Investigation of double beta decay of ^{58}Ni at the Modane Underground Laboratory

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on behalf of **Obelix** collaboration

Double beta decay

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

(Z-2,A) → (Z,A)+$2e^{-}$+$2\upsilon_e$ (2νβ⁻ β⁻) observables: 2 e^{-}

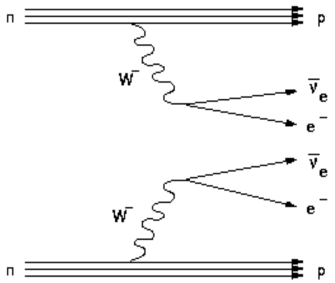
(Z+2,A) → (Z,A)+$2e^{+}$+$2\upsilon_e$ (2νβ⁺ β⁺) observables: 2 e^{+}, 4×511 keV γ

e^{-}+(Z+2,A) → (Z,A)+e^{+}+ $2\upsilon_e$ (2νβ⁺/EC) observables: 1 e^{+}, 2×511 keV γ, X-ray

$2e^{-}$+(Z+2,A) → (Z,A)+$2\upsilon_e$ +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⁻)

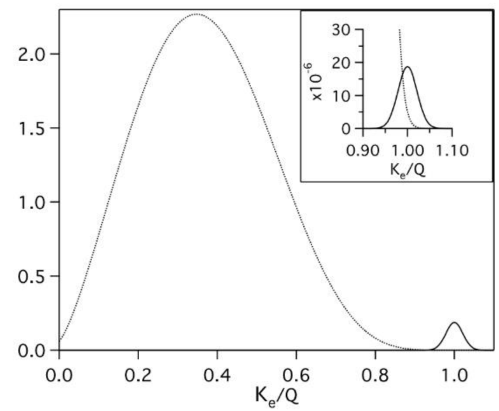
(Z+2,A) → (Z,A)+$2e^{+}$ (0νβ⁺ β⁺)

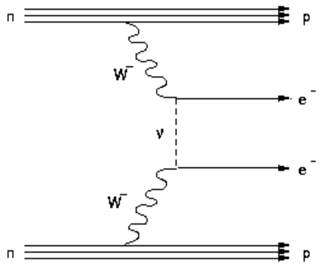
e^{-}+(Z+2,A) → (Z,A)+e^{+} (0νβ⁺/EC)

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

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

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





Feynman diagram for 0νββ

By present time 2νββ 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 geochem. experiment

Double beta decay to the excited states

Motivations:

- Nuclear spectroscopy (to know decay scheme of nuclei)
- NME problem
- $2\nu\beta\beta$ ($0^+ \rightarrow 0_1^+$) 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 $\beta\beta$ 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**)

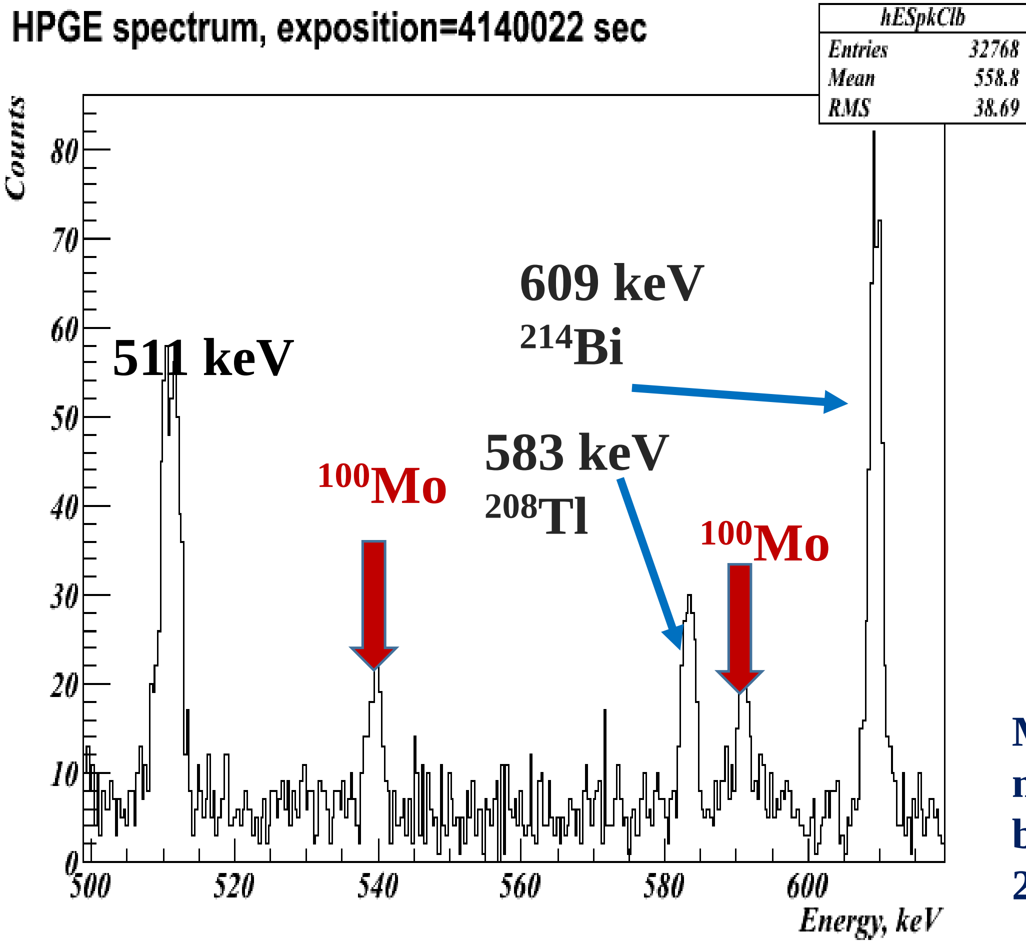
Present "positive" results on $2\nu\beta\beta$ decay of ^{100}Mo to the 0_1^+ excited state of ^{100}Ru.

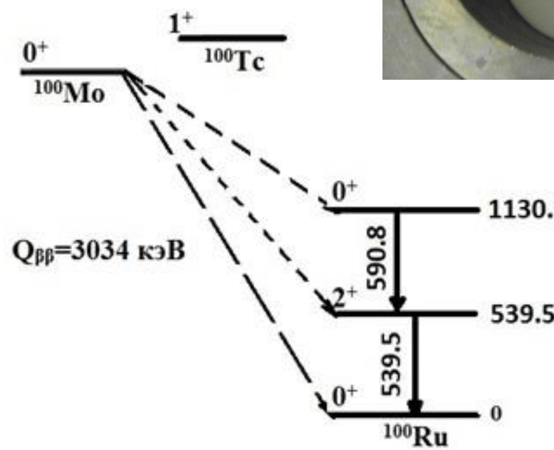
$T_{1/2}$ $[y]$	N	S/B	Year	Method
$6.1^{+1.8}_{-1.1}(stat.) \times 10^{20}$	133[a]	~1/7	1995	HPGe
$9.3^{+2.8}_{-1.7}(stat.) \pm 1.4(sys.) \times 10^{20}$	153[a]	~1/4	1999	HPGe
$6.0^{+1.9}_{-1.1}(stat.) \pm 0.6(sys.) \times 10^{20}$	19.5	8/1	2001	2×HPGe
$5.7^{+1.3}_{-0.9}(stat.) \pm 0.8(sys.) \times 10^{20}$	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

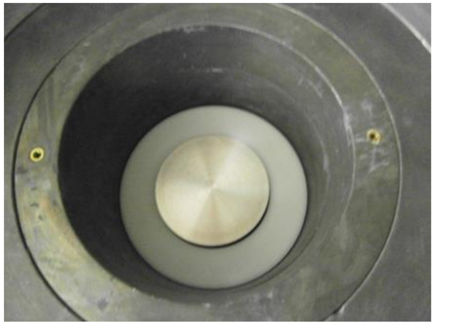
N is the number of useful events;
S/B is the signal-to-background ratio.

a) Sum of two peaks

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







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.

