Investigation of 2β decay of ^{150}Nd to the first 0^+ excited level of ^{150}Sm

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2β processes

$2\nu2\beta^-$: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\tilde{\nu}_e$

$0\nu2\beta^-$: $(A,Z) \rightarrow (A,Z+2) + 2e^-$

2ε: $2e^- + (A,Z) \rightarrow (A,Z-2) + (2\nu) + (\gamma)$

$2\nu2\beta$ – allowed in standard model (SM) ($2\beta^-$ was observed for **11 isotopes** and 2ε for **3 isotopes**)
$T_{1/2} \simeq 10^{18} - 10^{24}$ y

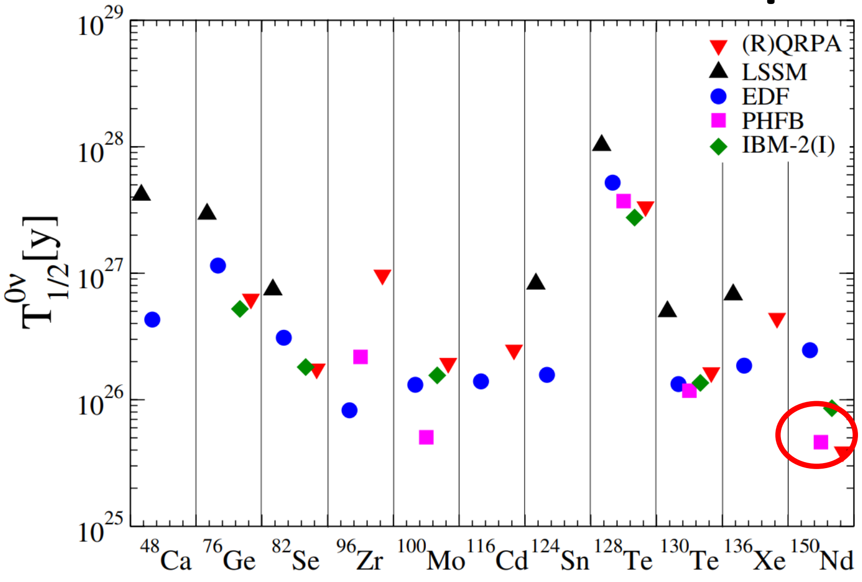
$0\nu2\beta$ – forbidden in SM (due to the lepton number violation $\Delta L=2$; predicted by many SM extensions).

The best current limits: $10^{24} - 10^{26}$ y

Investigation of $0\nu2\beta$ decay may allow us to test:

- the nature of neutrino (Dirac or Majorana?)
- the lepton number violation
- an absolute scale of neutrino mass and the neutrino mass hierarchy

^{150}Nd: one of the most promising nuclides for 2β experiments



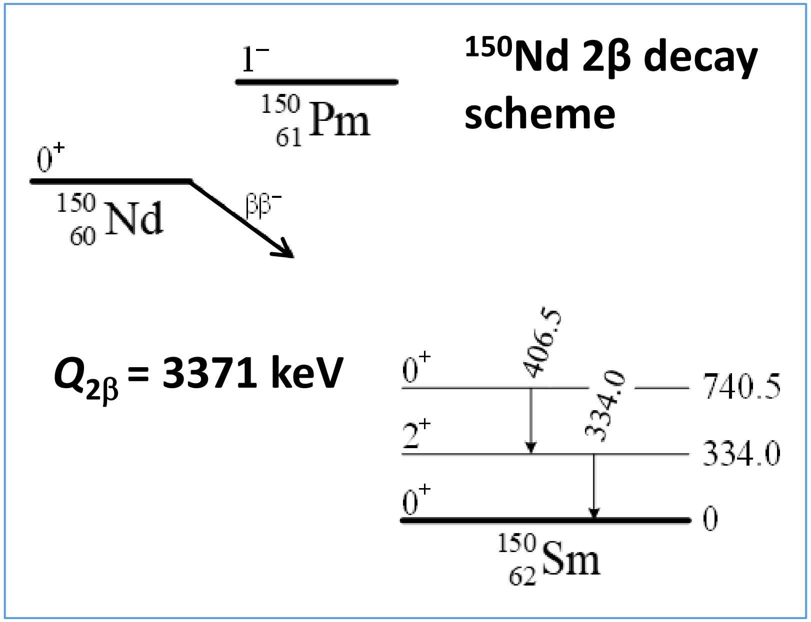
- Energy release

  $Q_{\beta\beta}$ = 3371.38(20) keV [1]

