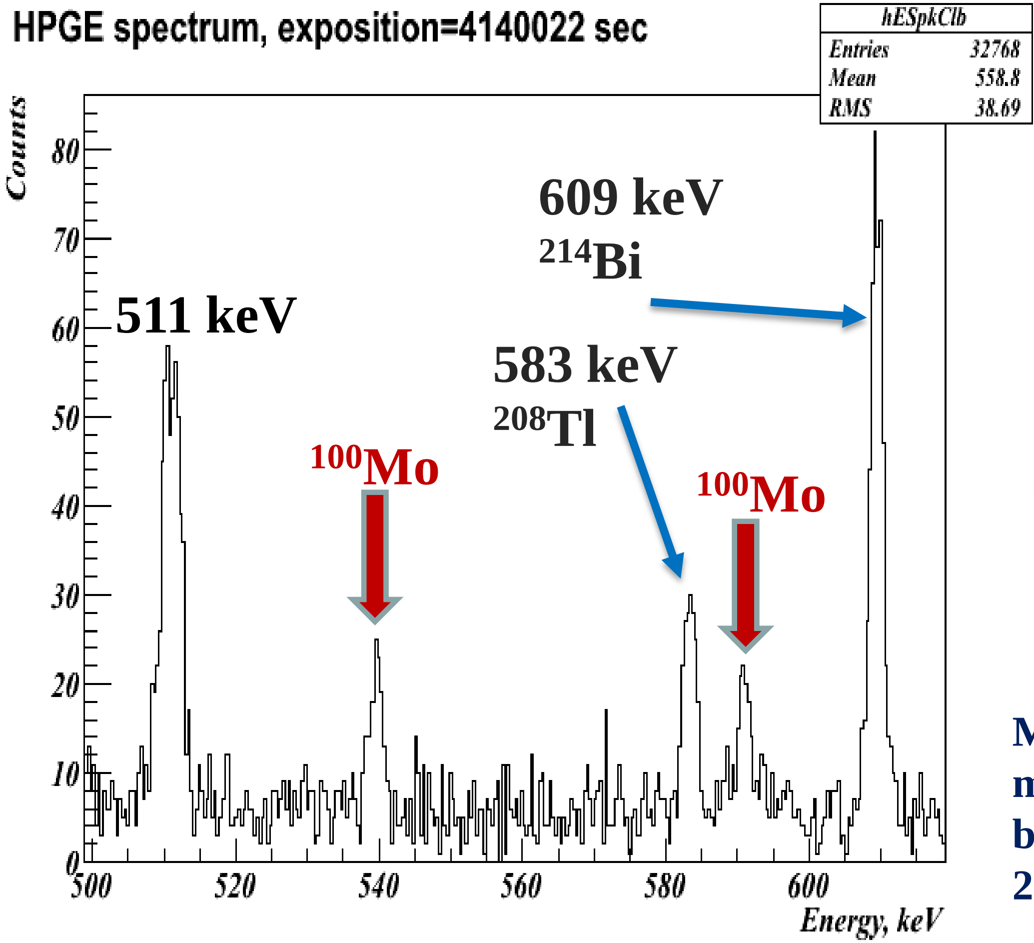
$T_{1/2}$ [y]	N	S/B	Year	Method
$6.1^{+1.8}_{-1.1}(stat.) \times 10^{20}$	133[a]	~1/7	1995	HPGe
$9.3^{+2.8}_{-1.7}(stat.) \pm 1.4(sys.) \times 10^{20}$	153[a]	~1/4	1999	HPGe
$6.0^{+1.9}_{-1.1}(stat.) \pm 0.6(sys.) \times 10^{20}$	19.5	8/1	2001	2×HPGe
$5.7^{+1.3}_{-0.9}(stat.) \pm 0.8(sys.) \times 10^{20}$	37.5	3/1	2007	NEMO-3
$5.5^{+1.2}_{-0.8}(stat.) \pm 0.7(sys.) \times 10^{20}$	35.5	8/1	2009	2×HPGe
$6.9^{+1.0}_{-0.8}(stat.) \pm 0.7(sys.) \times 10^{20}$	597[a]	1/10	2010	4×HPGe
$7.5 \pm 0.6(stat.) \pm 0.6(sys.) \times 10^{20}$	239[a]	2/1	2013	OBELIX

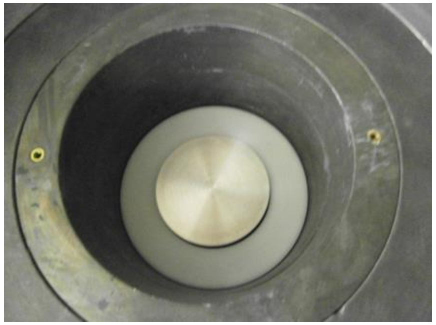
a) Sum of two peaks

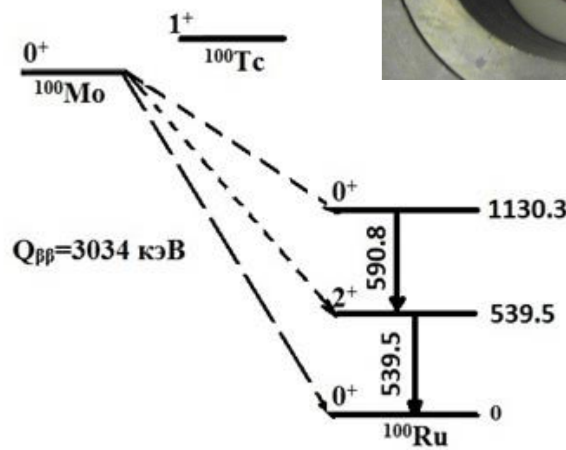
N is the number of useful events;
S/B is the signal-to-background ratio.

Investigation of 2νββ decay of ^{100}Mo-^{100}Ru to excited states

HPGE spectrum, exposition=4140022 sec







Metallic foil of enriched ^{100}Mo with a total mass of 2 505 g was measured in Marinelli bobbin with the Obelix spectrometer for 2 288 hours.

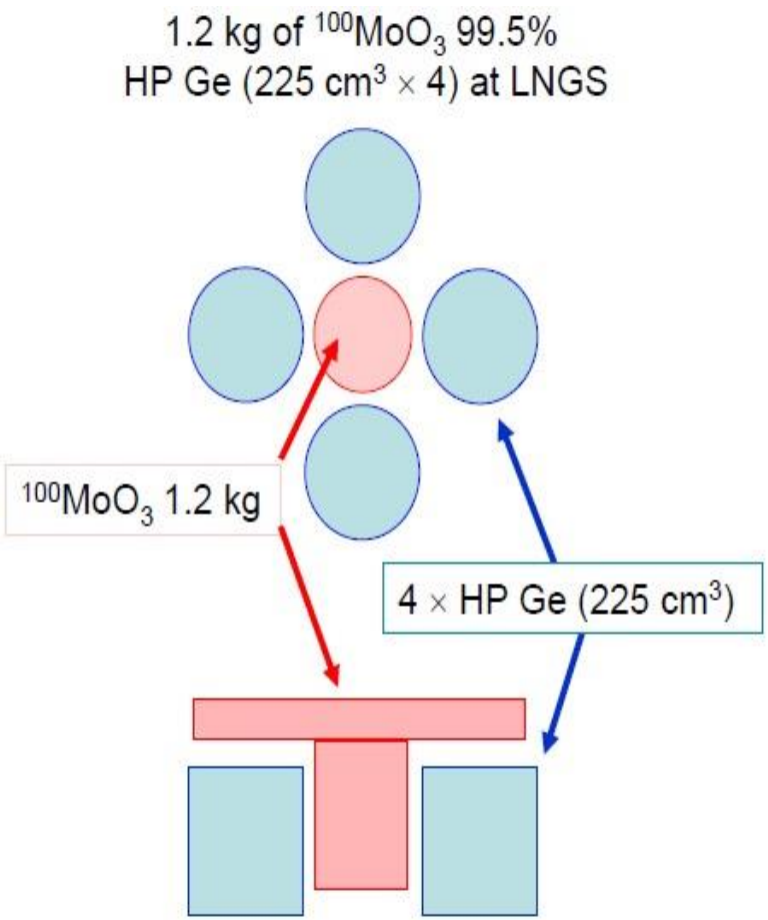
^{100}Mo → 0$^+$, 1130 keV ^{100}Ru* observable γ590.8+γ539.5 keV

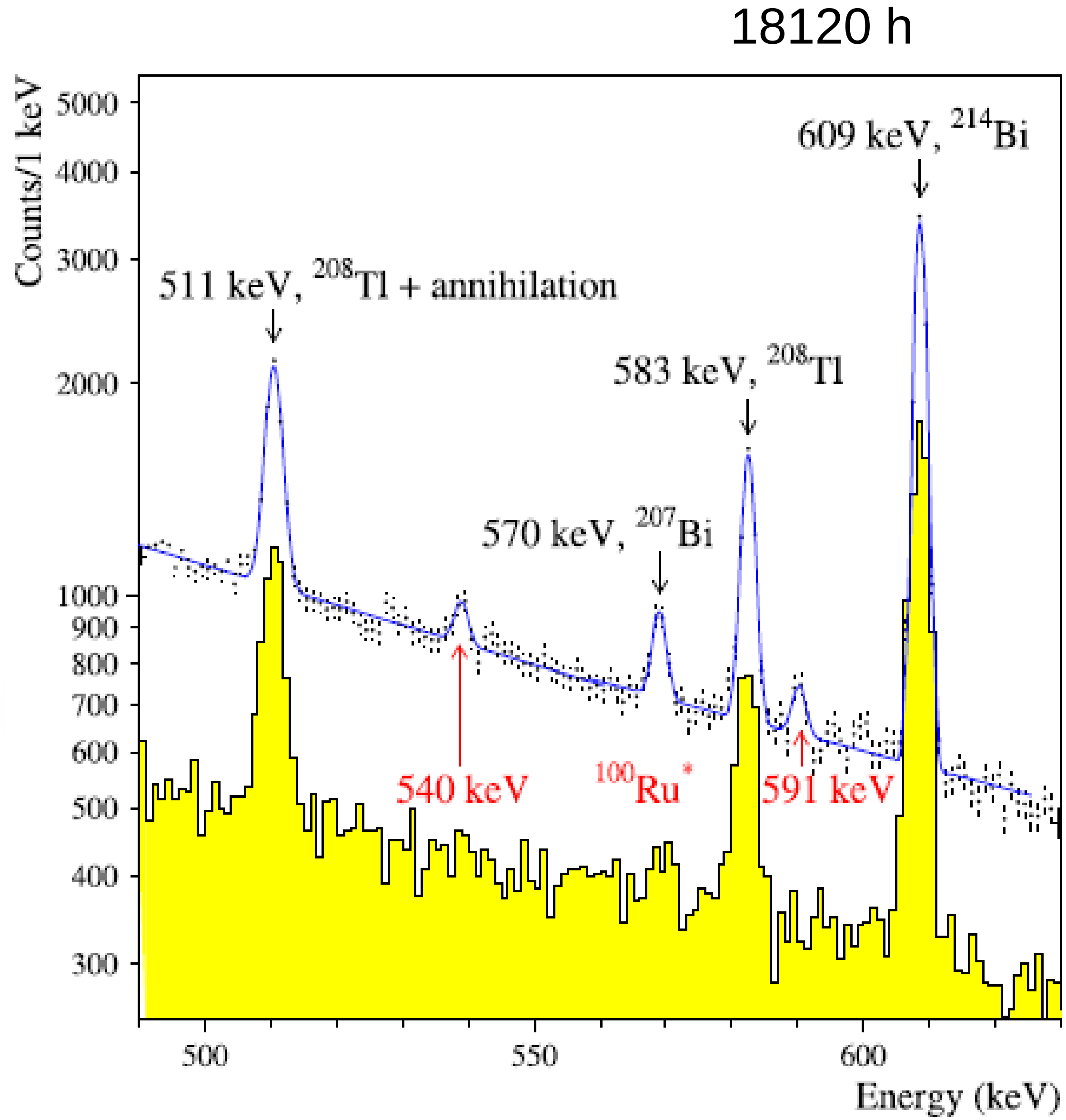
^{100}Mo → 2$^+$, 540 keV ^{100}Ru observable γ539.5 keV

$T_{1/2}$ (0^+_1, 1130.3 keV) = [7.5 ± 0.6(stat.) ± 0.6(sys.)] × 10^{20} yr (90 % CL)

R. Arnold et al., Nuclear Physics A925 (2014) 25

Measurement of ^{100}Mo at ARMONIA experiment

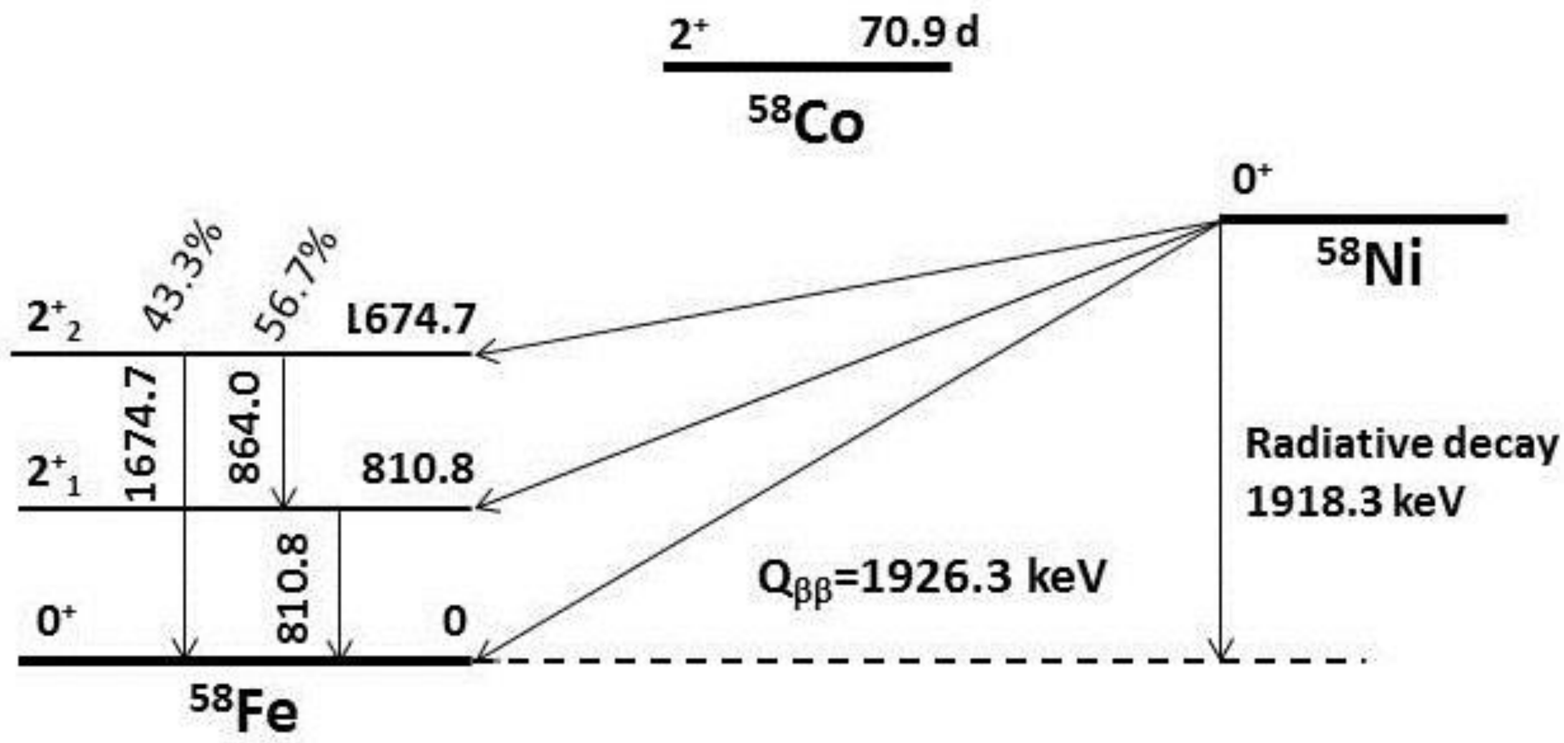




P. Belli et al., NPA 846 (2010) 143

$$\mathbf{6.9^{+1.0}_{-0.8}(stat.) \pm 0.7(sys.) \times 10^{20}}$$

Double beta decay of ^{58}Ni



$2\nu EC/EC$: $^{58}\text{Ni} + 2e^- \rightarrow {}^{58}\text{Fe}(2_1^+) + 2\upsilon_e + 2\gamma_{shell} + \gamma_{(810.8\ keV)}$