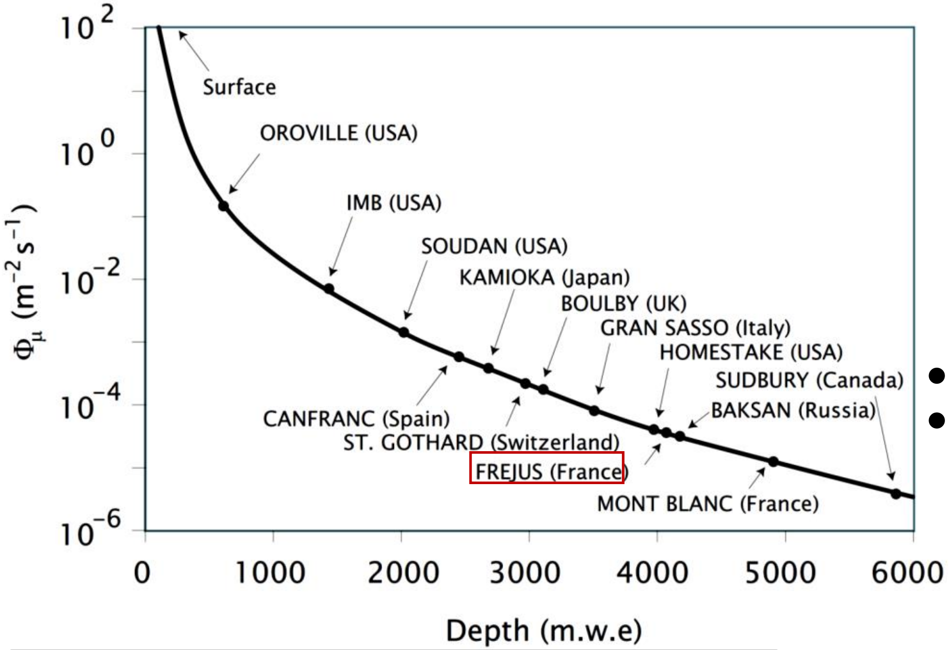
^{100}Mo → 0$^+$, 1130 keV ^{100}Ru* observable γ590.8+γ539.5 keV

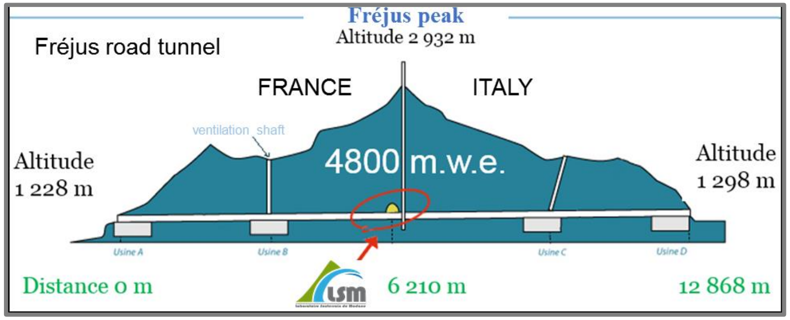
^{100}Mo → 2$^+$, 540 keV ^{100}Ru observable γ539.5 keV

$T_{1/2}$ (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

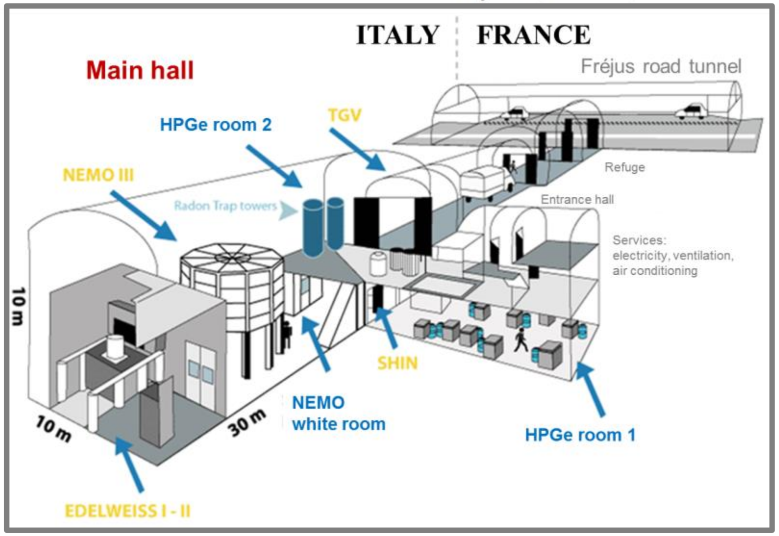
Laboratoire Souterrain de Modane





- Road tunnel Fréjus (France – Italy border)
- Depth of ~ 4800 m.w.e. (muon suppression factor ~ 10^6)

  - Muon flux: 4×10^{-5} μ.m^{-2}.s^{-1}
  - Neutron flux: 4×10^{-2} n.m^{-2}.s^{-1}(fast); 1.6×10^{-2} n.m^{-2}.s^{-1} (thermal)
  - Radon: 15 Bq.m^{-3}



Main hall

HPGe room 1

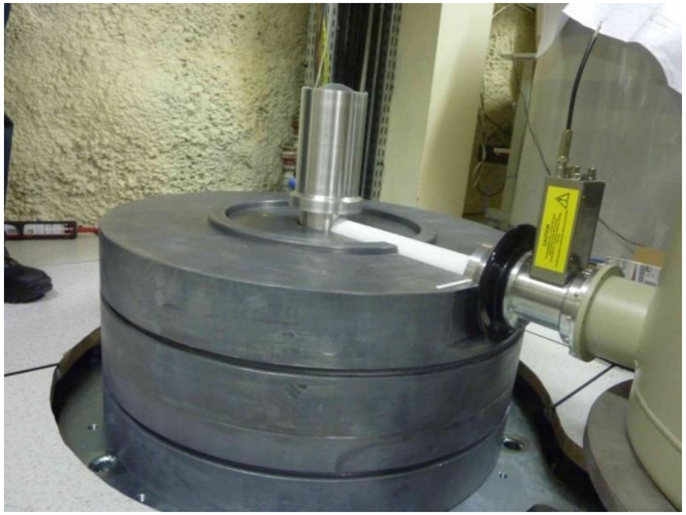
Detector Obelix*

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

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

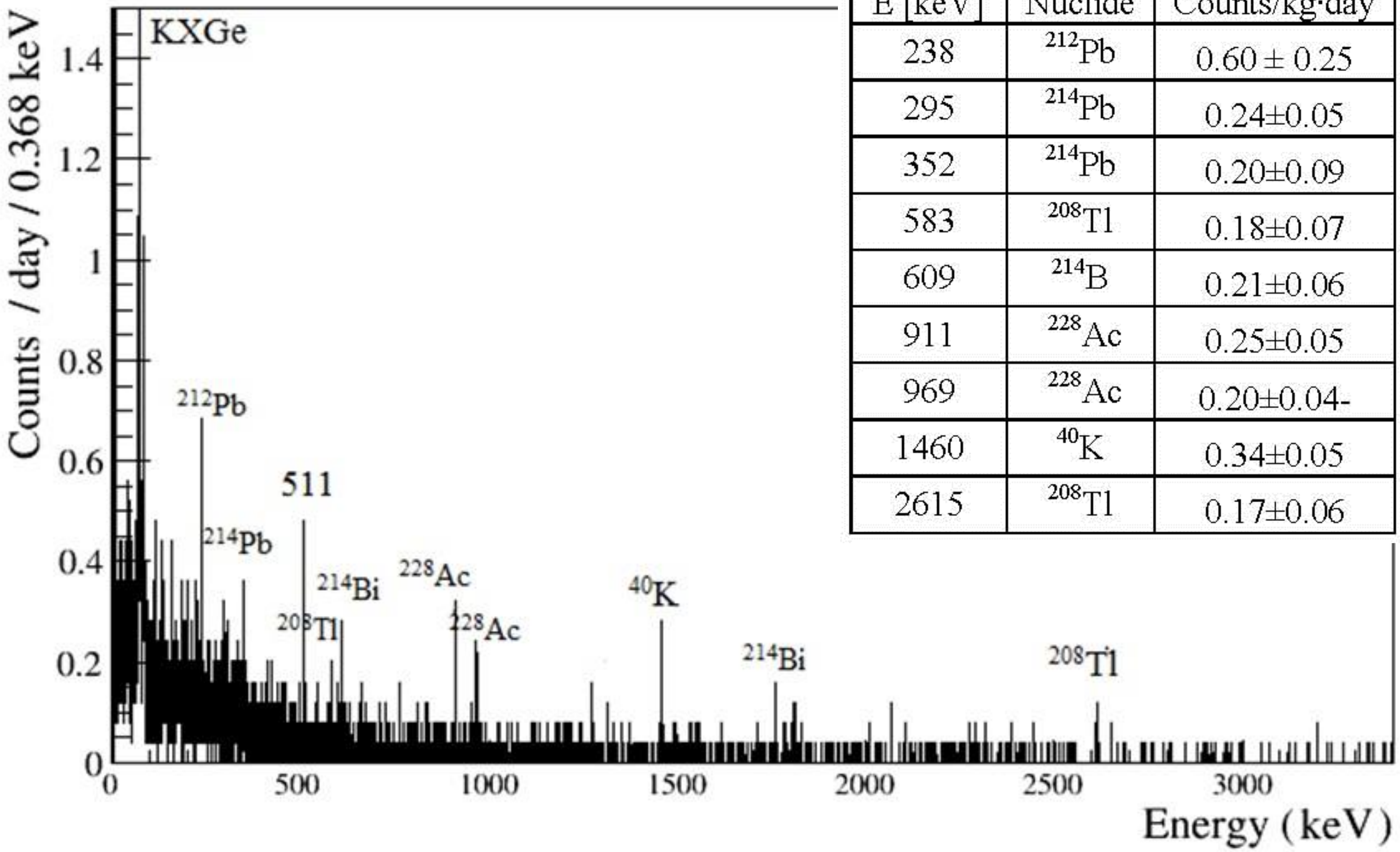
Sensitive volume	600 cm^3
Efficiency	~160%
Peak / Compton	83
Energy resolution	~1.2 keV at 122 keV (^{57}Co), ~2 keV at 1332 keV (^{60}Co)
Distance from cap	4 mm
Entrance window	Al, 1.6 mm

- ~ 12 cm of archeological lead (PbI) (activity of < 60 mBq/kg) (~7 cm can be removed)
- ~ 20 cm low-active lead (PbII) (activity of 5 - 20 Bq/kg)
- Detection part is flushed by radon free air from radon trapping facility



*JINST 12 (2017) P02004.