- Optimistic theoretical estimations of $T_{1/2}$

- Comparatively high natural isotopic abundance

  $\boldsymbol{\delta}$ = 5.638(28)% [2]



- Possibility to investigate the decay to excited levels of ^{150}Sm

[1] V.S. Kolhinen et al., Phys. Rev. C 82 (2010) 022501
[2] J. Meija et al., Pure Appl. Chem. 88 (2016) 293

Experimental results for $^{150}Nd \to {}^{150}Sm$ (0^+, 740.5 keV)

Short description	$T_{1/2}$, 10^{19}y	Year [Ref.]
Modane underground laboratory (4800 m w.e.), HP Ge 400 cm^3, 3046 g of Nd_2O_3 (δ = 5.638%), 11321 h, 1-d spectrum	14^{+5}_{-4}	2004 [1]
Re-estimation of the result [1]	$13.3^{+4.5}_{-2.6}$	2009 [2]
Modane underground laboratory (4800 m w.e.), NEMO-3 detector, foil with 57.2 g of $^{150}Nd_2O_3$ (δ = 91.0%), 40774 h, energies of e^- and γ, tracks for e^- (preliminary result)	7.1 ± 1.6	2013 [3]
Kimballton Underground Research Facility (1450 m w.e.), 2 HP Ge (~304 cm^3 each one), 50 g $^{150}Nd_2O_3$ (δ = 93.6%), 15427 h, coincidence spectrum	$10.7^{+4.6}_{-2.6}$	2014 [4]

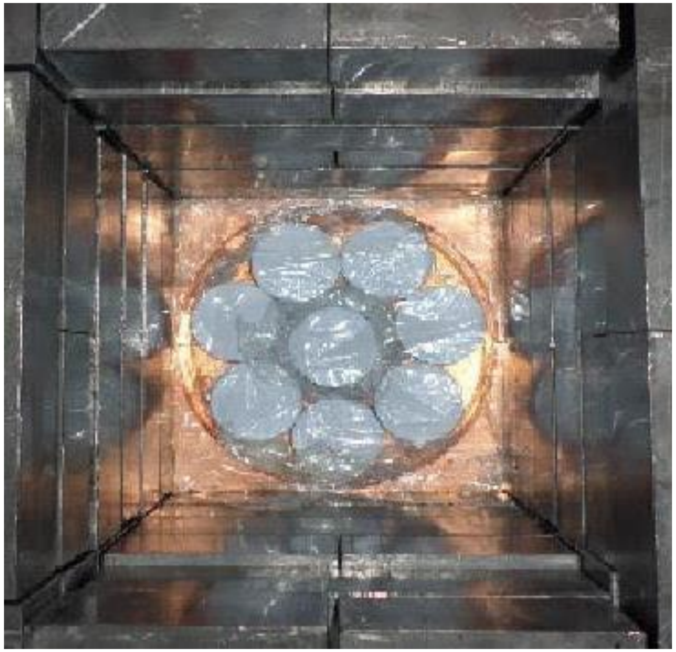
[1] A.S. Barabash et al., Phys. Atom. Nucl. 67 (2004) 1216.

[2] A.S. Barabash et al., Phys. Rev. C 79 (2009) 045501.

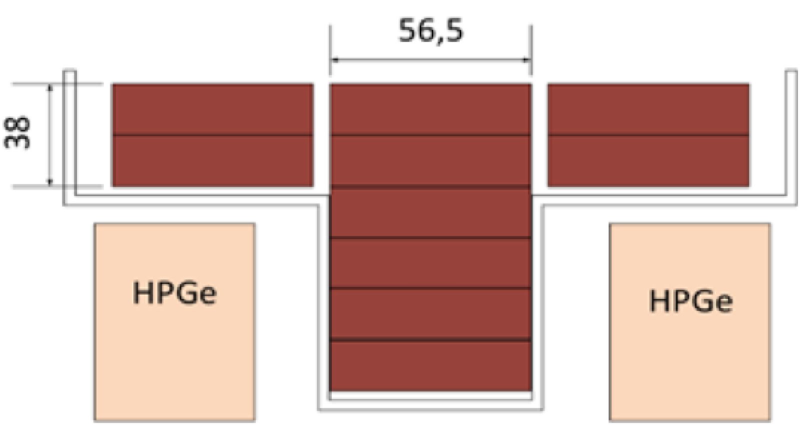
[3] S. Blondel, PhD thesis, LAL, Orsay, France, LAL 13-154 (2013).