$2\nu EC/EC$: $^{58}\text{Ni} + 2e^- \rightarrow {}^{58}\text{Fe}(2_2^+) + 2\upsilon_e + 2\gamma_{shell} + \gamma_{(1674.8\ keV)}$

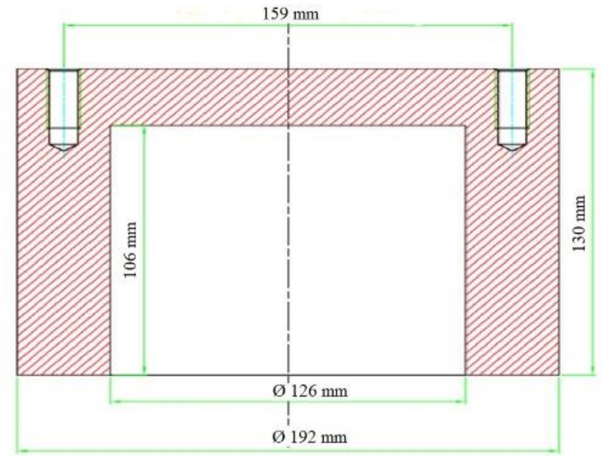
$\rightarrow {}^{58}\text{Fe}(2_2^+) + 2\upsilon_e + 2\gamma_{shell} + \gamma_{(810.8\ keV)} + \gamma_{(864.0\ keV)}$

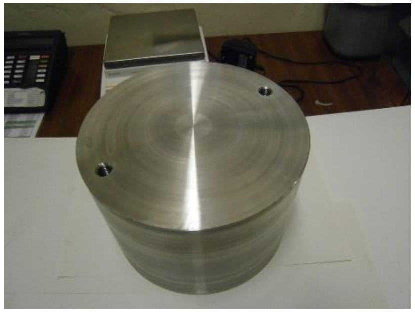
$2\nu\beta^+ EC$: $^{58}\text{Ni} + e^- \rightarrow {}^{58}\text{Fe}(g.s.) + 2\upsilon_e + e^+ + \gamma_{shell} + 2\gamma_{(511\ keV)}$

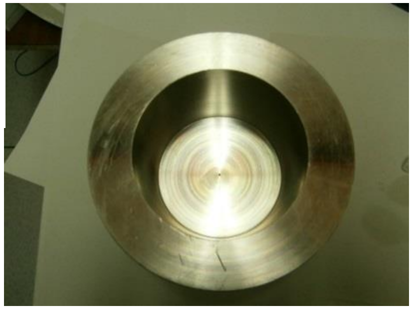
$0\nu EC/EC$: $^{58}\text{Ni} + 2e^- \rightarrow {}^{58}\text{Fe}(g.s.) + \gamma_K + \gamma_L + \gamma_{(1918.3\ keV)}$

Measurement of ^{58}Ni

Sample of natural nickel with a mass of ~21.7 kg, containing ~68% of ^{58}Ni







Run 1 - 2014

15.10.2014-11.11.2014

T_1=652.4 h

14.11.2014- 08.12.2014

T_2=488.5 h

T= 1141 h**= 47.5 d**

Run 2 - 2015

28.08.2015 – 17.09.2015

T= 456 h **= 19 d**

Run 3 - 2017

07.04.2017 – 12.10.2017

T= 3452 h = **143.8 d**

Theoretical prediction:

$T_{1/2}(2\nu\beta^+EC, 0^+\to0^+) = 8.6\times10^{25}$ y

$T_{1/2}(2\nu EC/EC, 0^+\to0^+) = 6.1\times10^{24}$ y

$T_{1/2}(0\nu EC/EC$ radiative$) = 2\times10^{35} - 3\times10^{36}$ y

Existing experimental limits:

$T_{1/2}\,(2\nu\beta^+EC,0^+\to0^+) > 7.0\times10^{20}$ y (68%CL)

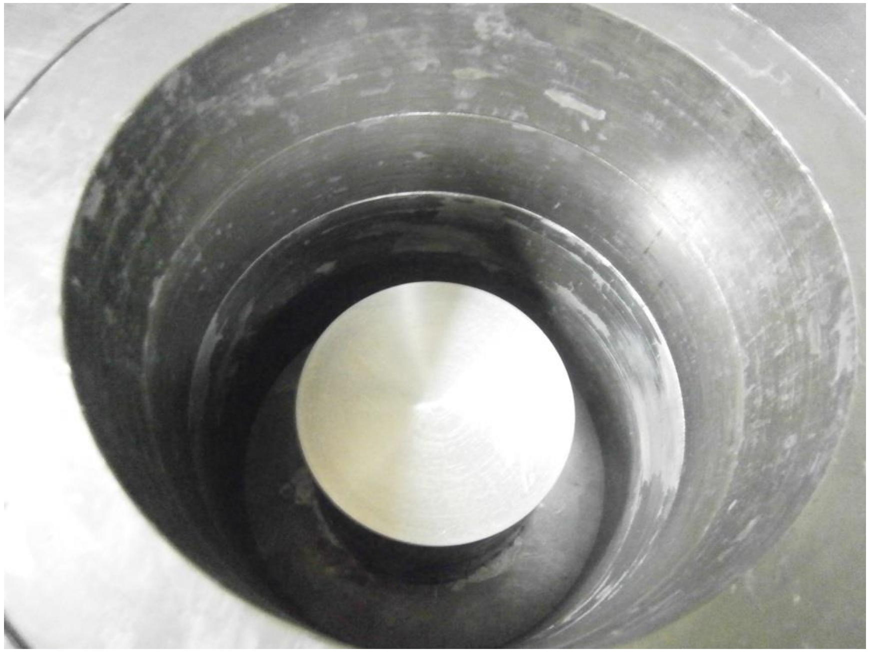
$T_{1/2}\,(2\nu\beta^+EC,0^+\to2_1^+) > 4.0\times10^{20}$ y (68%CL)

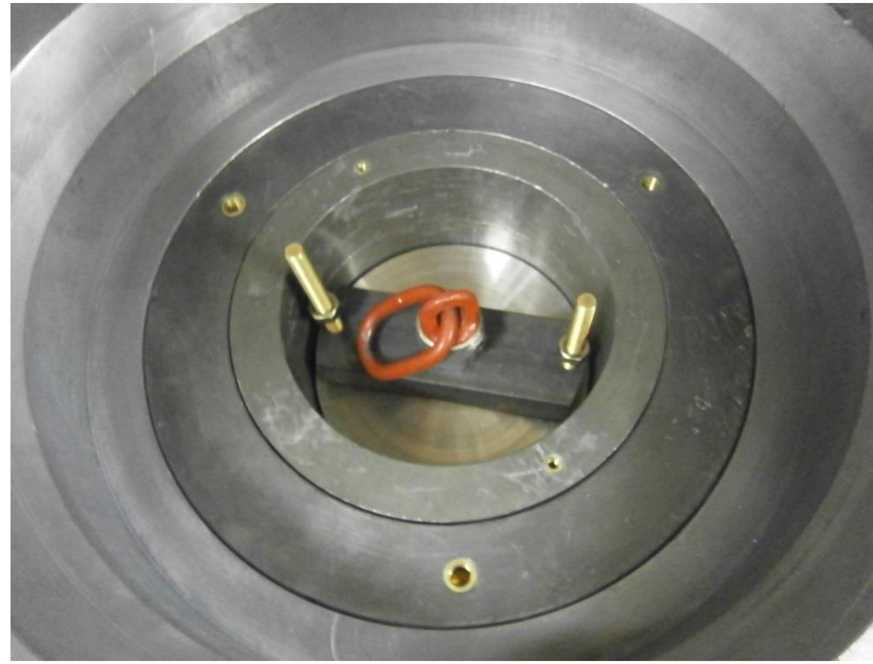
$T_{1/2}\,(2\nu EC/EC,0^+\to2_1^+) > 4.0\times10^{19}$ y (90%CL)

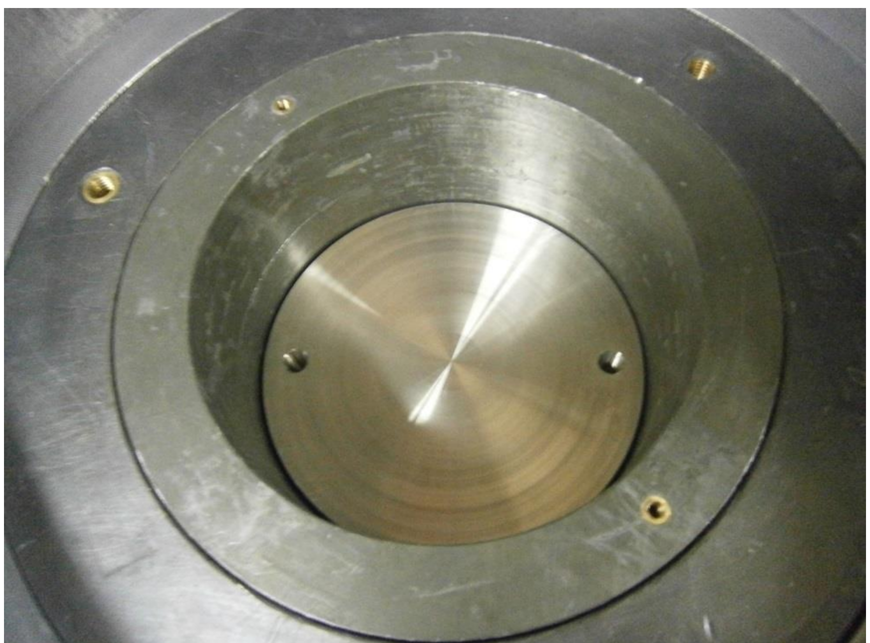
$T_{1/2}\,(2\nu EC/EC,0^+\to2_2^+) > 4.0\times10^{19}$ y (90%CL)

$T_{1/2}\,(0\nu EC/EC$ radiative$) > 2.1\times10^{21}$ y (90%CL)