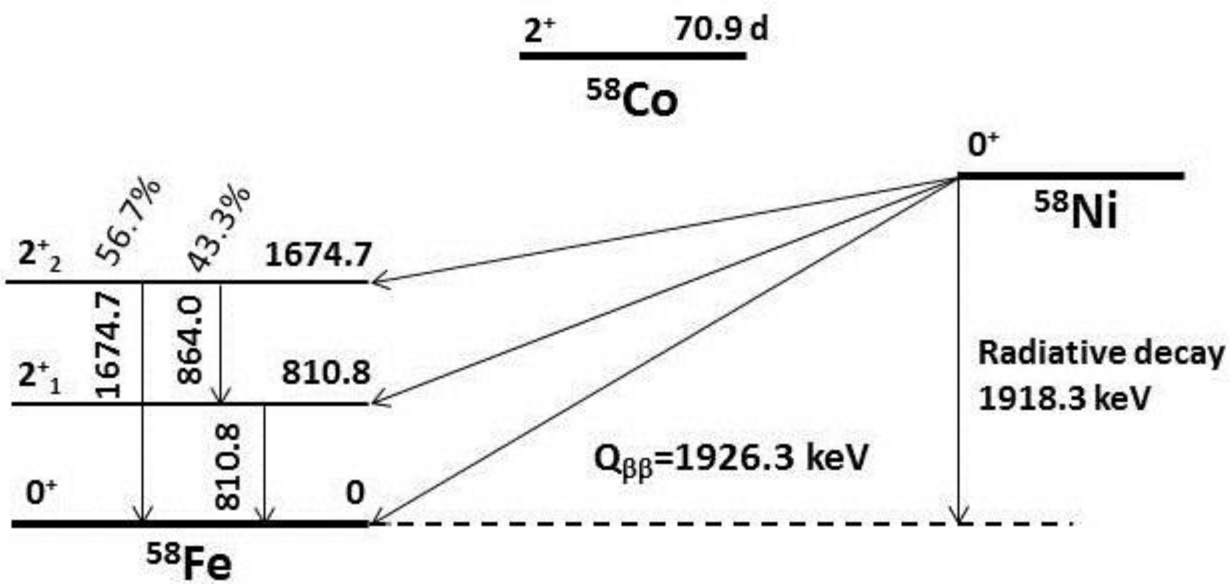
Background of the Obelix spectrometer



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)

Double beta decay of ^{58}Ni



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

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

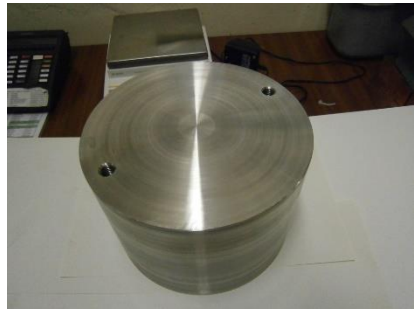
$\rightarrow$ ^{58}Fe$(2_2^+) + 2\upsilon_e + 2\gamma_{shell} + \gamma_{(810.8\ keV)} + \gamma_{(864.0\ keV)}$

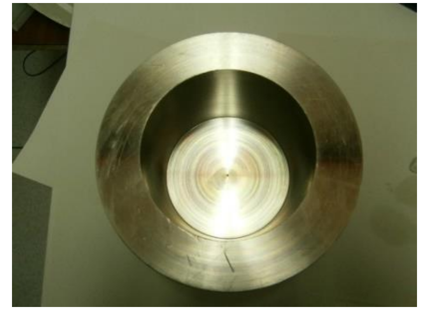
$2\nu\beta^{+}EC$: ^{58}Ni + e^{-} $\rightarrow ^{58}$Fe$(g.s.) + 2\upsilon_e + e^{+} + \gamma_{shell} + 2\gamma_{(511\ keV)}$

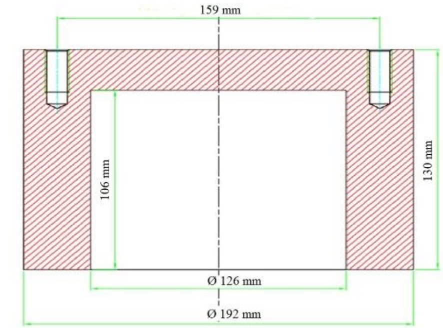
$0\nu EC/EC$: ^{58}Ni + $2e^{-}$ $\rightarrow ^{58}$Fe$(g.s.) + \gamma_K + \gamma_L + \gamma_{(1918.3\ keV)}$

Measurement of ^{58}Ni

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







Run 1 - 2014

15.10.2914-11.11.2014
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 - ….. (in progress)
T= 2118 h = **88.3 d**

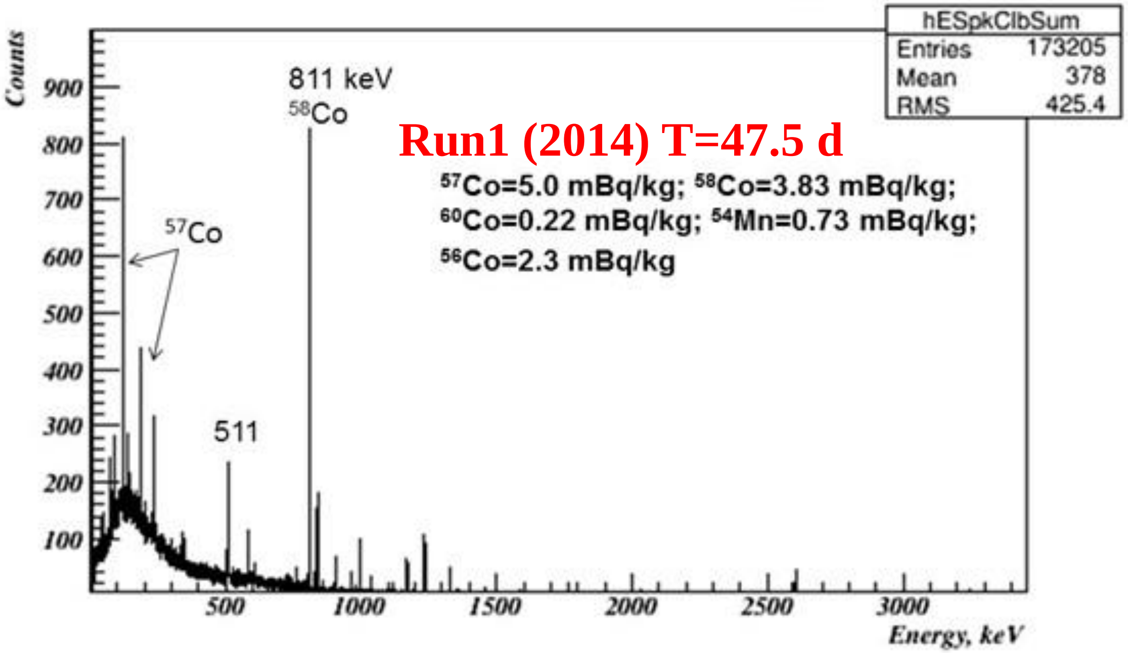
Theoretical prediction:

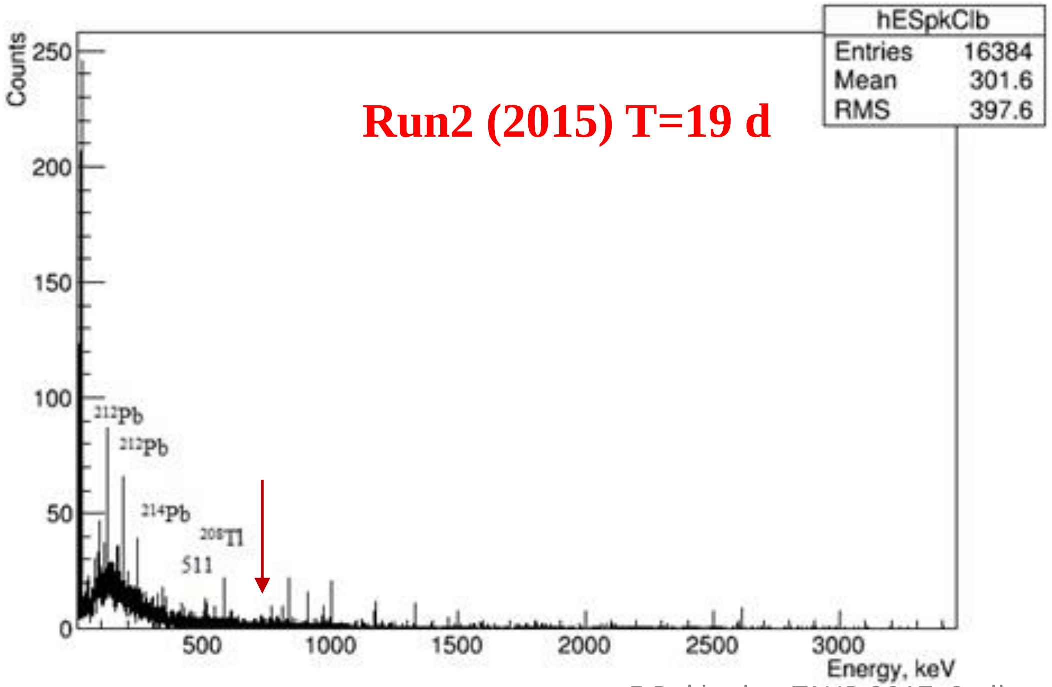
$T_{1/2}(2\nu\beta^+EC, 0^+\rightarrow0^+) = 8.6\times10^{25}$ y
$T_{1/2}(2\nu EC/EC, 0^+\rightarrow0^+) = 6.1\times10^{24}$ y
$T_{1/2}(0\nu EC/EC$ radiative$) = 2\times10^{35} - 3\times10^{36}$ y