[4] M.F. Kidd et al., Phys. Rev. C 90 (2014) 055501.

Experimental setup



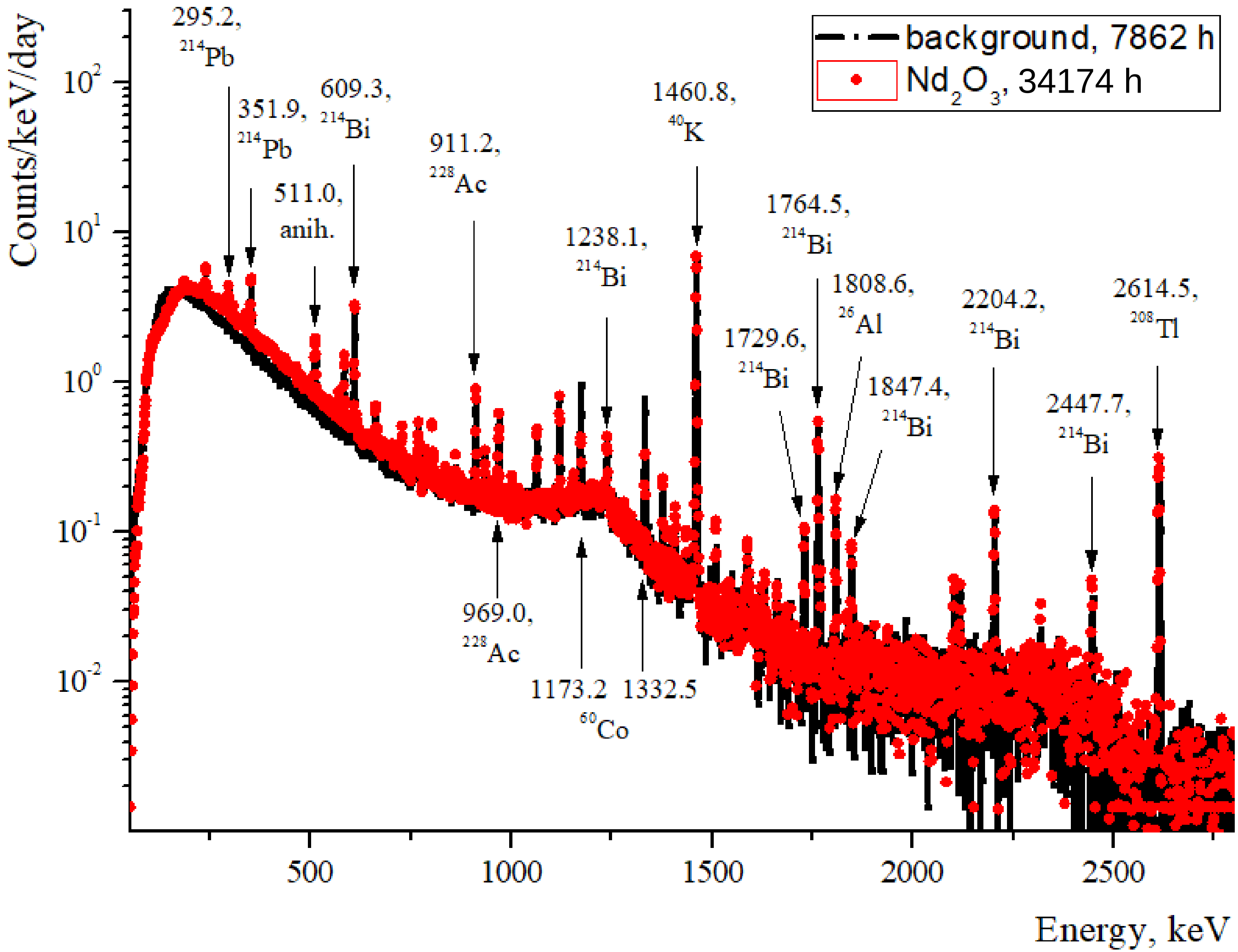
- 2381-g Nd_2O_3 sample (average density ~2.84 g/cm^3), used in previous experiment [1], additionally purified before the present measurements [2]
- 4 HP Ge detectors (≃225 cm^3 each) in a cryostat with cylindrical well in the center; Gran Sasso National Laboratory (LNGS)
- Shield: copper (10 cm), lead (20 cm)
- Plexiglas container flushed with high-purity nitrogen gas (to remove radon)