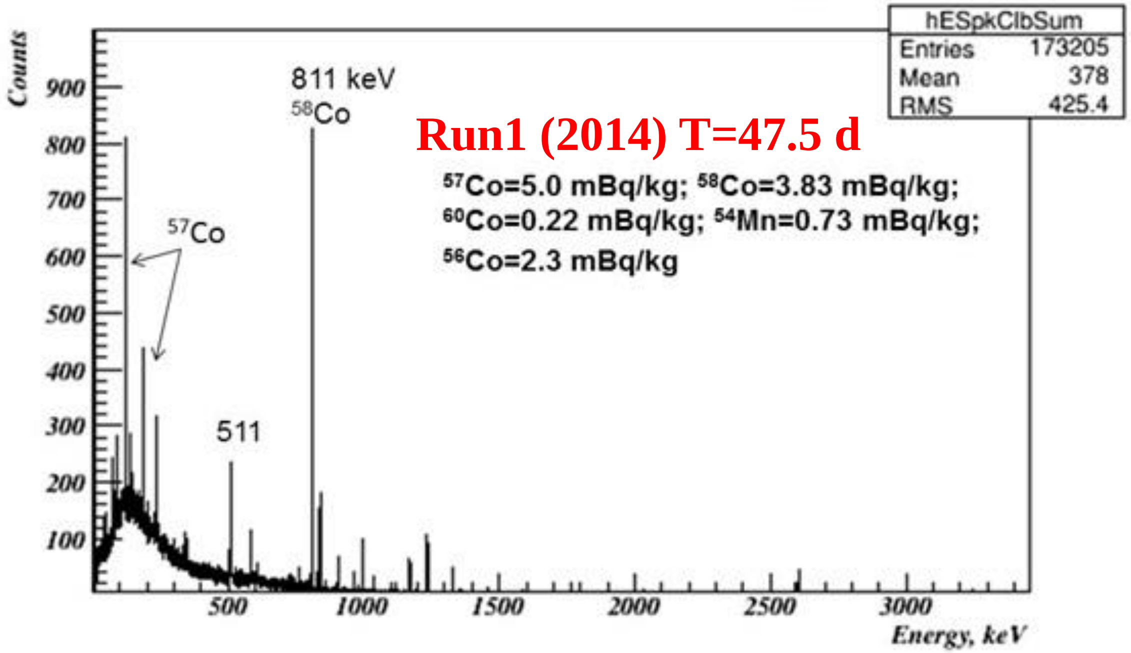
Measurement of ^{58}Ni



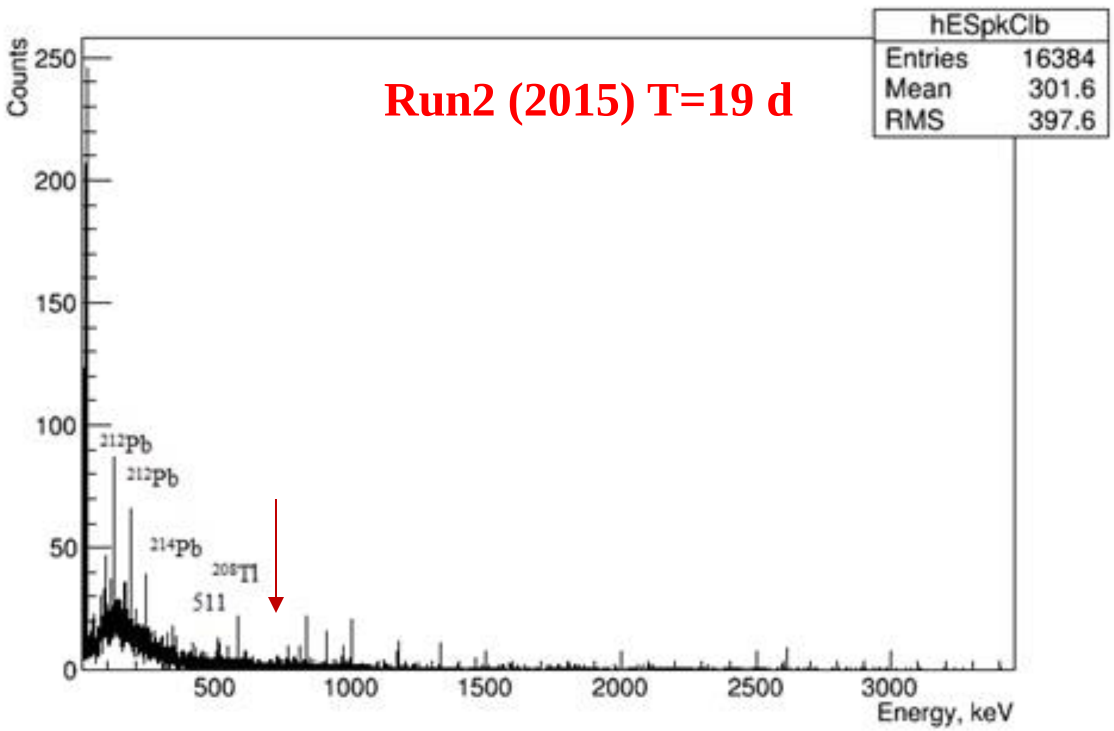




Measurement of ^{58}Ni



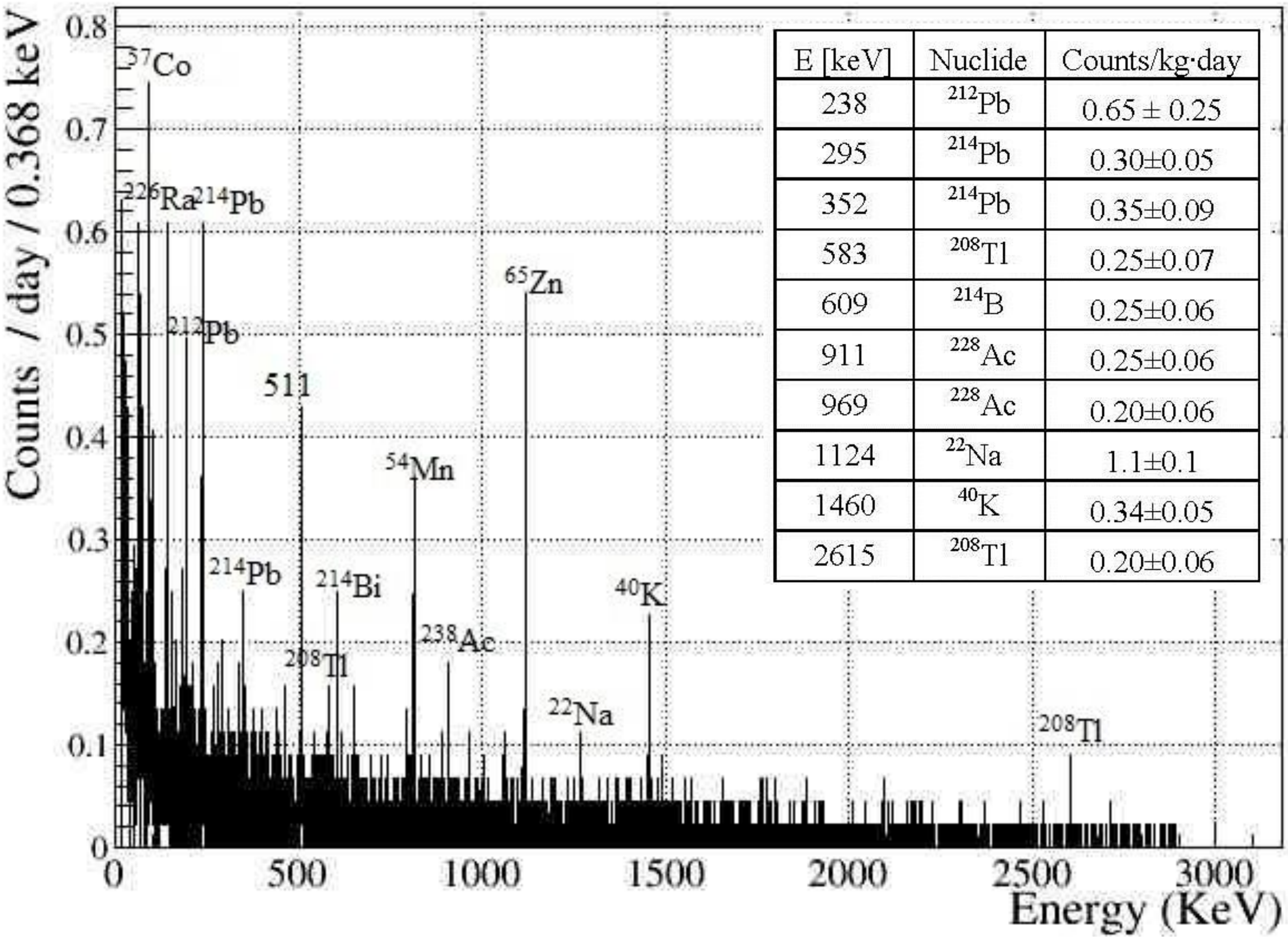
Sample: natural Ni **(~68% of ^{58}Ni)**
Total mass: ~**21.7 kg**
The investigations of double beta decay (β^+EC, EC/EC)
Regions of interest: 511 keV , 811 keV, 864 keV, 1675 keV, 1918 keV



^{56}Co ($T_{1/2}$ = 77.3 d)
^{57}Co ($T_{1/2}$ = 271.8 d)
^{58}Co ($T_{1/2}$ = 70.9 d)
^{54}Mn ($T_{1/2}$ = 312.3d)

Background measurement with Obelix in 2017

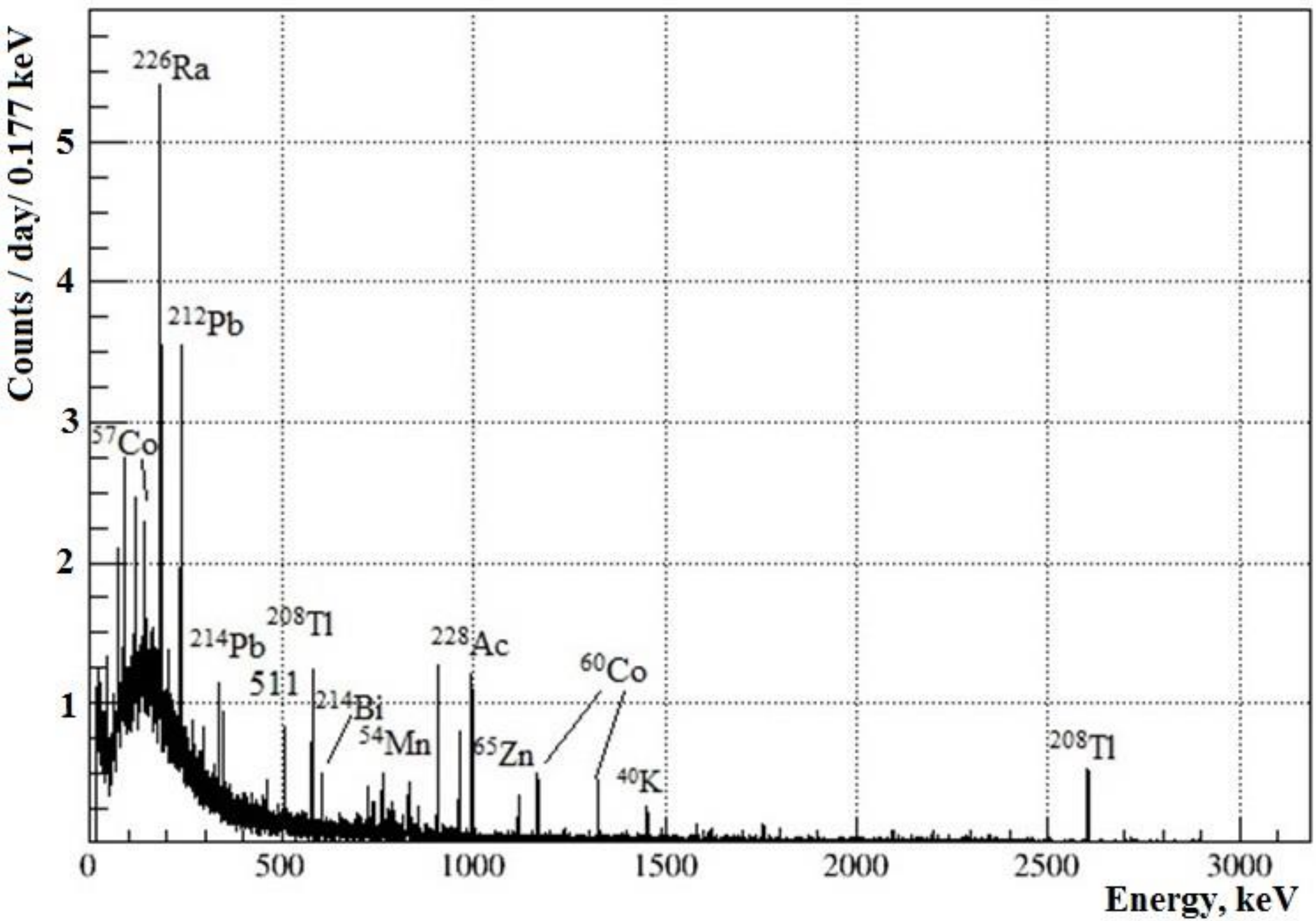
T=44d

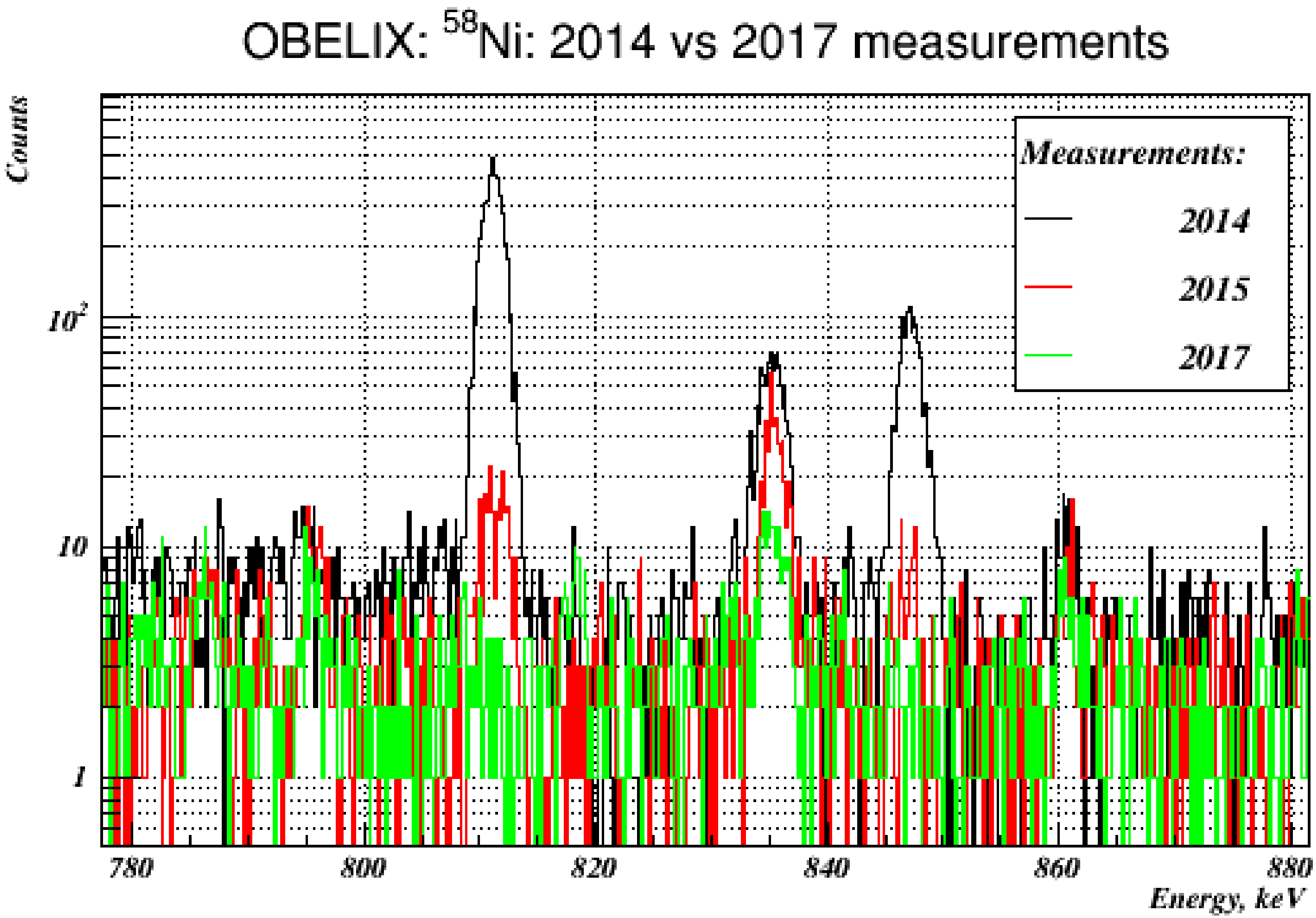


E [keV]	Nuclide	Counts/kg·day
238	^{212}Pb	0.65 ± 0.25
295	^{214}Pb	0.30±0.05
352	^{214}Pb	0.35±0.09
583	^{208}Tl	0.25±0.07
609	^{214}B	0.25±0.06
911	^{228}Ac	0.25±0.06
969	^{228}Ac	0.20±0.06
1124	^{22}Na	1.1±0.1
1460	^{40}K	0.34±0.05
2615	^{208}Tl	0.20±0.06

Counting rate [30 – 2900 keV]   95 counts/day•kg

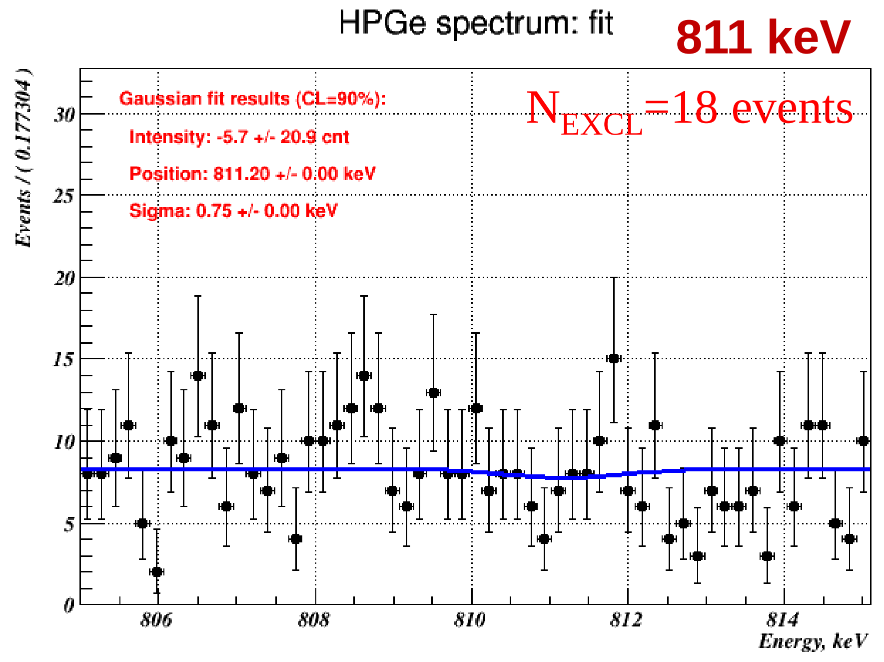
Measurement of ^{58}Ni at 2017 (third run)