Existing experimental limits:

$T_{1/2}(2\nu\beta^+EC, 0^+\rightarrow0^+) > 7.0\times10^{20}$ y (68%CL)
$T_{1/2}(2\nu\beta^+EC, 0^+\rightarrow2_1^+) > 4.0\times10^{20}$ y (68%CL)
$T_{1/2}(2\nu EC/EC, 0^+\rightarrow2_1^+) > 4.0\times10^{19}$ y (90%CL)
$T_{1/2}(2\nu EC/EC, 0^+\rightarrow2_2^+) > 4.0\times10^{19}$ y (90%CL)
$T_{1/2}(0\nu EC/EC$ radiative$) > 2.1\times10^{21}$ y (90%CL)

Measurement of ^{58}Ni





Sample: natural Ni **(~68% of ^{58}Ni)**
Total **mass**: ~**21.7 kg**
The investigations of double beta decay (**β^+EC, EC/EC**)

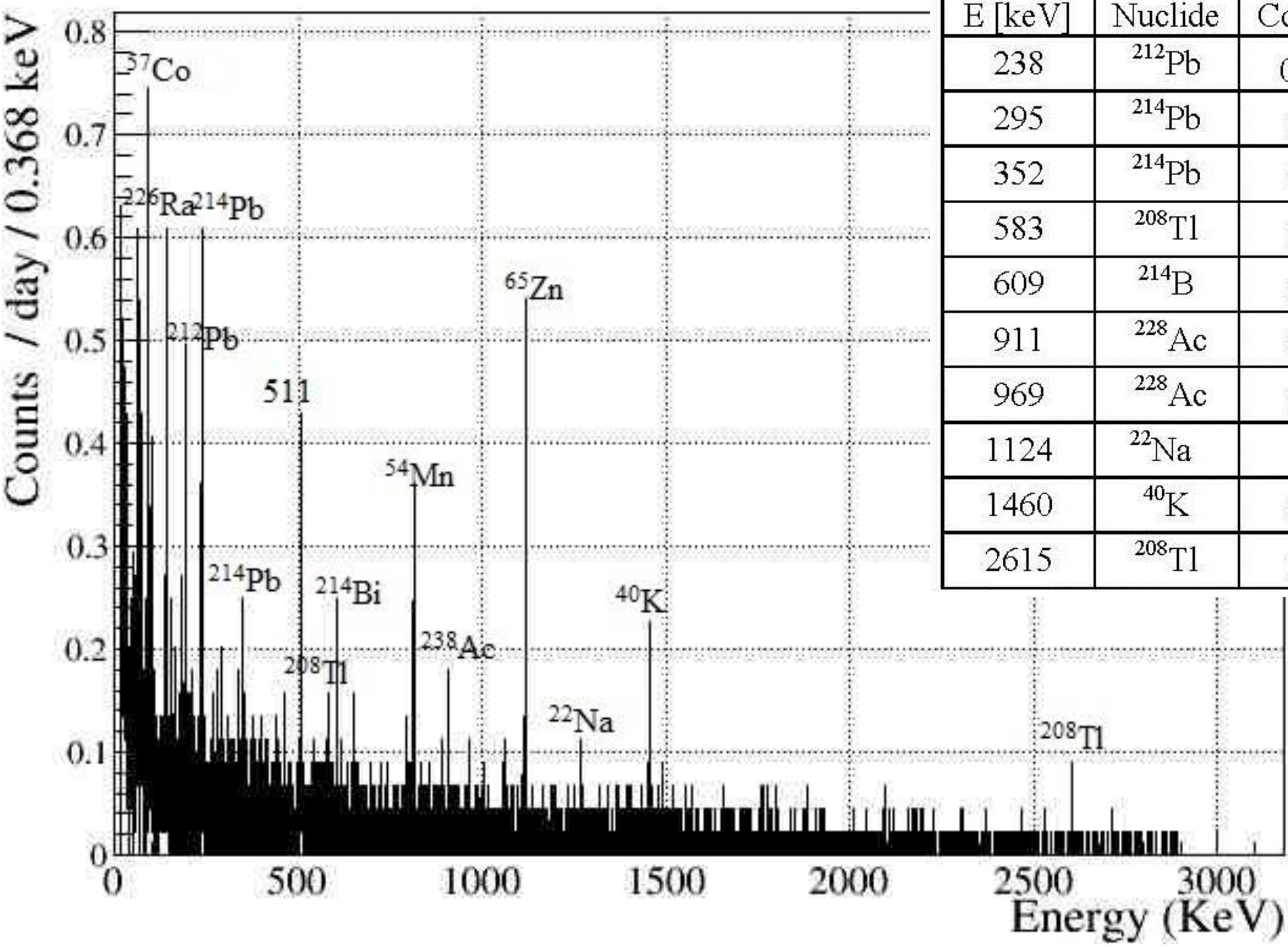
Regions of interest:

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
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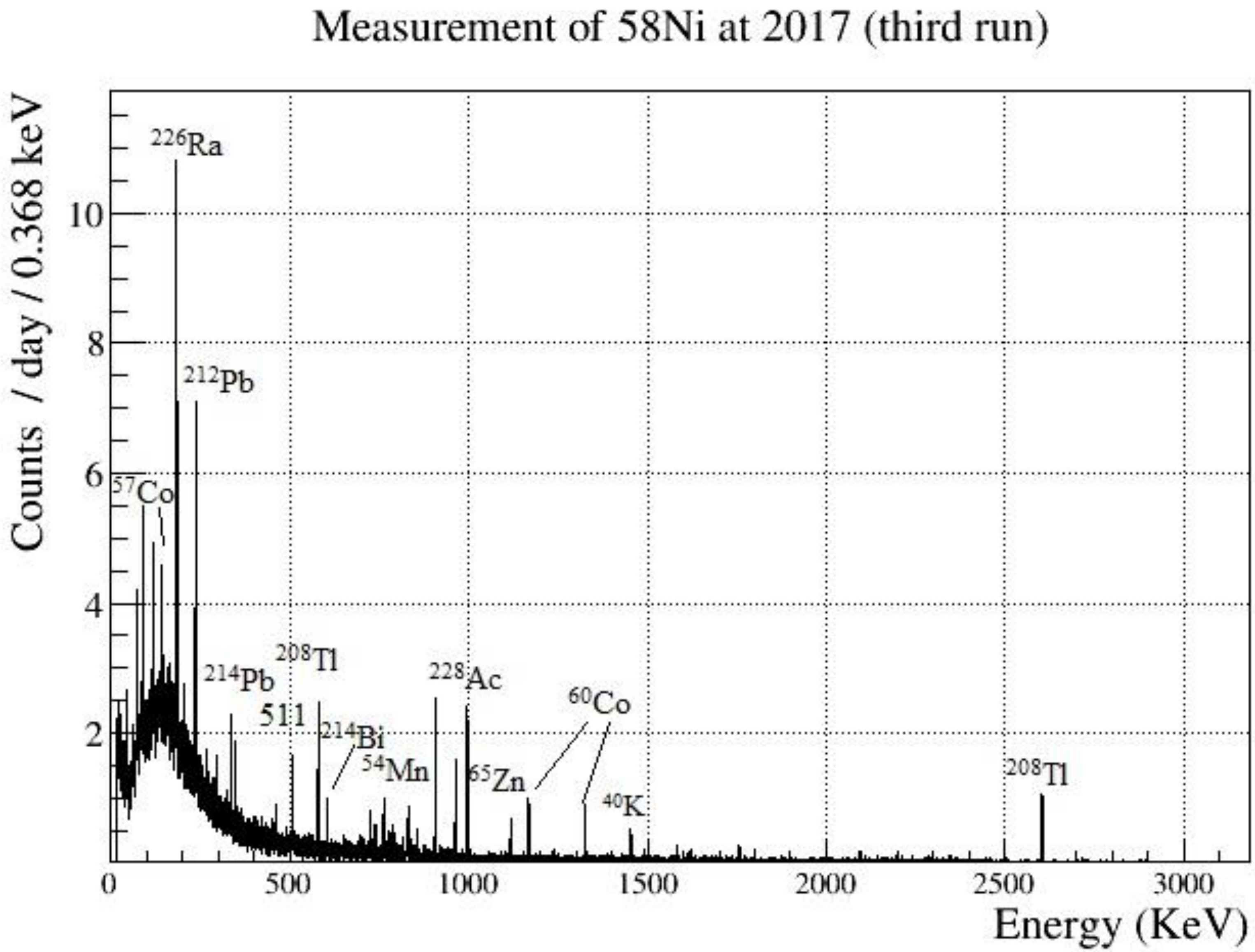
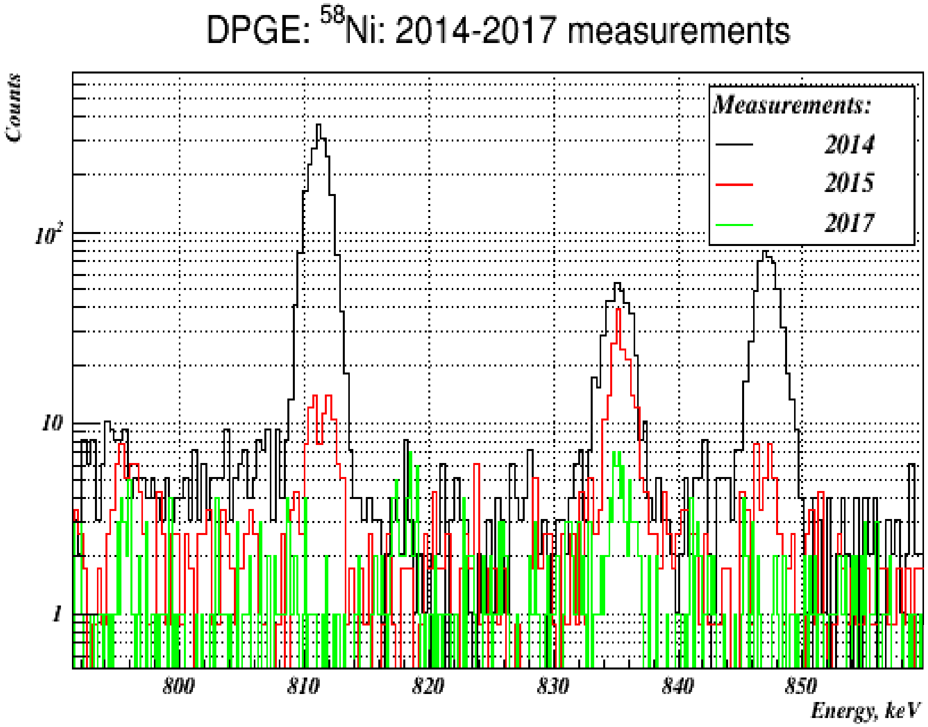
609	^{214}B	0.25±0.06
911	^{228}Ac	0.25±0.06
969	^{228}Ac	0.20±0.06
1124	^{22}Na	1.1±0.1
1460	^{40}K	0.34±0.05
2615	^{208}Tl	0.20±0.06

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

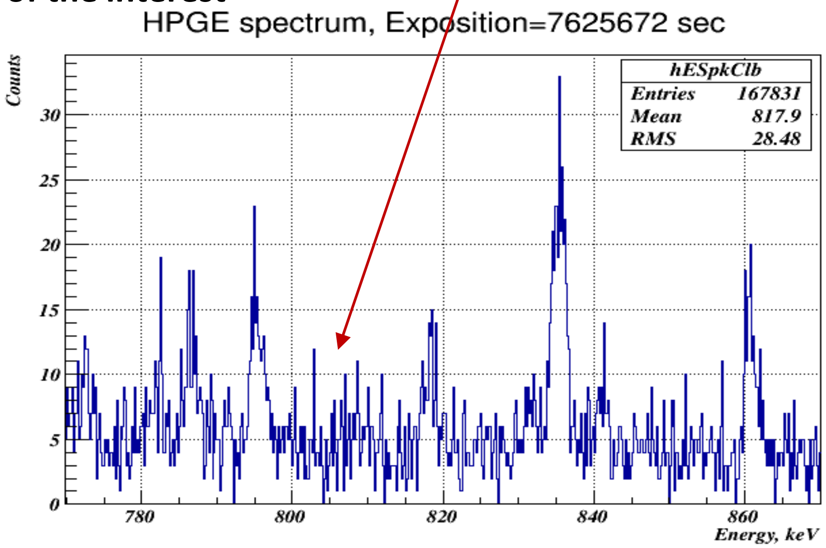
T=88.3 d= 7625672 sec



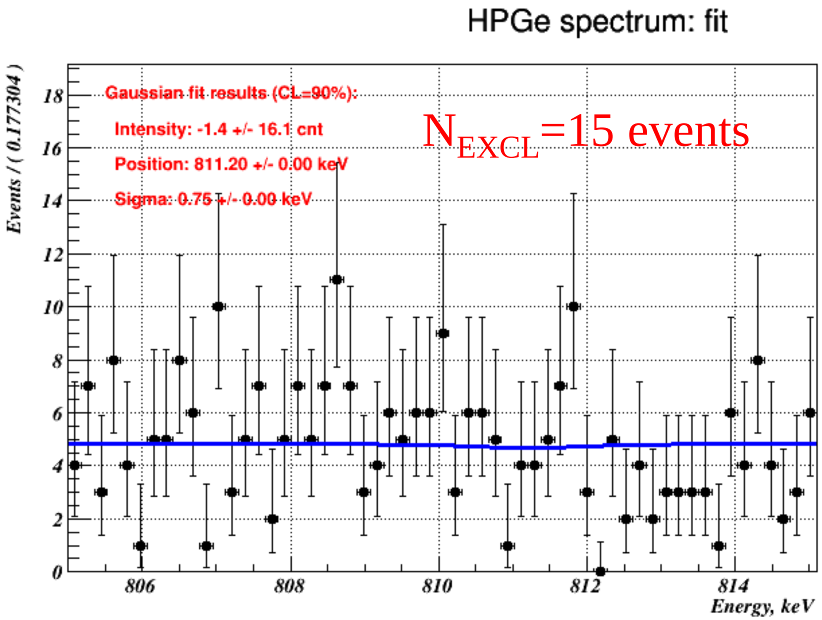
811 keV ROI



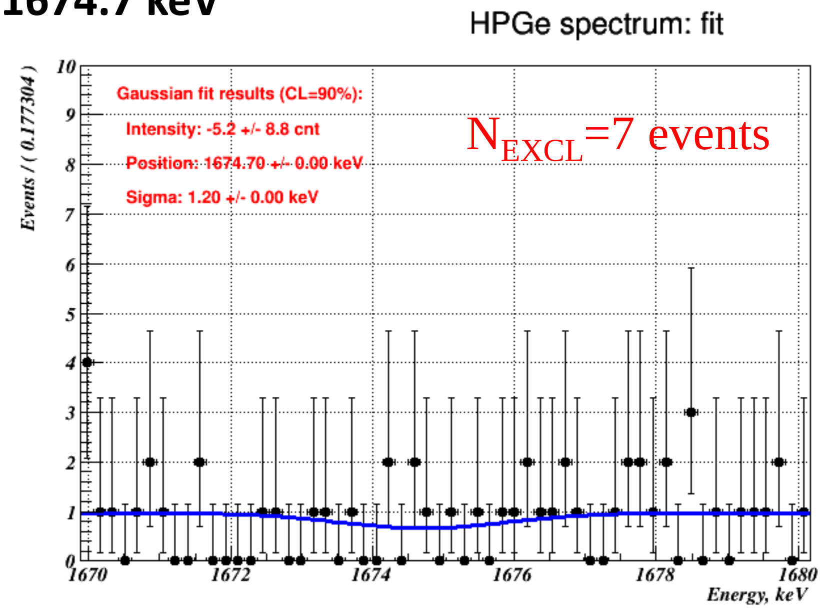
2017: No background events from ^{58}Co in the region of the interest