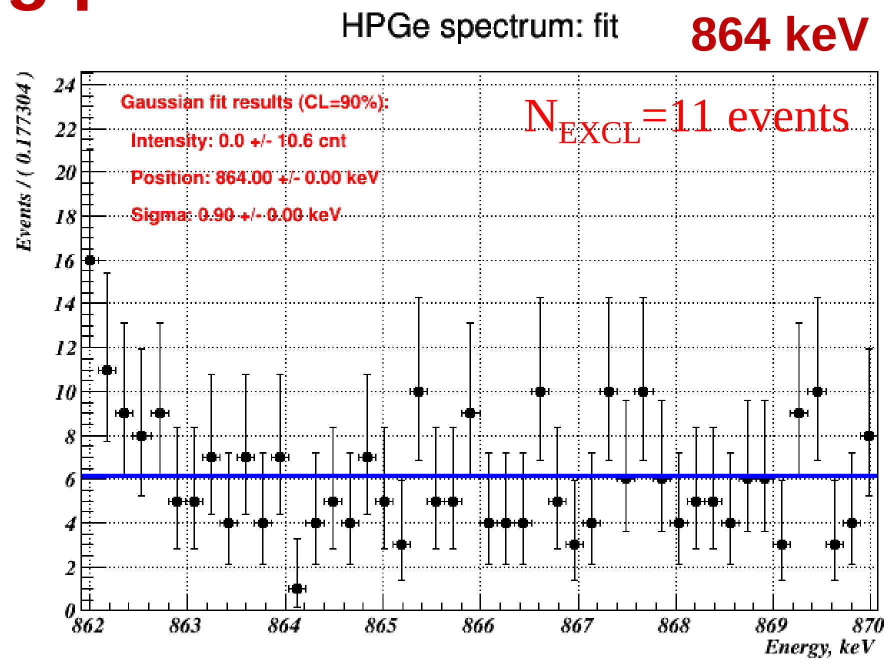


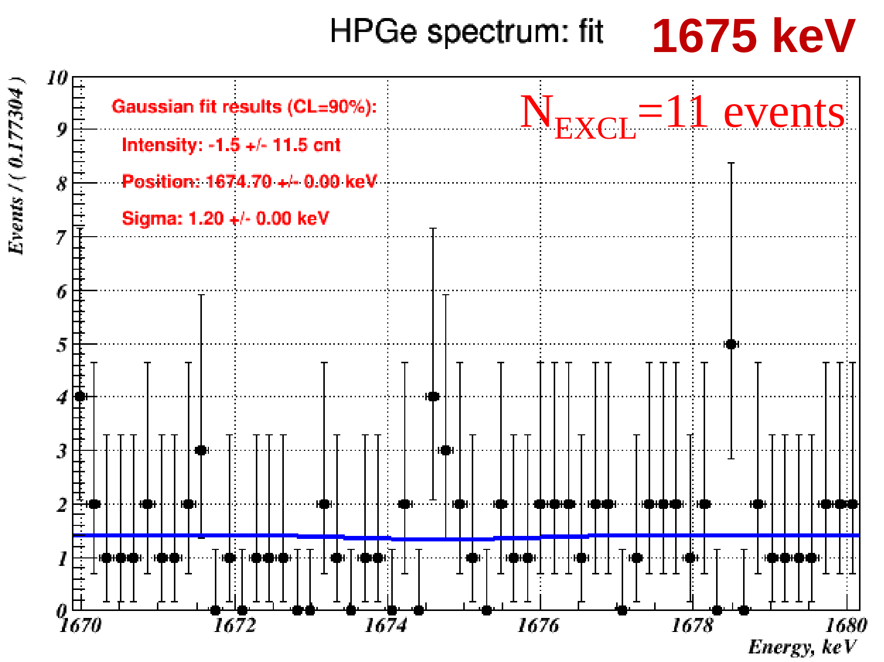


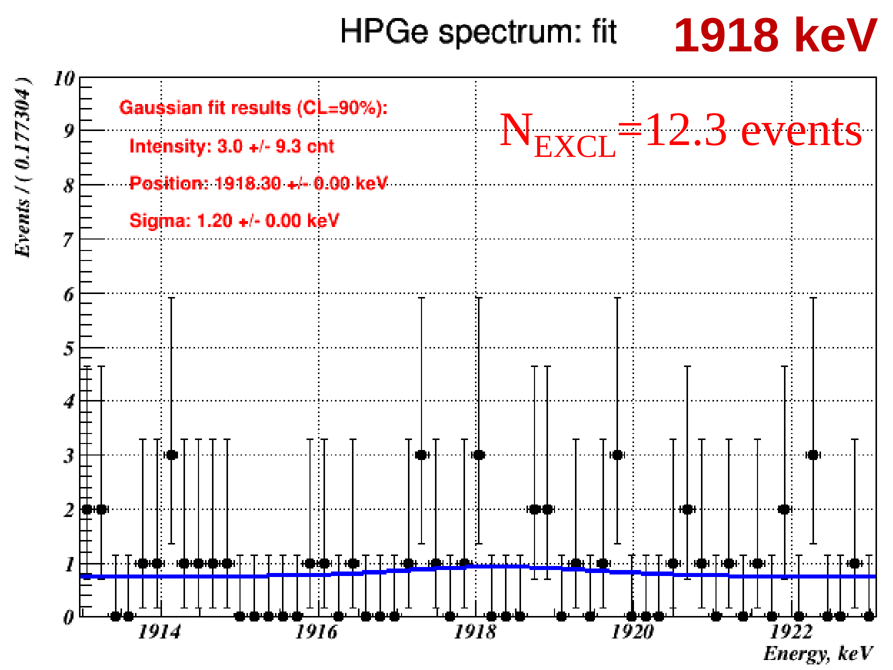
OBELIX: ^{58}Ni: 2014 vs 2017 measurements
Counts
10^2
10
1
780
800
820
840
860
880
Energy, keV
Measurements:
2014
2015
2017

Fitting peaks









Results for double beta decay of ^{58}Ni obtained with the Obelix detector

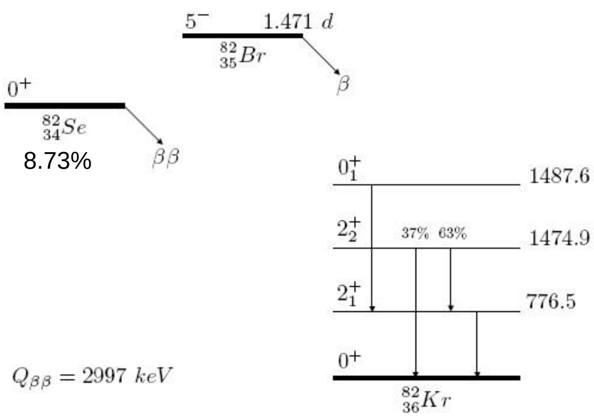
Decay mode	Final state or Decay transition	$T_{1/2}$, (90% CL)	Previous limits, $T_{1/2}$
β^+EC	g.s.	1.7×10^{22} y	7.0×10^{20} y (68%CL)*
β^+EC	811 keV	2.3×10^{22} y	4.0×10^{20} y (68%CL)*
EC/EC	811 keV	3.3×10^{22} y	4.0×10^{19} y (90%CL)**
EC/EC	1675 keV	3.4×10^{22} y	4.0×10^{19} y (90%CL)**
0νEC/EC resonant	Radiative 1918 keV	4.1×10^{22} y	2.1×10^{21} y (90%CL)***

*S.I. Vasil'ev et al., JETP Lett. 57 (1993) 631.
**E. Bellotti et al., Lett. Nuovo Cim. 33 (1982) 273.
***B. Lehnert et al., J. Phys. G: Nucl. Part. Phys. 43 (2016) 065201

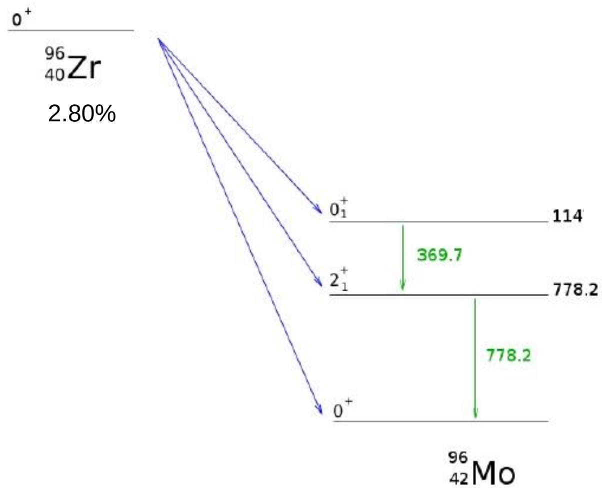
Future plans of measurements with Obelix

Investigations of double beta decay of ^{74}Se, ^{82}Se, ^{96}Zr and ^{150}Nd to excited states of daughter nucley will be performed with detectors Obelix and Idefix (new P type coaxial ultra low-background HPGe detector similar to Obelix). Idefix was produced by company of Mirion (Canberra) in 2017.

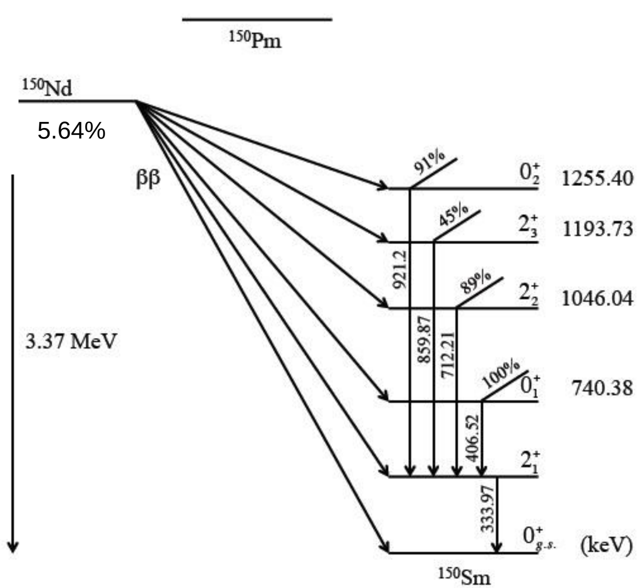
^{82}Se decay scheme



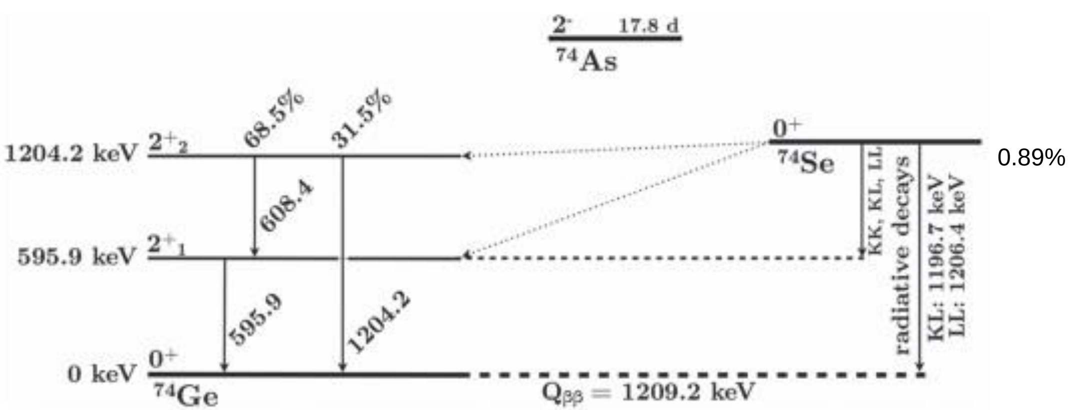
^{96}Zr decay scheme



^{150}Nd decay scheme



^{74}Se decay scheme

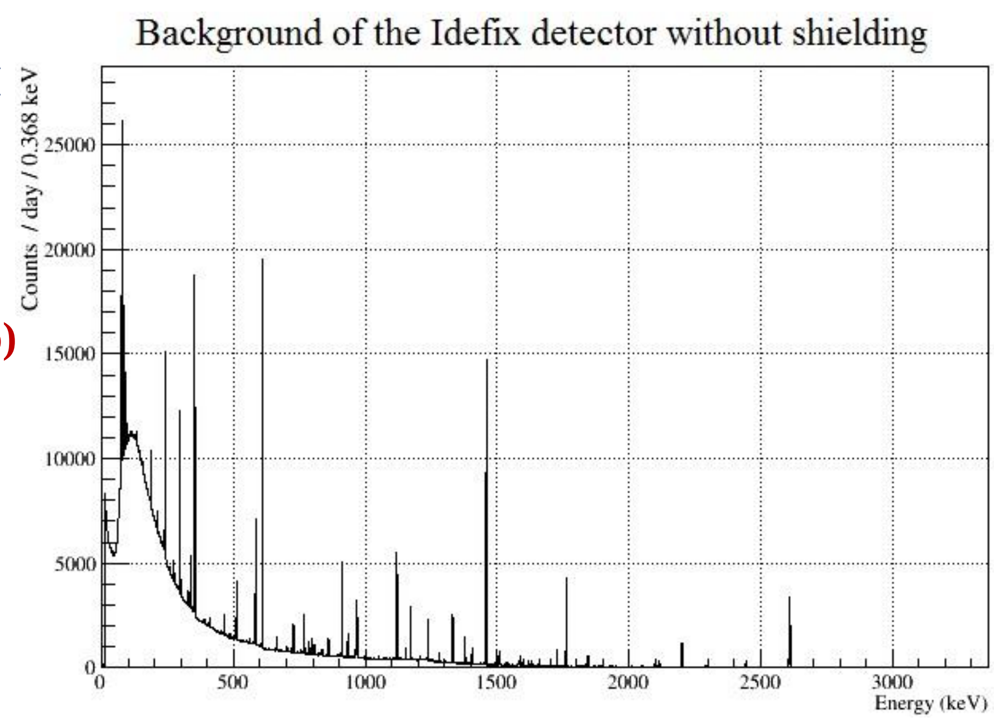


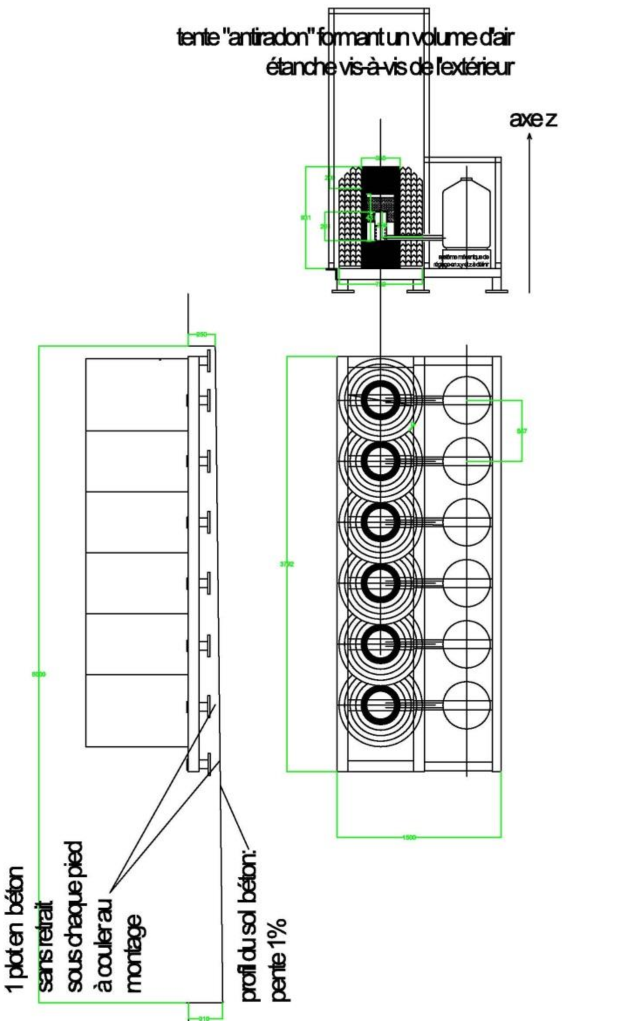
Idefix – new HPGe detector at Modane Underground Laboratory (LSM)