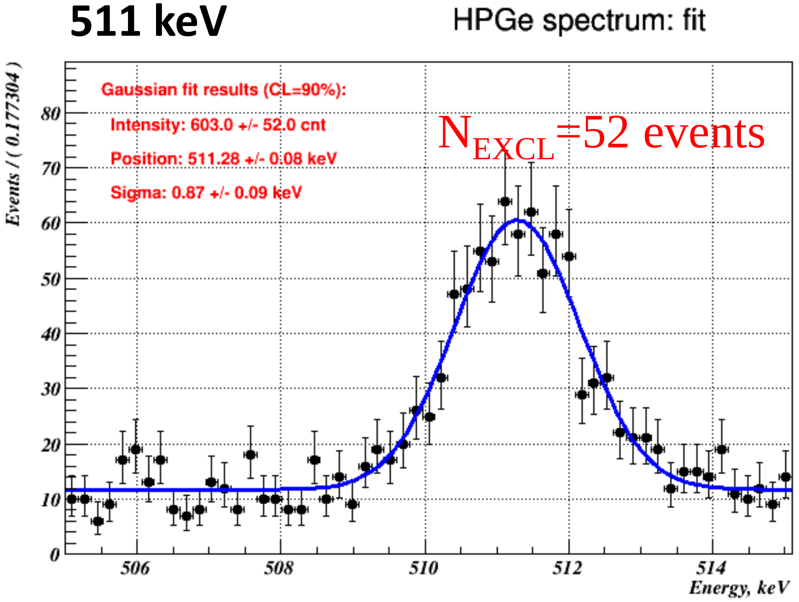
811 keV



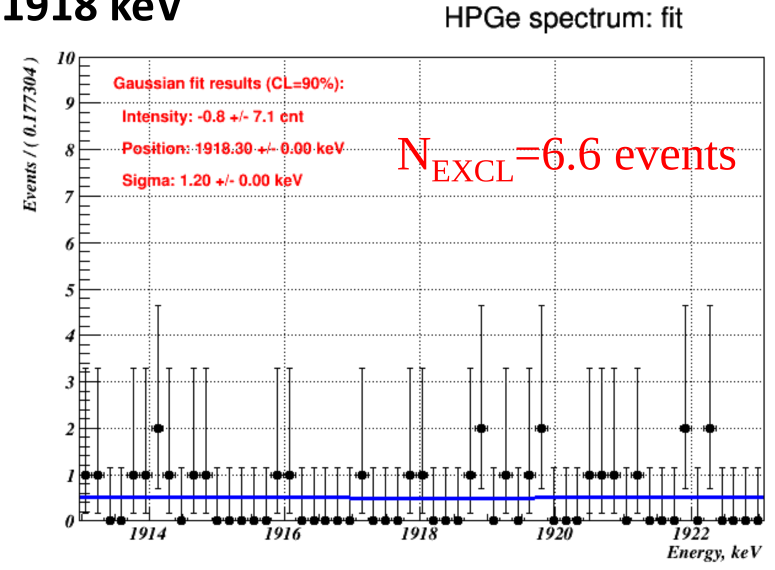
1674.7 keV



511 keV



1918 keV



Preliminary results for double beta decay of ^{58}Ni

Decay mode	Final state or Decay transition	$T_{1/2}$, (90% CL)	Previous limits, $T_{1/2}$
β^+EC	g.s.	1.4×10^{22} y	7.0×10^{20} y (68%CL)*
β^+EC	811 keV	1.7×10^{22} y	4.0×10^{20} y (68%CL)*
EC/EC	811 keV	2.4×10^{22} y	4.0×10^{19} y (90%CL)**
EC/EC	1675 keV	2.1×10^{21} y	4.0×10^{19} y (90%CL)**
0νEC/EC resonant	Radiative 1918 keV	4.7×10^{22} y	2.1×10^{21} y (90%CL)***

*S.I. Vasil'ev et al., JETP Lett. 57 (1993) 631.

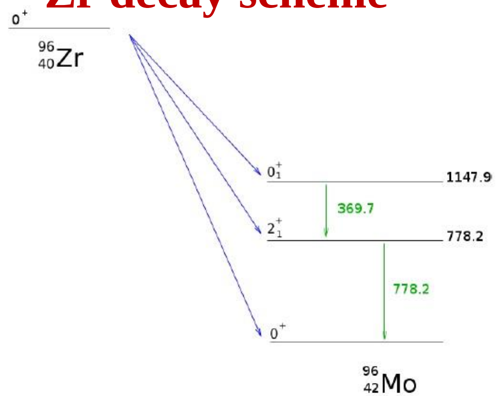
**E. Bellotti et al., Lett. Nuovo Cim. 33 (1982) 273.

***B. Lehnert et al., J. Phys. G: Nucl. Part. Phys. 43 (2016) 065201

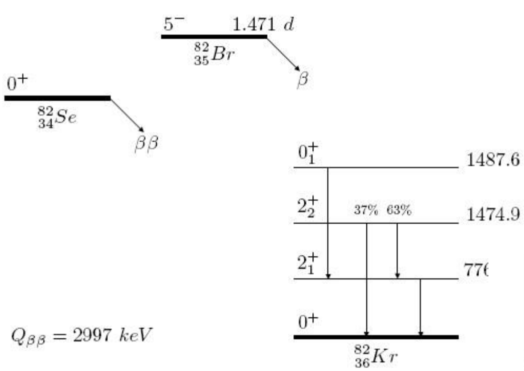
Future plans of measurements with Obelix

1. **Continue our measurement of ^{58}Ni to improve our experimental limits on various double beta decay modes of ^{58}Ni which are now the best.**
2. **Perform the investigation of double beta decay of ^{74}Se , ^{82}Se, ^{96}Zr and ^{150}Nd to excited states**
3. **Idefix – new P type coaxial HPGe detector** (IEAP/JINR/LSM) **in U-type ultra low-background cryostat produce by company Mirion (Canberra).** The design of the internal part of the Canberra cryostat for such detectors was modified in our common activity with Mirrion (France)

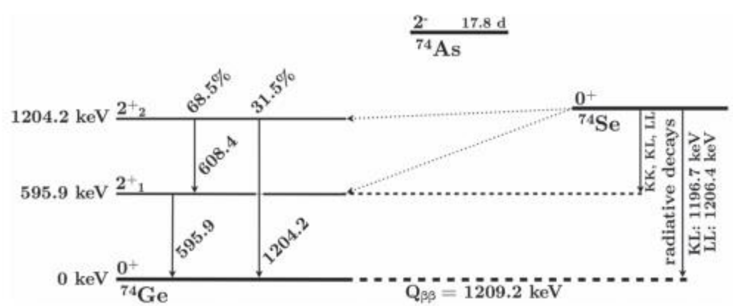
^{96}Zr decay scheme



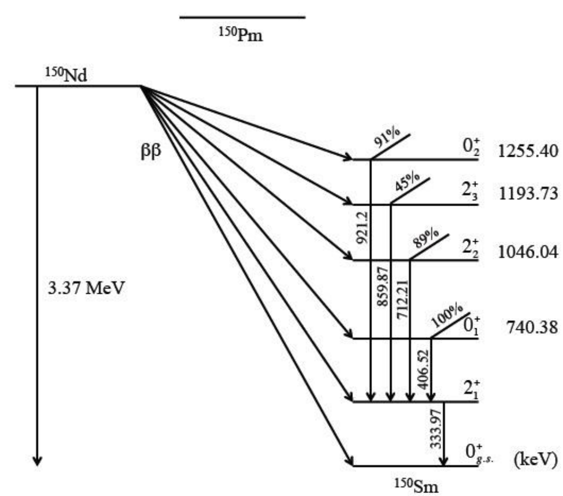
^{82}Se decay scheme



^{74}Se decay scheme

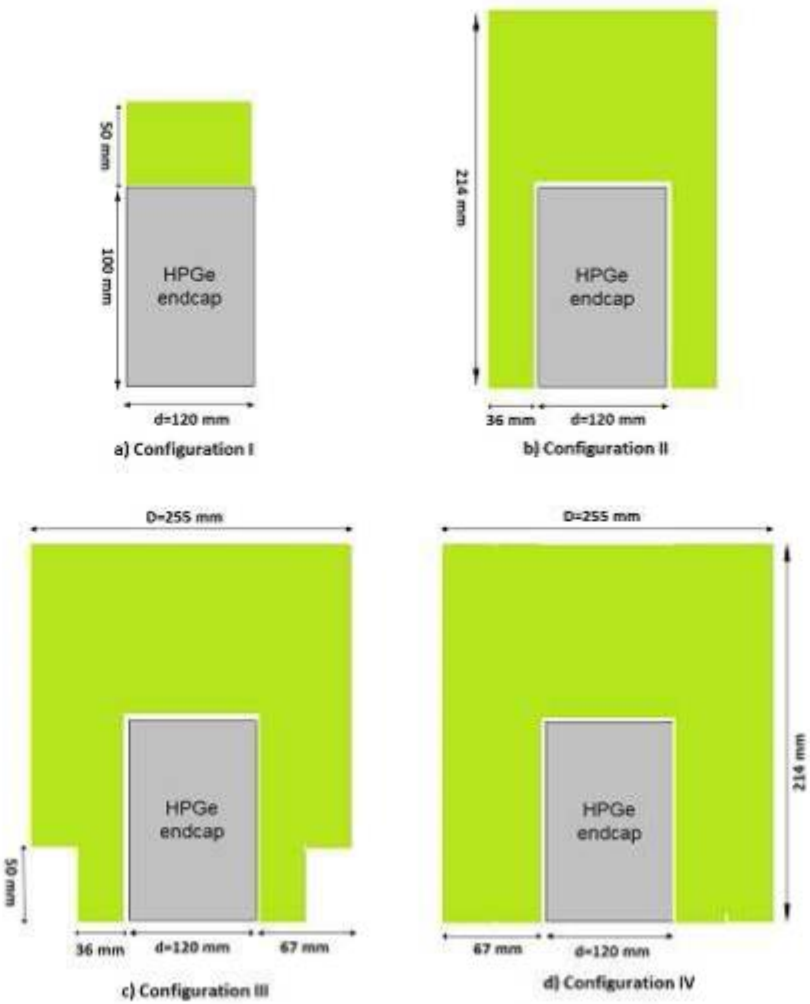


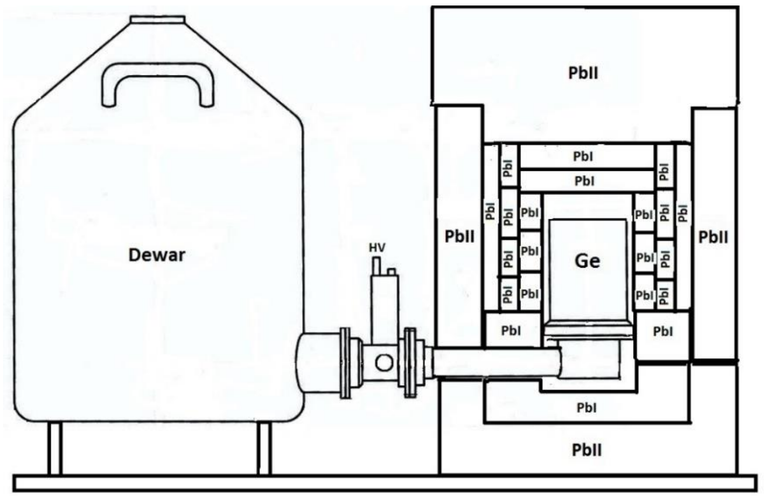
^{150}Nd decay scheme



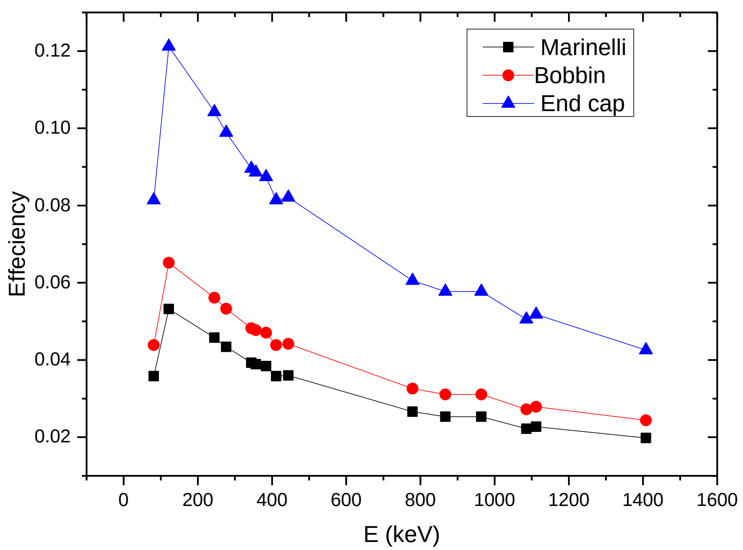
Thank you for your attention

Configurations of the Obelix passive shielding

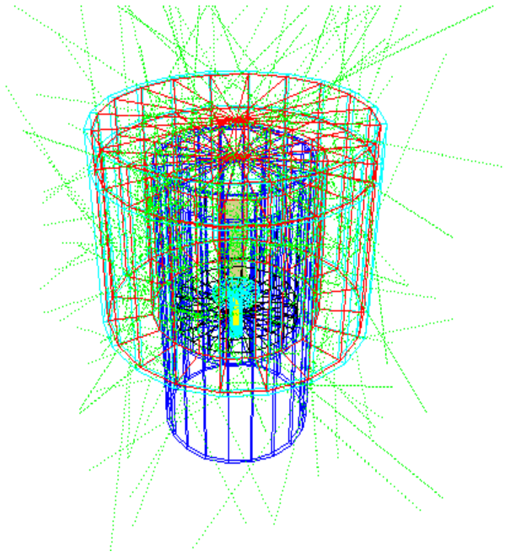




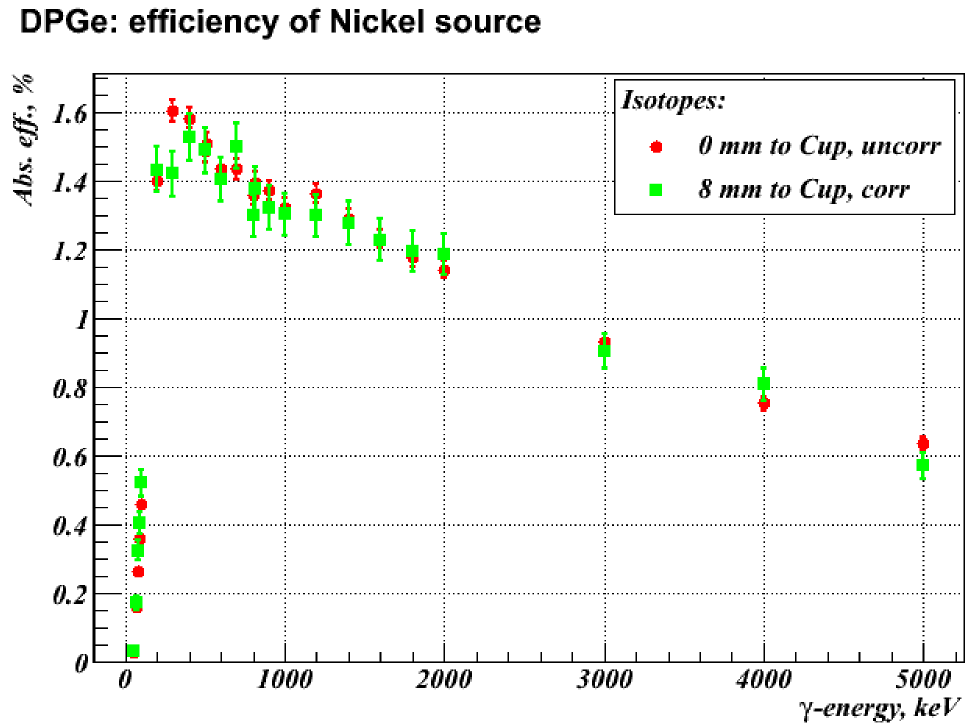
Efficiency curves for measurements of double beta emitters in several "standard" geometries



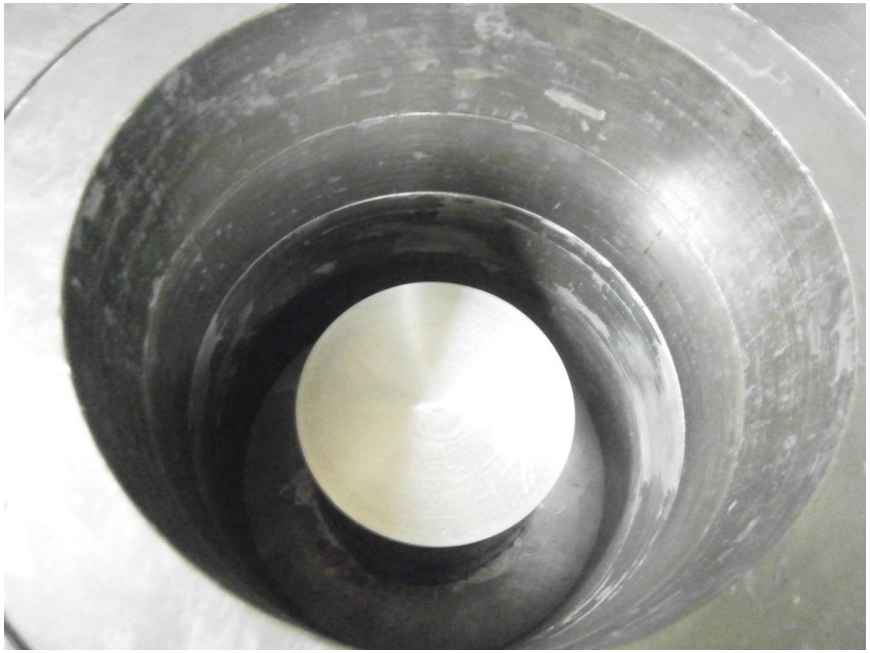
Calculated efficiency

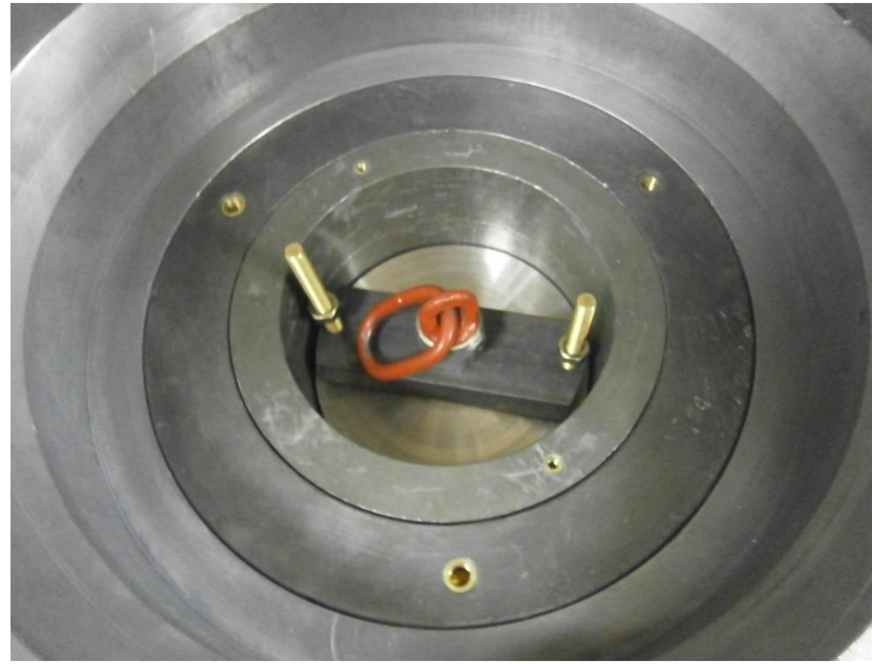


Simulation was performed using ROOT-VMC-GEANT4 DPGE package in the energy region of 0.05- 5 MeV.