22.11.2017 Idefix detector was delivered in LSM

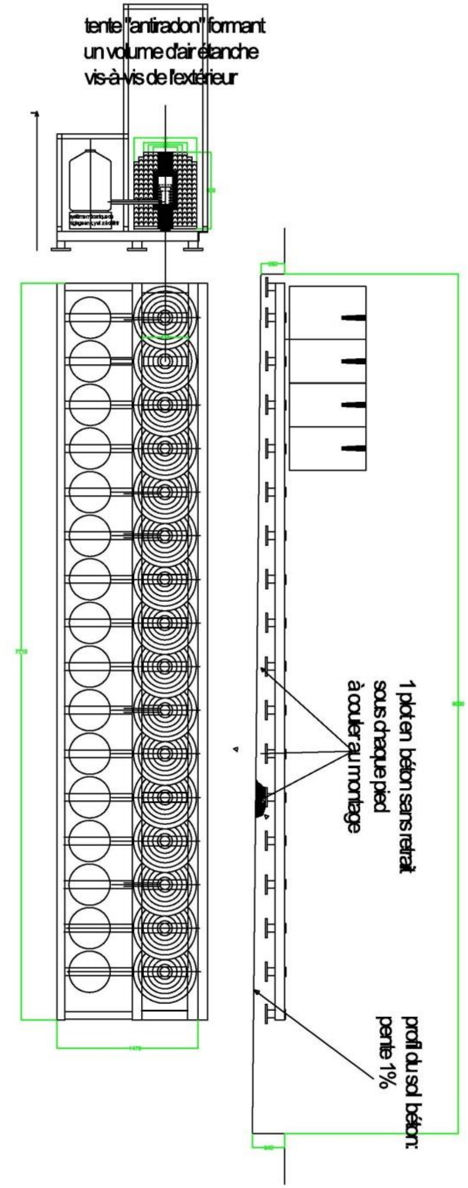
Sensitive volume **606 cm^3**
Peak / Compton **102**
Energy resolution **~ 0.95 keV at 122 keV (^{57}Co),**
~ 2.05 keV at 1 332 keV (^{60}Co)
Distance from cap **6 mm**
Entrance window **Al, 1.6 mm**
Relative efficiency **165%**

Passive shielding for Idefix detector will be produced in 2018





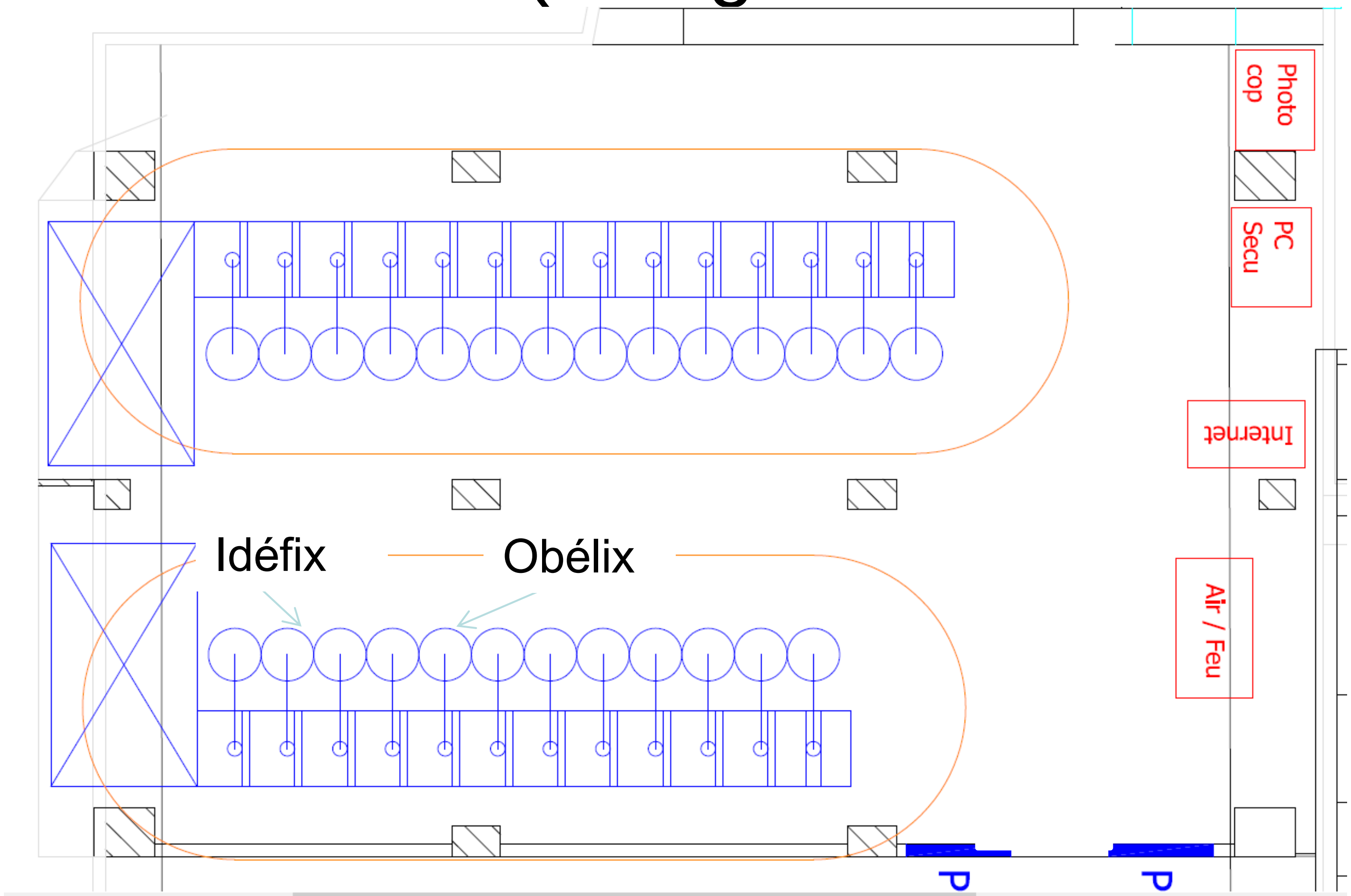
Montage d'un ensemble de 6 détecteurs physique



Montage d'un ensemble de 16 détecteurs "environnement"

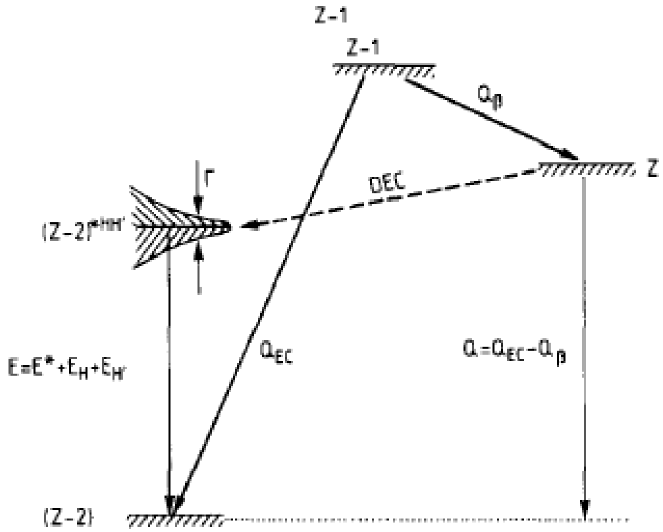
Location in the lab

- At the place of tgv room and germanium small room (imagine circles instead of



Thank you for attention

Additional slides



Neutrinoless double electron capture
(resonance transitions)
(A,Z)→(A,Z-2)*HH'

J. Bernabeu, A. DeRujula, C. Jarlskog, Nucl. Phys. B 223, 15 (1983)

Atom mixing amplitude ΔM

$$E \simeq E^* + E_{\mathrm{H}} + E_{\mathrm{H}'},$$

$$\Gamma \simeq \Gamma^* + \Gamma_{\mathrm{H}} + \Gamma_{\mathrm{H}'}.$$

Decay rate

$$\frac{1}{\tau} \simeq \frac{(\Delta M)^2}{(Q-E)^2 + \frac{1}{4}\Gamma^2}\Gamma,$$

2νECEC-background depends strongly on Q-value

transitions, abundance, daughter nuclear excitation, atomic vacancies and figure of merit of some isotopes [10]

$Z \to Z-2$	Z-natural abundance in %	Nuclear excitation E^* (in MeV), J^P	Atomic vacancies H, H′	Figure of merit $Q-E$ (in keV)
$^{74}_{34}$Se → $^{74}_{32}$Ge	0.87	1.204 (2^+)	2S(P), 2S(P)	2 ± 3
$^{78}_{36}$Kr → $^{78}_{34}$Se	0.36	2.839 (2^+) 2.864 (?)	1S, 1S	19 / −6 ± 10
$^{102}_{46}$Pd → $^{102}_{44}$Ru	1	1.103 (2^+) 1.107 (4^+)	1S, 1S	29 / 25 ± 9
$^{106}_{48}$Cd → $^{106}_{46}$Pd	1.25	2.741 (?)	1S, 1S	−8 ± 10
$^{112}_{50}$Sn → $^{112}_{48}$Cd	1.01	1.871 (0^+)	1S, 1S	−3 ± 10
$^{130}_{56}$Ba → $^{130}_{54}$Xe	0.11	2.502 (?) 2.544 (?)	1S, 1S 1S, 2S(P)	8 / −6 ± 13
$^{152}_{64}$Gd → $^{152}_{62}$Sm	0.20	0 (0^+)	1S, 2S	4 ± 4
$^{162}_{68}$Er → $^{162}_{66}$Dy	0.14	1.783 (2^+)	1S, 2S	1 ± 6
$^{164}_{68}$Er → $^{164}_{66}$Dy	1.56	0 (0^+)	2S, 2S	9 ± 5
$^{168}_{70}$Yb → $^{168}_{68}$Er	0.14	1.355 (1^-) 1.393 (?)	1S, 2S 2S, 2S	−1 / 8 ± 4
$^{180}_{74}$W → $^{180}_{72}$Hf	0.13	0 (0^+) 0.093 (2^+)	1S, 1S 1S, 3S	26 / −4 ± 17
$^{196}_{80}$Hg → $^{186}_{78}$Pt	0.15	0.689 (2^+)	1S, 2S	26 ± 9

^{106}Pd levels before 2008

Table of Isotopes, Eighth Edition,
Ed. Richard B. Firestone

E_{level}(keV)	Jπ	Eγ(keV)
2748.2(4)	2,3-	γ2236.3→γ511.85
2746(5)	4+	?
2741.0(5)	(1,2+)	γ2741 (2229.5+511.85)
2717.56(21)	?	γ1159.9→γ1557.7

^{106}Pd levels from 2008

Nuclear Data Sheets 109 (2008) 943
D. De Frenne and A. Negret

E_{level}(keV)	Jπ	Eγ(keV)
2748.2(4)	2,3-	γ2236.3→γ511.85
2741.0(5)	4+	γ2741(2229.5+511.85)
2737	?	?
2717.56(21)	?	γ1159.9→γ1557.7

0νEC/EC Resonant Decay of ^{106}Cd

Q= 2775.39±0.10 keV, E_K=24.3 keV, E_L=3.33 keV

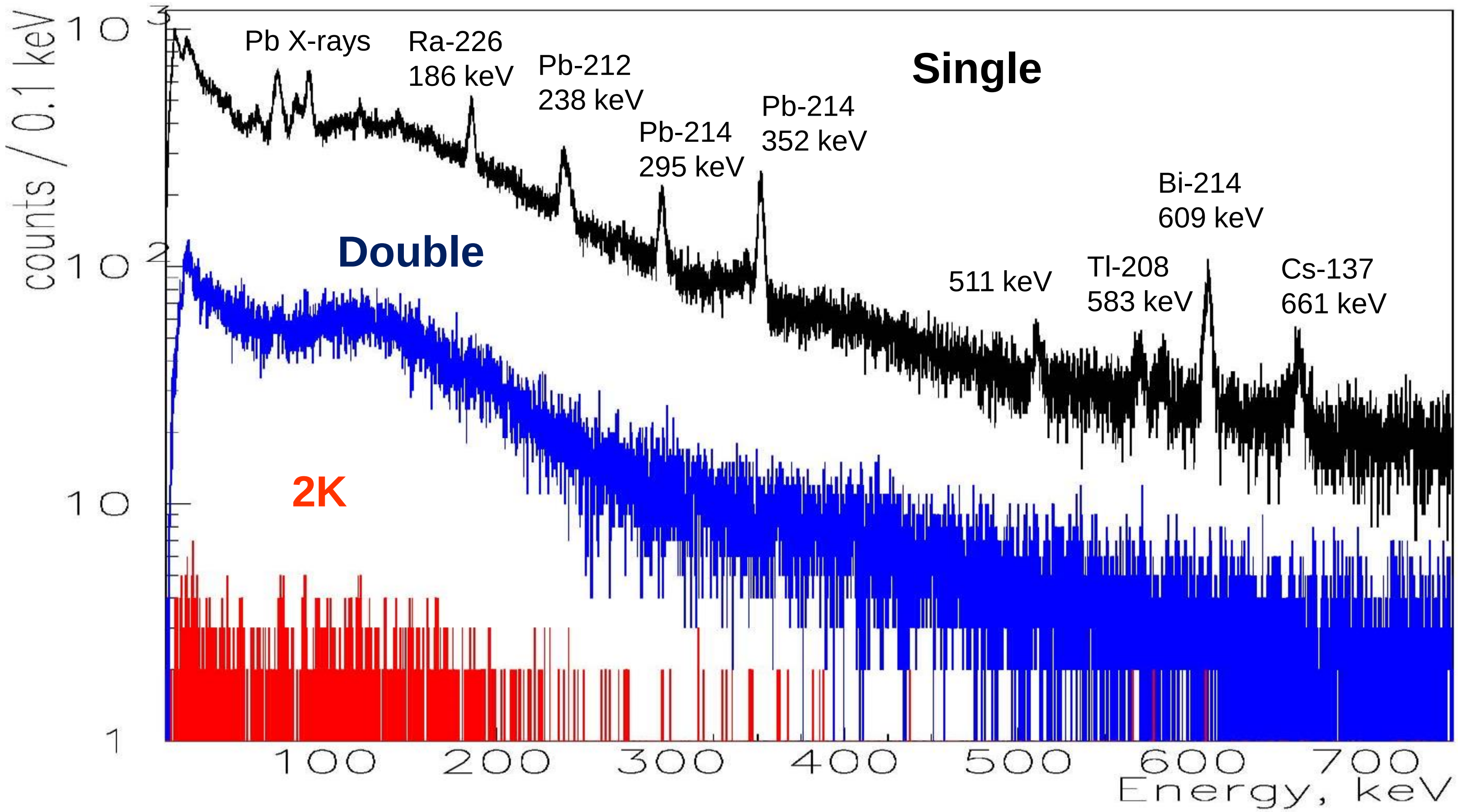
E^*_1= 2741.0 keV KL observables γ – 2741 (2229+512) keV

E^*_2= 2717.6 keV KK observables γ – (1160 + 1046 + 512) keV

E^*_3= 2737 keV (?) KL observables γ – ?

Phase III - Search for 0νEC/EC decay of ^{106}Cd → Obelix det.