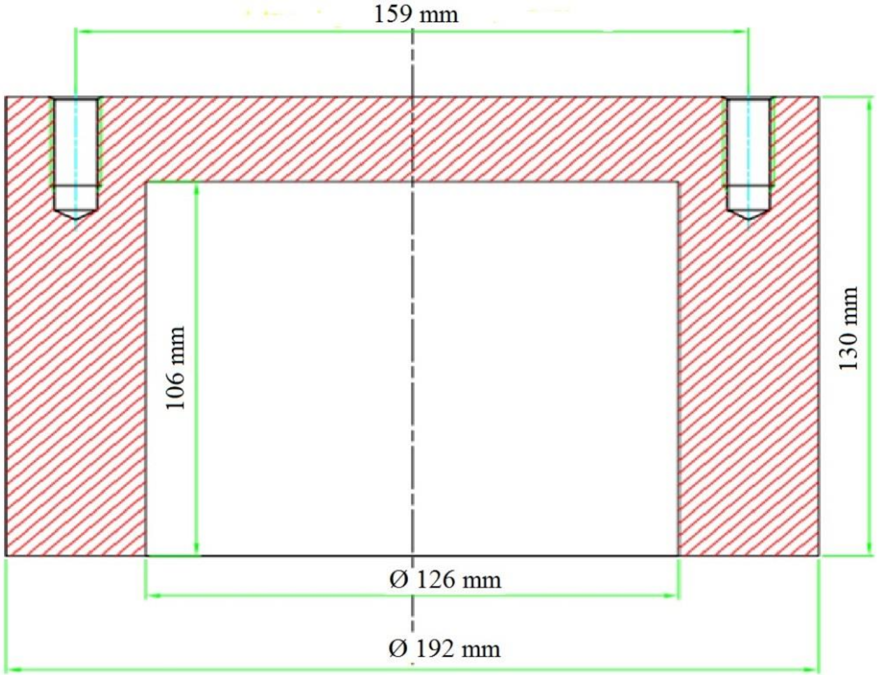


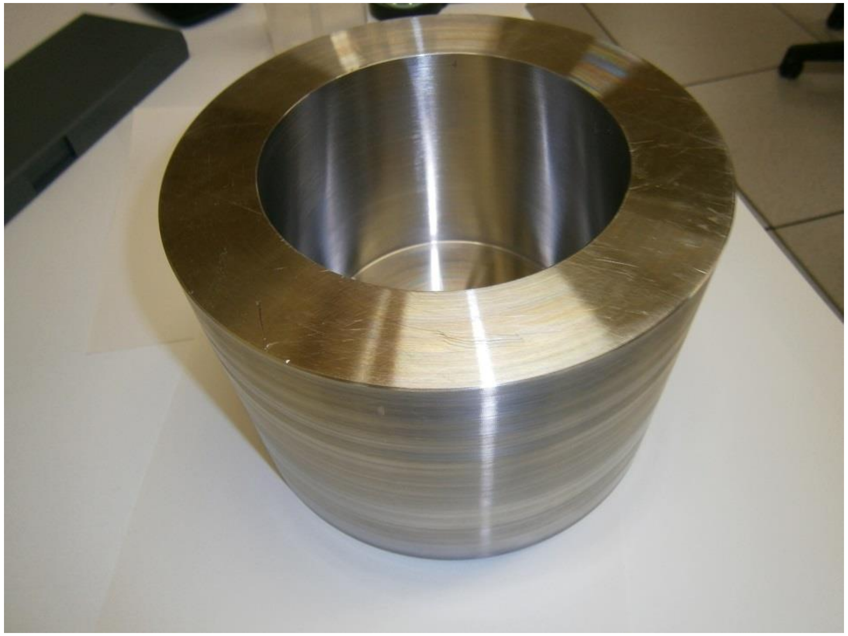
Measurement of ^{58}Ni

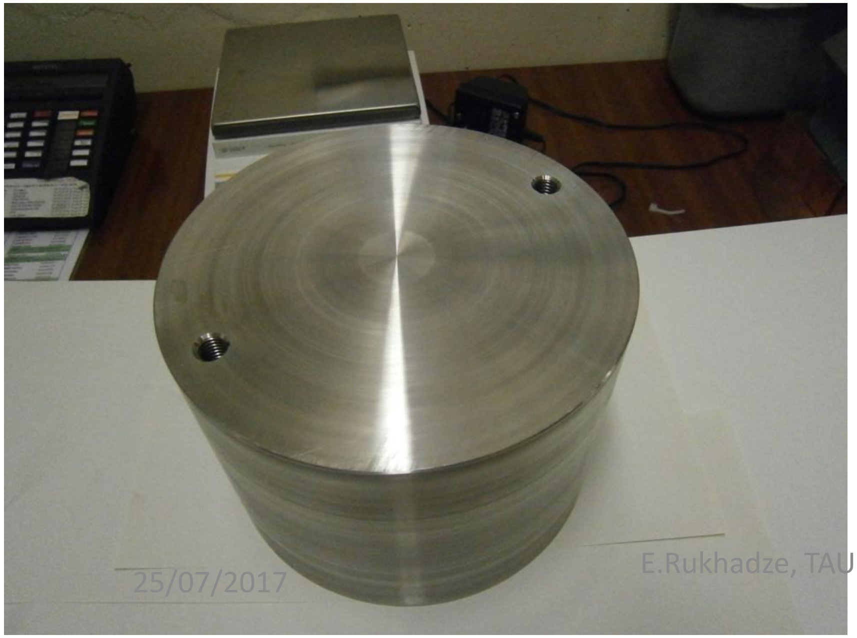




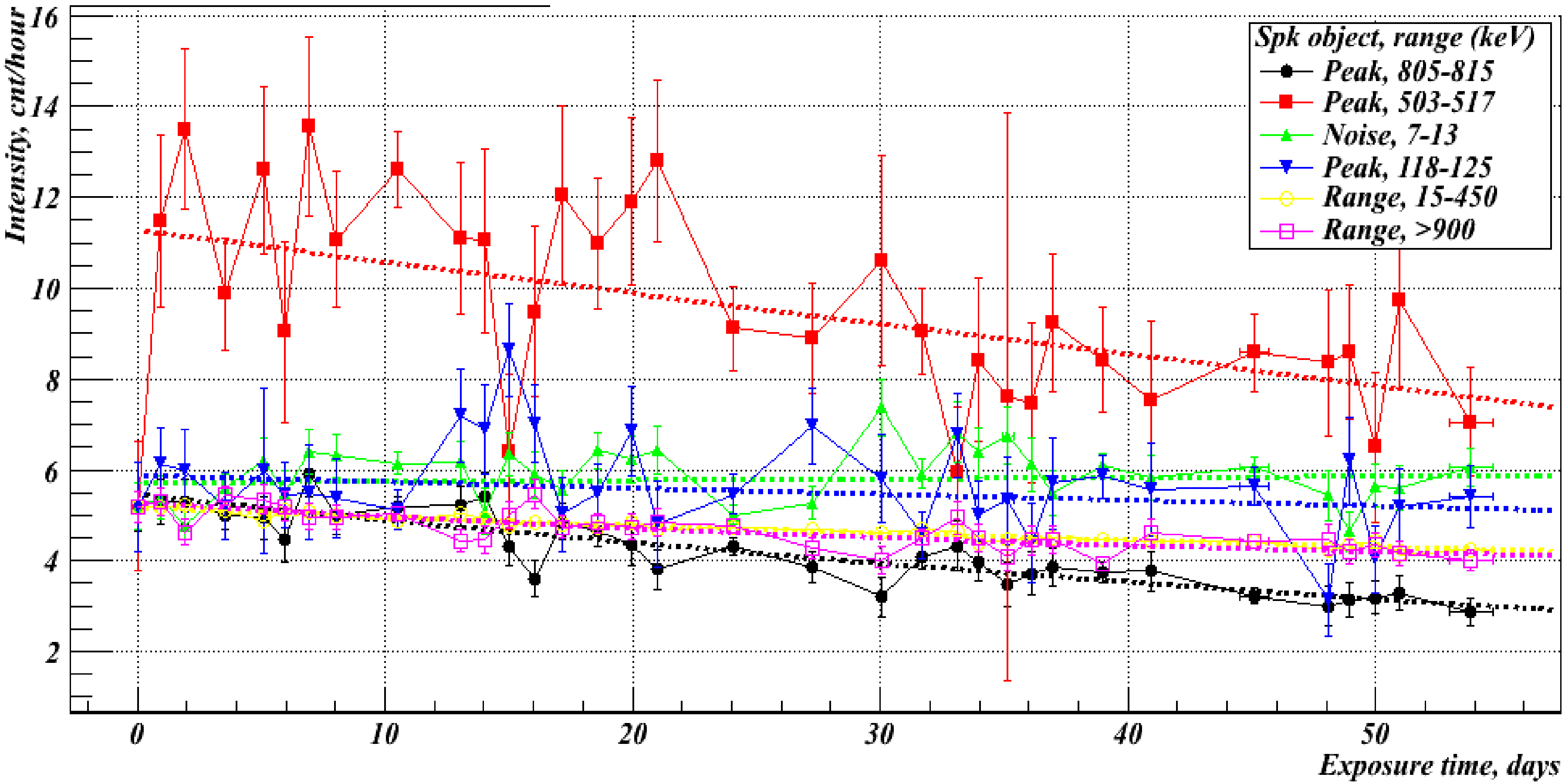
Measurement of ^{58}Ni







Time dependence of radiation intensity in 2014



Activity of ^{58}Co in nickel sample at the start of measurements in 15/10/2014 was

A(^{58}Co) = 5.4 ± 0.5 mBq/kg

Cosmogenic isotopes in 2017