T=19333 h



Single
Double
2K
Pb X-rays
Ra-226
186 keV
Pb-212
238 keV
Pb-214
295 keV
Pb-214
352 keV
511 keV
Tl-208
583 keV
Bi-214
609 keV
Cs-137
661 keV
counts / 0.1 keV
Energy, keV

Calculation of the limit for ^{58}Ni

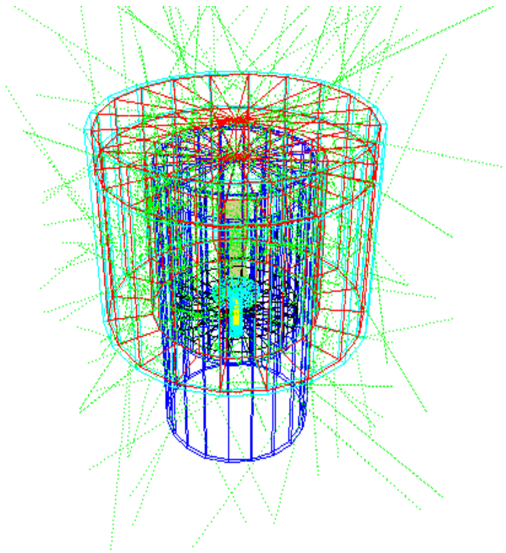
$$T_{1/2}^{LIM} > \ln(2) \times \varepsilon \times M_{TOT} \times O(^{58}Ni) \times T_{EXP} \times N_A / A / N_{EXCL}$$

- ε – detection efficiency,
- O – enrichment of isotop
- M_{TOT} – mass of sample(s),
- T_{EXP} -time of measurement
- N_{EXCL} - the number of excluded signal events

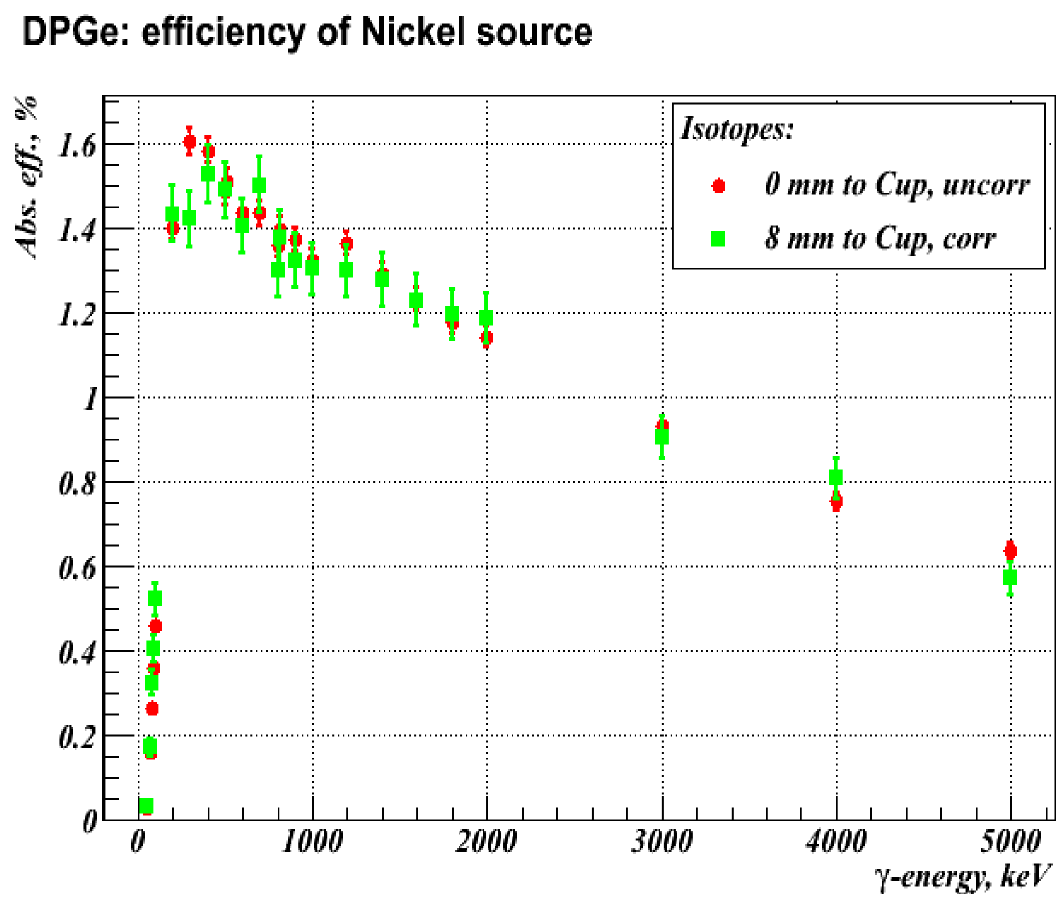
Использованные в расчетах параметры	
Параметр	**Величина**
NA/10^20	**6022.142**
M_{TOT},г	**21754**
O(^{58}Ni)	**68.27%**
A	**58**

K.Zuber

http://wwwarchive.ph.ed.ac.uk/sussp61/lectures/05_Zuber_NeutrinolessDoubleBetaDecay/StAndrews_2006_lect2_orig.ppt

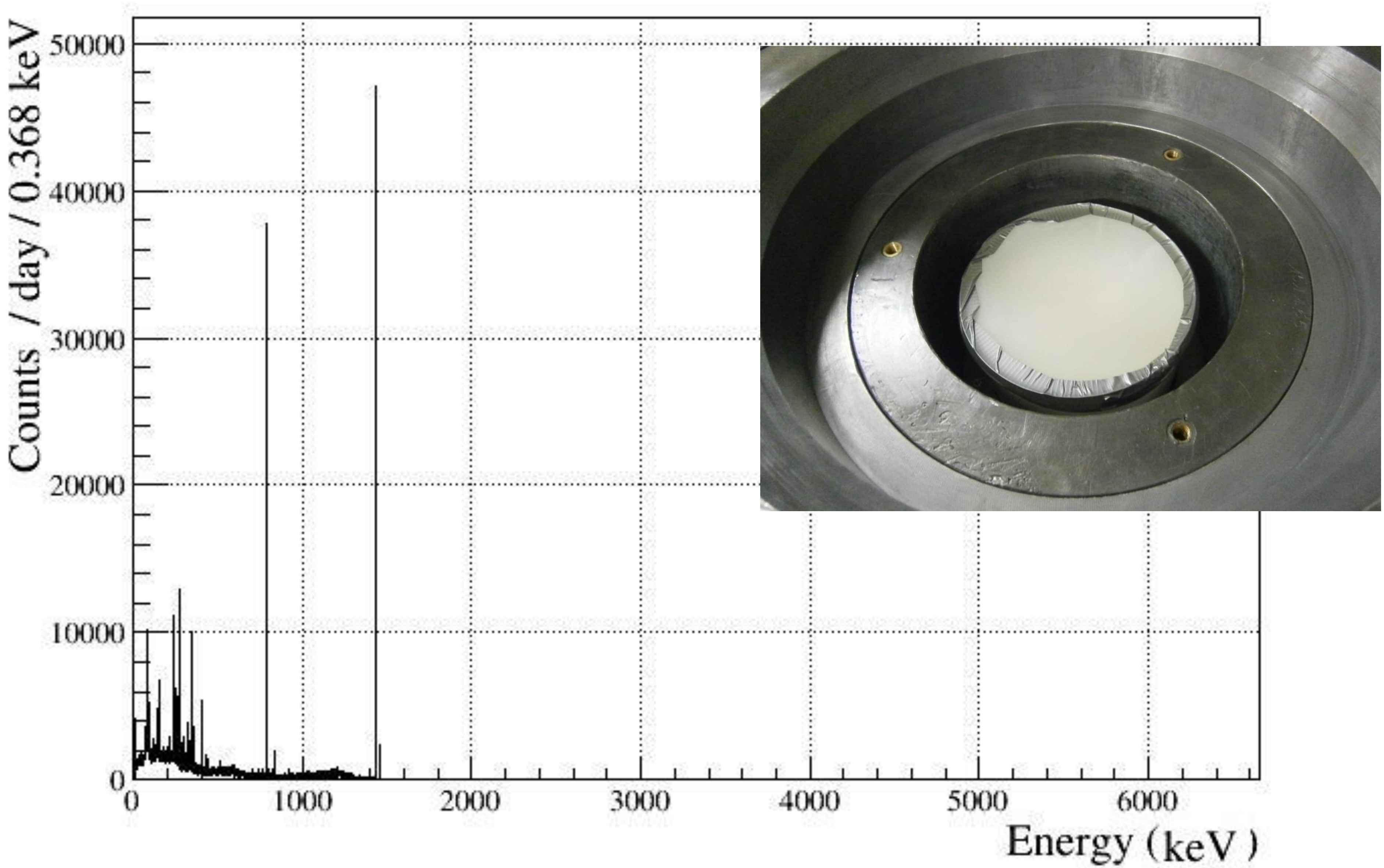


Calculated efficiency

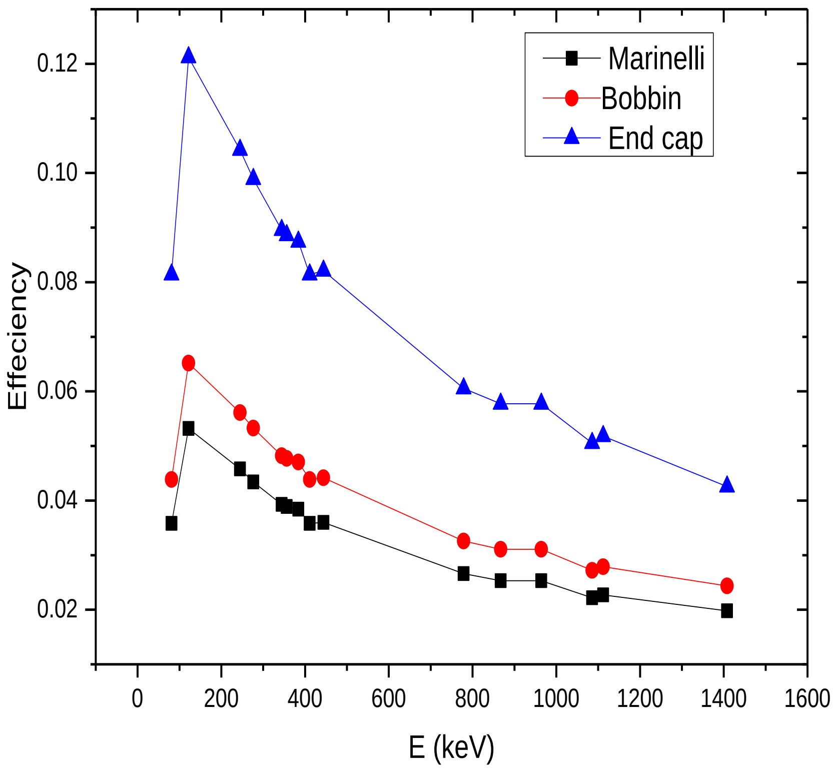


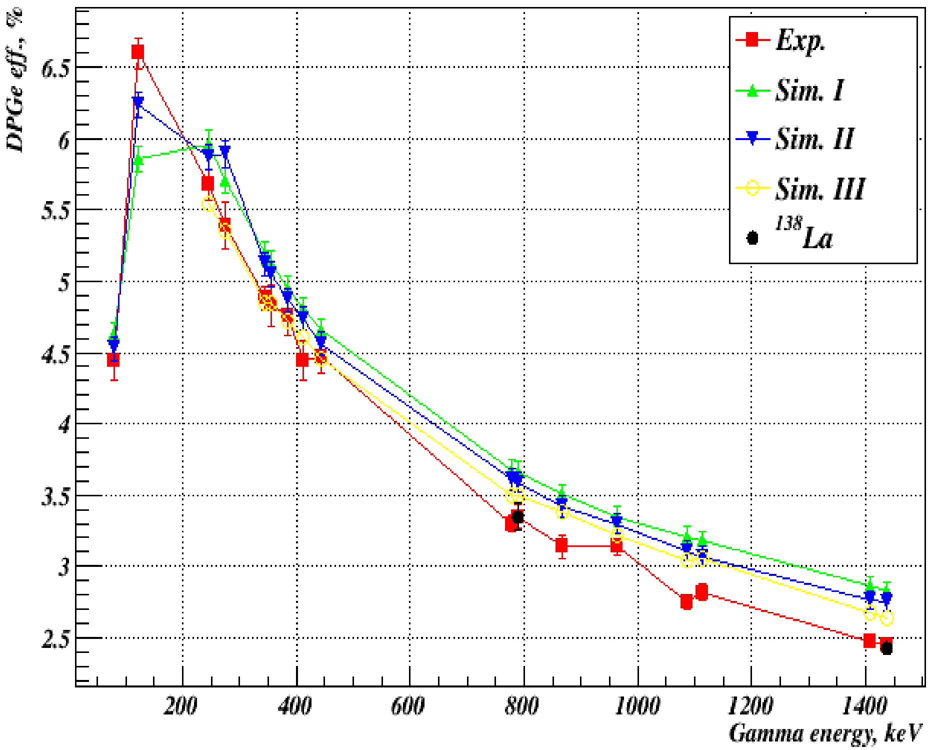
Simulation was performed using ROOT-VMC-GEANT4 DPGE package in the energy region of 0.05- 5 MeV.

Measurement of La powder at Marinelli backer



Efficiencies of OBELIX detector for some „standard“ geometries of measurement





To obtain the detector efficiency an original method using special low-active samples with known mass and activity was developed. Based on results obtained in measurements of La_2O_3 and standard sources of ^{152}Eu and ^{133}Ba, efficiency curves for measurements of double beta emitters in several “standard” geometries were obtained.

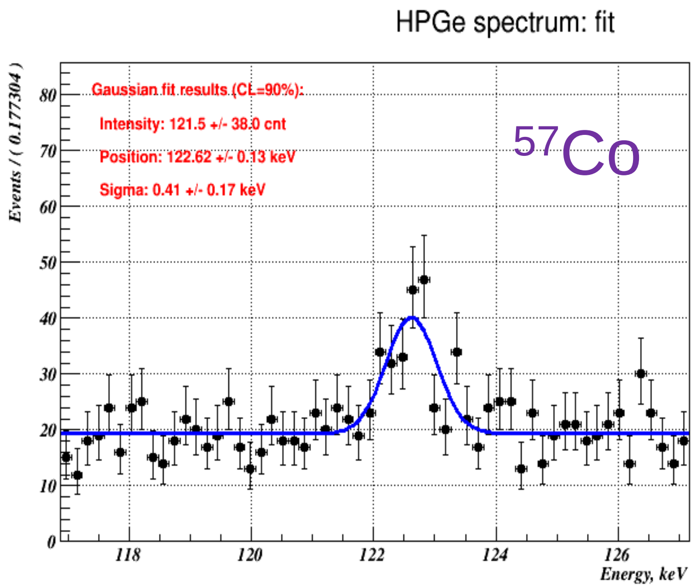
Obtained efficiencies are in a good agreement with MC simulations (for example the measurement with bobbin). Measured sample was specially prepared in the same geometry like investigated sample of ^{100}Mo.

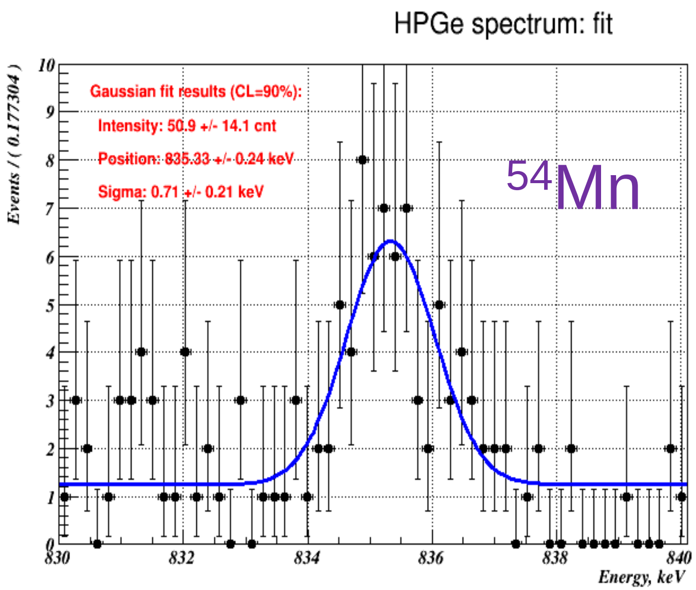
Preliminary results

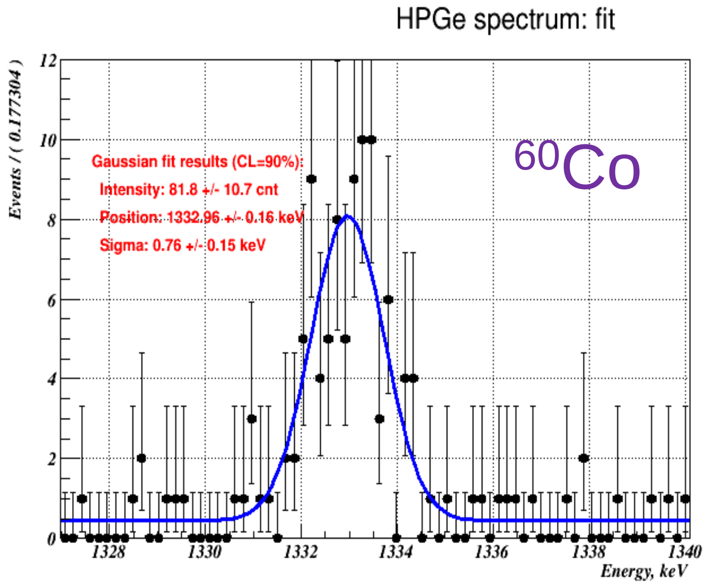
Energy	Efficiency	Nexcl	$T_{1/2}$, (90% CL)	Previous limits
Kb+ (811 keV)				
811 keV	1.0%	18.0	2.3×10^{22} y	4.0×10^{20} y (68%CL)*
Kb+ (g.s.)				
511 keV	2.9%	69.5	1.7×10^{22} y	7.0×10^{20} y (68%CL)*
KK (811 keV)				
811 keV	1.4%	18.0	3.3×10^{22} y	4.0×10^{19} y (90%CL)**
0νKK-resonant (1918 keV)				
1918 keV	1.2%	12.3	5.1×10^{22} y	2.1×10^{21} y (90%CL)***
KK (1675 keV)				
864 keV	1.0%	19.4	2.2×10^{22} y	
1675 keV	1.3%	16.2	3.4×10^{22} y	4.0×10^{19} y (90%CL)**

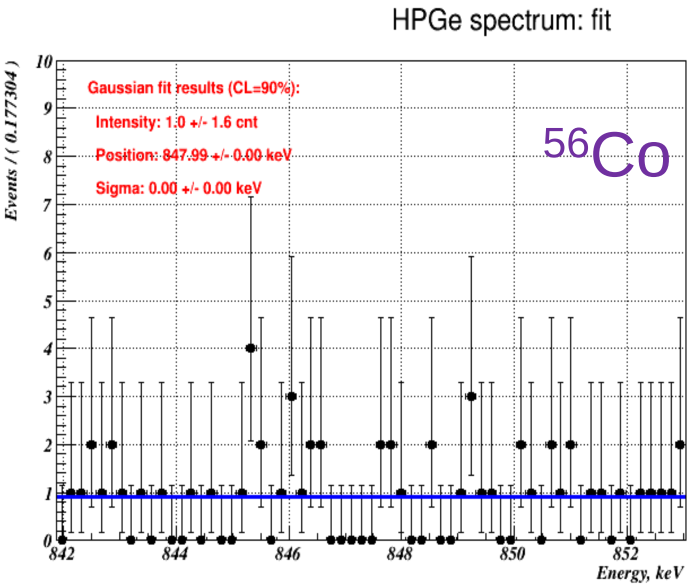
*S.I. Vasil'ev et al., JETP Lett. 57 (1993) 631.
**E. Bellotti et al., Lett. Nuovo Cim. 33 (1982) 273.
***B. Lehnert et al., J. Phys. G: Nucl. Part. Phys. 43 (2016) 065201

Cosmogenic isotopes in 2017



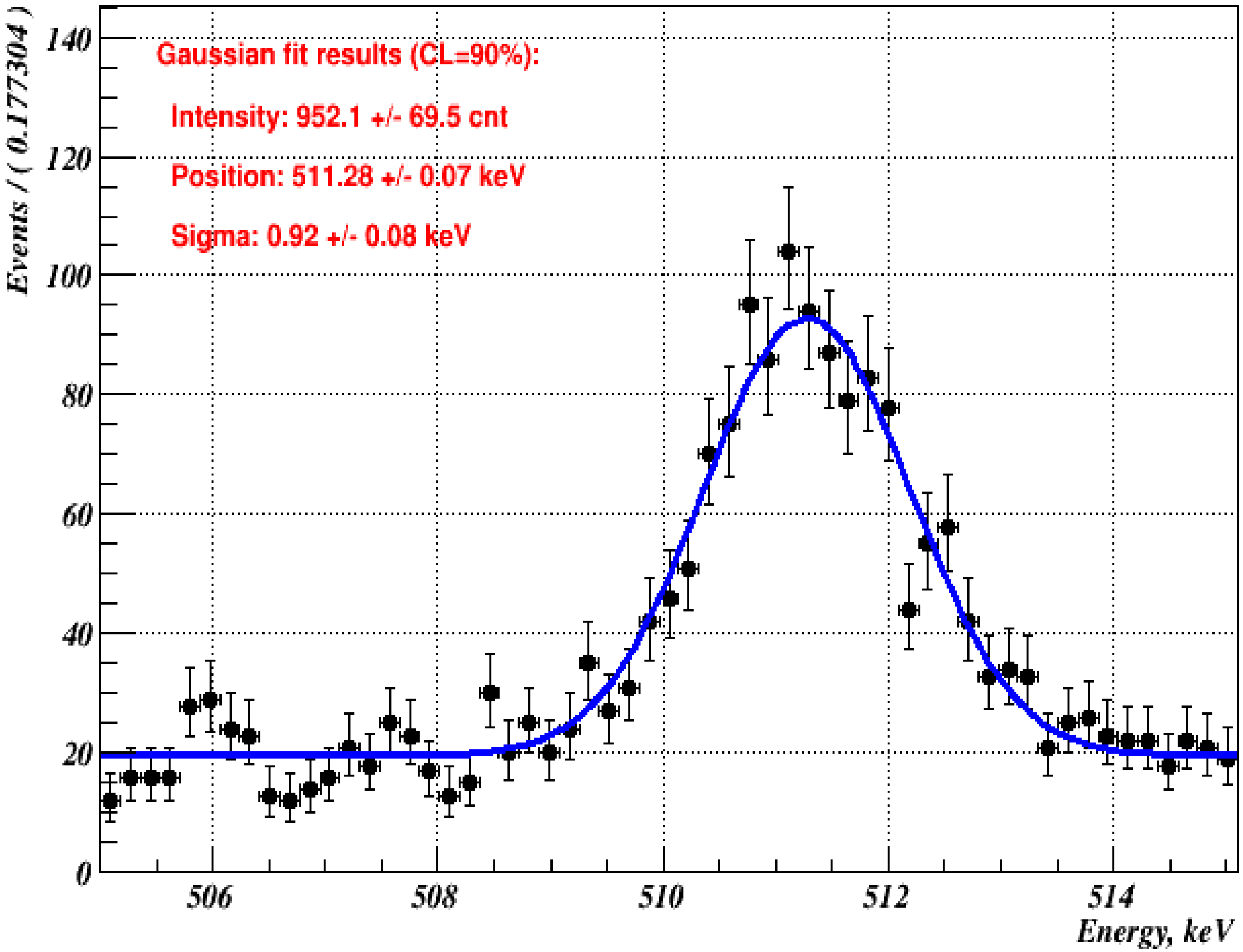






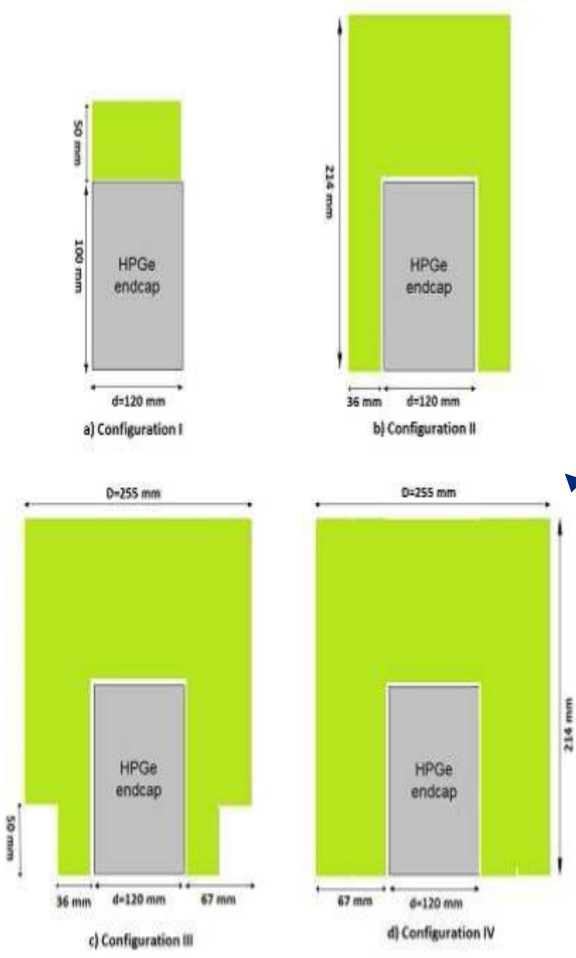
511 keV (2017)

HPGe spectrum: fit

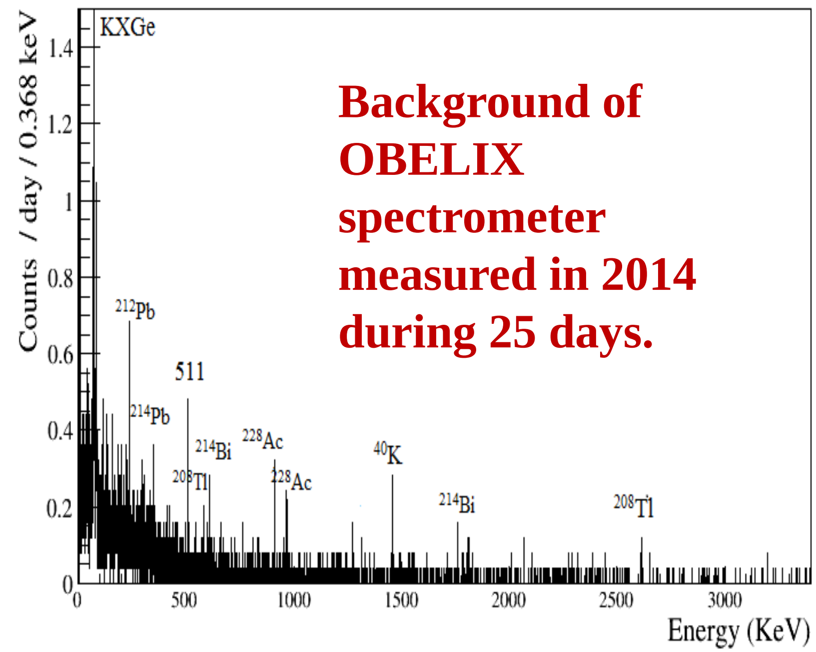


N_{EXCL}=69.5 events

Background studies



Integral count rate [30-3000 keV]:
2011 – **173 counts/kg · d**
2014 – **73 counts/kg · d**
To compare background, HPGe in LSM:
108 counts/kg · d



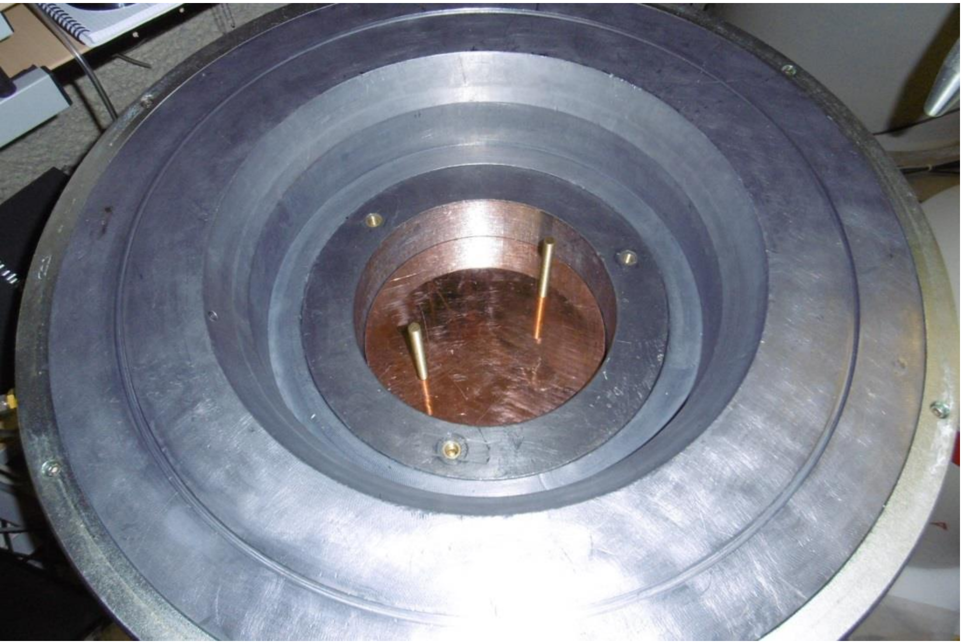
Background of OBELIX spectrometer measured in 2014 during 25 days.

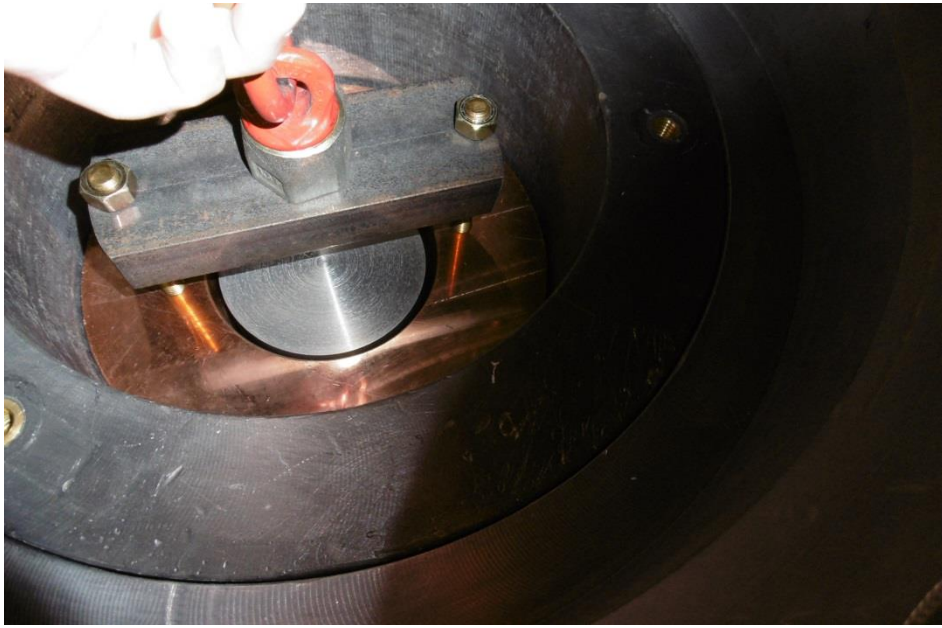
Possible measurement configurations with OBELIX

E [keV]	Nuclide	Counts/kg·day
238	^{212}Pb (Th chain)	0.60±0.25
295	^{214}Pb (U chain)	0.24±0.05
352	^{214}Pb (U chain)	0.20±0.09
583	^{208}Tl (Th chain)	0.18±0.07
609	^{214}B (U chain)	0.21±0.06
911	^{228}Ac (Th chain)	0.25±0.05
969	^{228}Ac (Th chain)	0.20±0.04
1460	^{40}K	0.34±0.05
2615	^{208}Tl (Th chain)	0.17±0.06

Minimal Detectable Activities (in Bq/unit, 7 days, 3 l Marinelli):

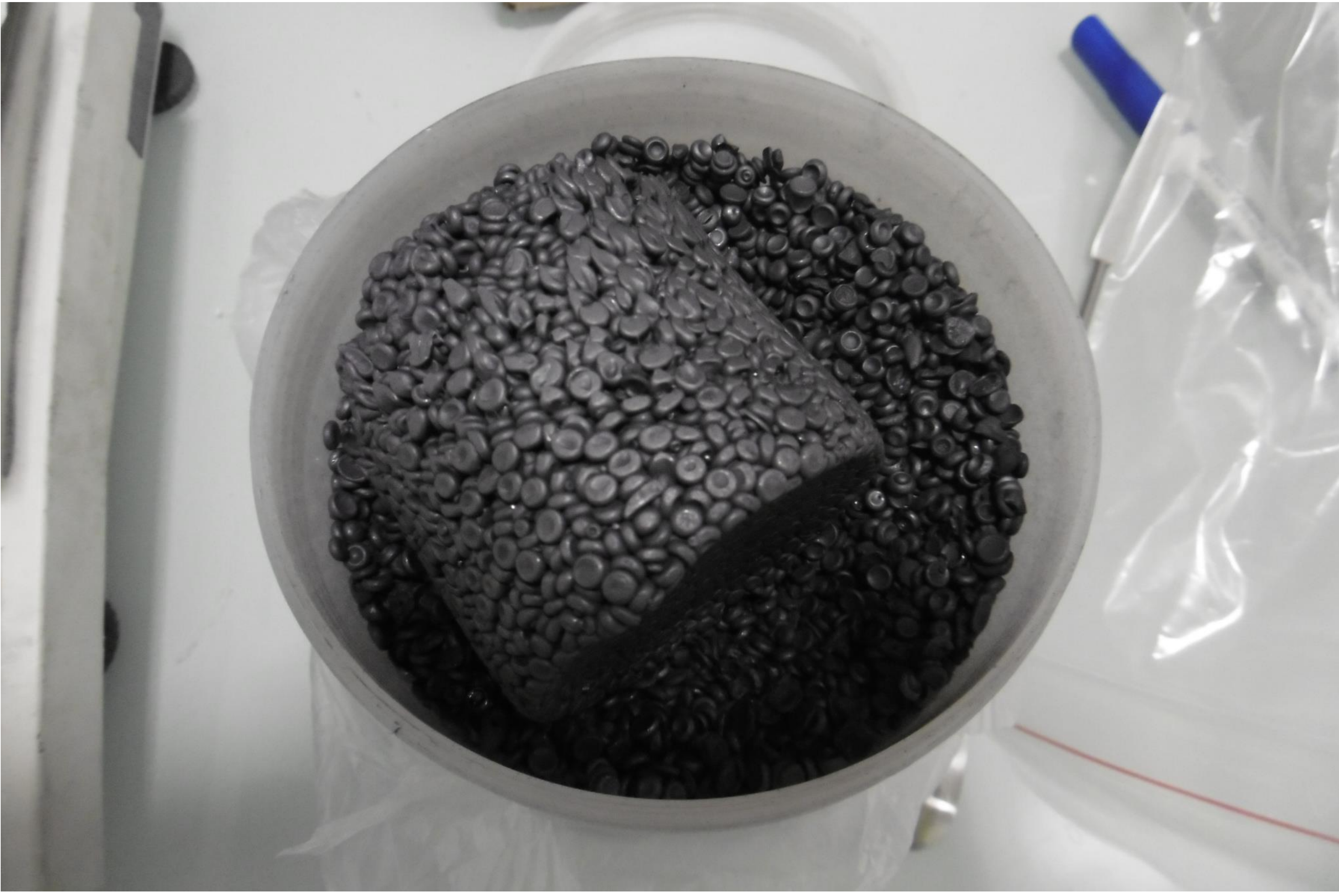
E [keV]	**46.5**	**186**	**352**	**511**	**609**	**1173**
100% det	6.2e-2	2.4e-2	2.9e-2	2.2e-2	2.5e-2	1.5e-2
OBELIX	4.9e-4	5.6e-4	4.5e-4	4.5e-4	4.7e-4	2.5e-4





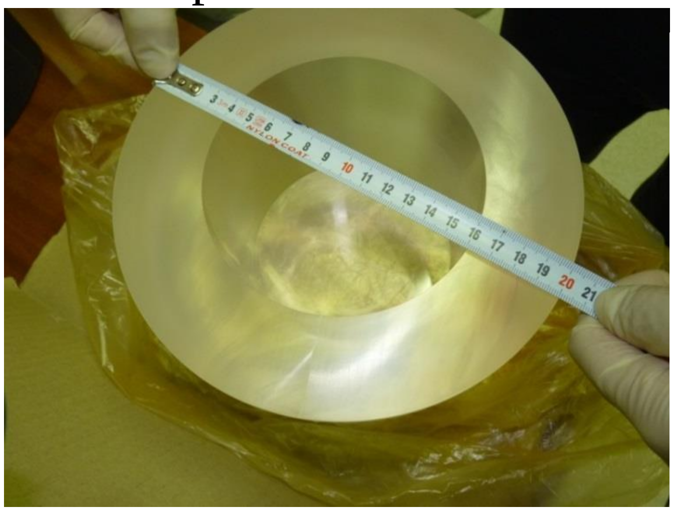
Copper sample
22.3+35.4 kg

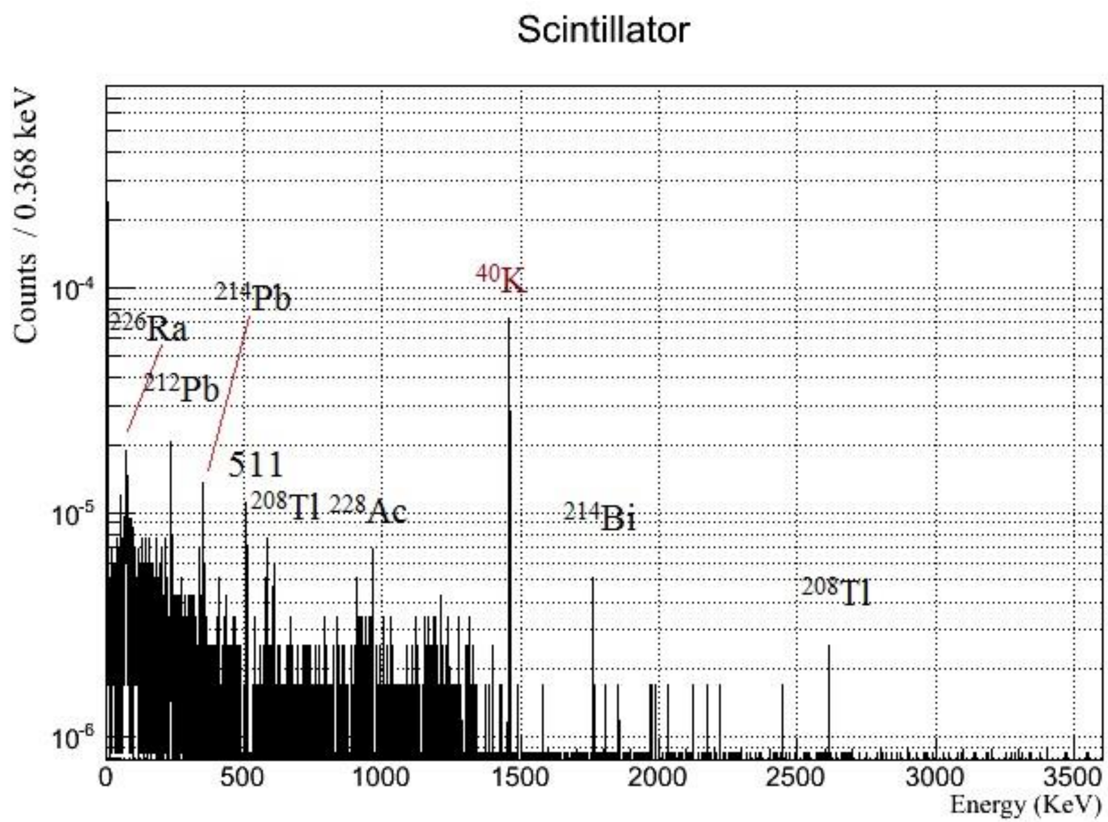
Se-nat.



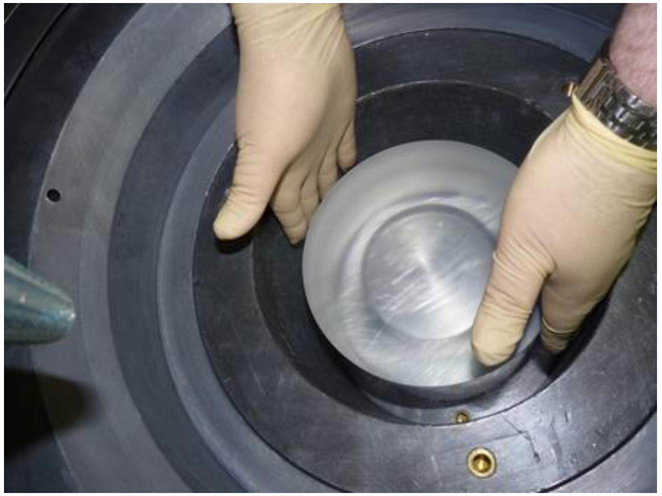
Measurement of scintillator for SuperNEMO

- Scintillator was produced by ENVINET for NRPI and IEAP
- The sample was prepared by the request of NRPI in the form of 3L Marinelli with the mass of 4500 g
- The scintillator was measured in May 2014 with the OBELIX spectrometer





Results (in comparison with the similar scintillator measured by Bordeux group)



HPGe (LSM)	Sample	Mass g	Time h	40K mBq/kg	238U mBq/kg	214Bi mBq/kg	208Tl mBq/kg
OBELIX (IEAP)	**Scintillator in the shape of Marinelli**	**4500**	**325**	**20.6**	**1.8**	**< 0.14**	**< 0.09**
IRIS (Bordeaux)	Scintillator In the shape of Marinelli	3300	742	<3.4	3.5	< 0.45	< 0.15

Ge detectors at LSM

Detector	Type	Volume	Total and peak background rate (counts/day)			
			40-2700 keV	352 keV	583 keV	1461 keV
MONDEUSE	well	220 cc	770	4.2	2.7	5
ROUSSETE	well	430 cc	692	4.1	2.9	7.2
ABYMES	well	980 cc	828	5.6	5.6	5.6
XXL	well	844 cc	821	6.8	<1.8	11.6
HERMINE	N	197 cc	313	1.2	1.5	2.3
HELLAZ	P	204 cc	515	4.5	0.5	1.4
JASMIN	P	380 cc	529	2.0	1.41	1.71
GENTIANE	N	215 cc	178	<0.21	0.38	0.65
IRIS	P	400 cc	282	1.02	1.46	3.01

TABLE 1. Half-lives (in years) of 2νEC/EC($0^+ \rightarrow 0^+$, g.s.) of ^{106}Cd calculated using different values of axial coupling (g_A) and nuclear models: special unitary group (SU); standard, renormalized (R), and selfconsistent (S, with small (s.b.) and large (l.b.) basis of single particle states) quasiparticle random phase approaches (QRPA) with standard and adjusted (A) Woods Saxon single particle energies (WS); projected Hartre-Fock-Bogoliubov model (PHFB); single state dominance hypothesis (SSDH).

Theory			
$T_{1/2}^{2\nu ECEC}$		Method	Ref.
$g_A = 1.0$	$g_A = 1.25$		
$4.2 \cdot 10^{21}$	$1.7 \cdot 10^{21}$	SU(4)	[11]
$2.5 \cdot 10^{22}$	$9.7 \cdot 10^{21}$	PHFB	[7]
$2.2 \cdot 10^{21}$	$8.7 \cdot 10^{20}$	QRPA	[12]
$1.5 \cdot 10^{20}$	$6.1 \cdot 10^{19}$	QRPA	[13]
$2.3 \cdot 10^{20}$	$9.0 \cdot 10^{19}$	QRPA (WS)	[14]
$2.6 \cdot 10^{20}$	$1.1 \cdot 10^{20}$	QRPA (AWS)	
$5.5 \cdot 10^{21}$	$2.3 \cdot 10^{21}$	QRPA (WS)	[15]
$3.0 \cdot 10^{20}$	$1.2 \cdot 10^{20}$	QRPA (AWS)	
$5.3 \cdot 10^{20}$	$2.1 \cdot 10^{20}$	RQRPA (WS)	[16]
$5.1 \cdot 10^{20}$	$2.0 \cdot 10^{20}$	RQRPA (AWS)	
$5.0 \cdot 10^{20}$	$2.0 \cdot 10^{20}$	SQRPA (s.b.)	[17]
$6.6 \cdot 10^{20}$	$2.6 \cdot 10^{20}$	SQRPA (l.b.)	

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11. O.A. Rumyantsev, M.H. Uhrin, *Phys. Lett.* B **443** (1998) 51.
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^{150}Nd. Transition to the 0^+ excited state

I. $T_{1/2} = [1.33^{+0.36}_{-0.23}(stat)\ ^{+0.27}_{-0.13}(syst)]\cdot 10^{20}$ yr

(JETP. Lett. 79 (2004) 10; PRC 79 (2009) 045501)

II. $T_{1/2} = [1.07^{+0.45}_{-0.25}(stat) \pm 0.07(syst)]\cdot 10^{20}$ yr

(PRC 90 (2014) 055501)

Average value: $1.2^{+0.3}_{-0.2}\cdot 10^{20}$ yr

From presentation of A.Barabash (MEDEX'17)

Half-life for $0\nu\beta\beta$:

Detection efficiency

Isotopical enrichment

Source mass

Exposure time

$$T_{1/2} = \frac{\varepsilon}{W} F_a \sqrt{\frac{M.t}{B.\Delta E}}$$

Energy resolution

Molecular weight

Background rate in c/(keV.kg.y)

- source = enriched material (F_a)
- big mass of the source (M)
- long time of measurement (t)
- “best” energy resolution of the detector (ΔE)
- background as low as possible (B)