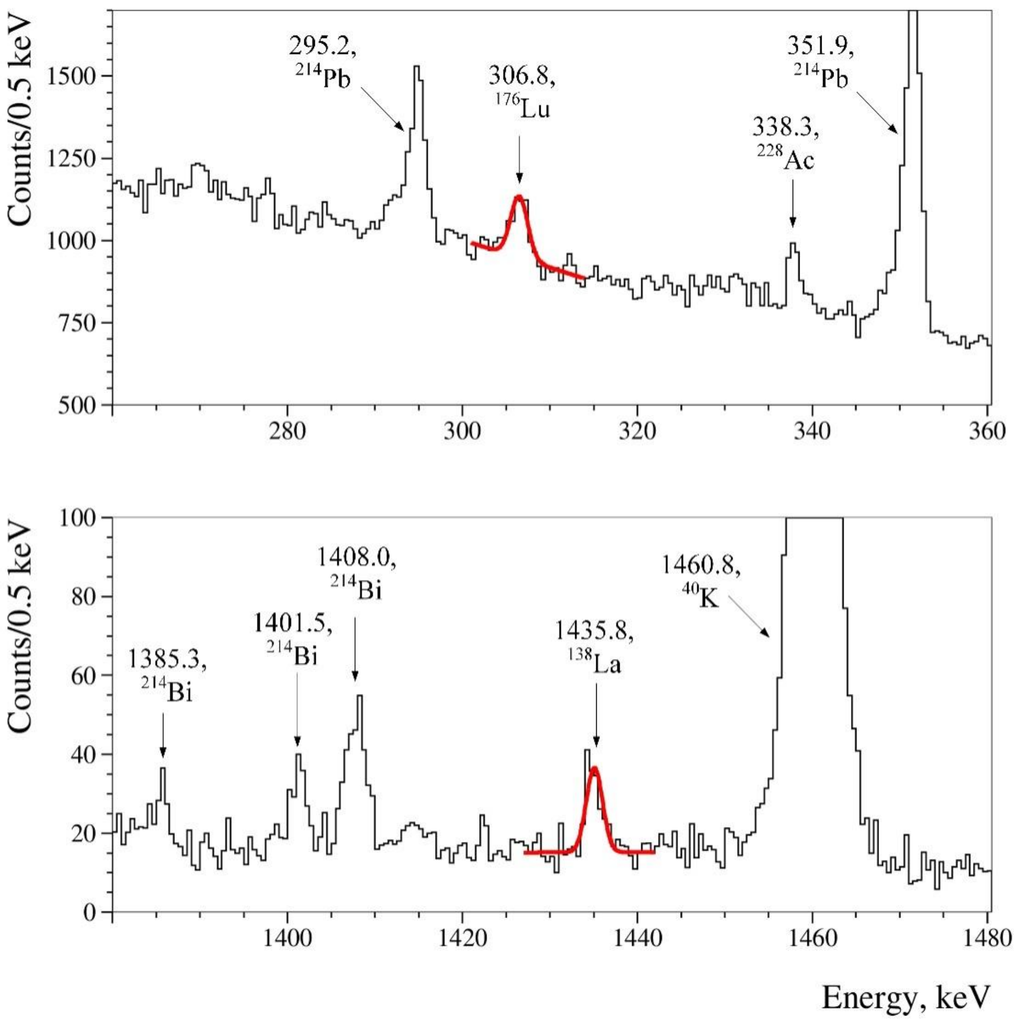
No. of detector	FWHM, keV (1333 keV, ^{60}Co calibration source)
1	2.36(2)
2	2.01(2)
3	2.06(2)
4	4.01(4)

[1] A.S. Barabash et al., Phys. Atom. Nucl. 67 (2004) 1216.
[2] R.S. Boiko, Int. J. Mod. Phys. A 32 (2017) 1743005.

Nd_2O_3 vs background spectra



Radioactive contamination of the Nd_2O_3 sample



Radiopurity of samples are important for our experiments.

In addition to usual background contaminations (^{40}K, U/Th), γ peaks of lanthanides ^{176}Lu (306.8 keV) and ^{138}La (1435.8 keV) were observed in the spectrum with Nd_2O_3 sample.

While for natural radioactive elements only limits have been set, the radioactive contamination of the sample by the lanthanides have been estimated as:

^{138}La: 0.057(9) mBq/kg

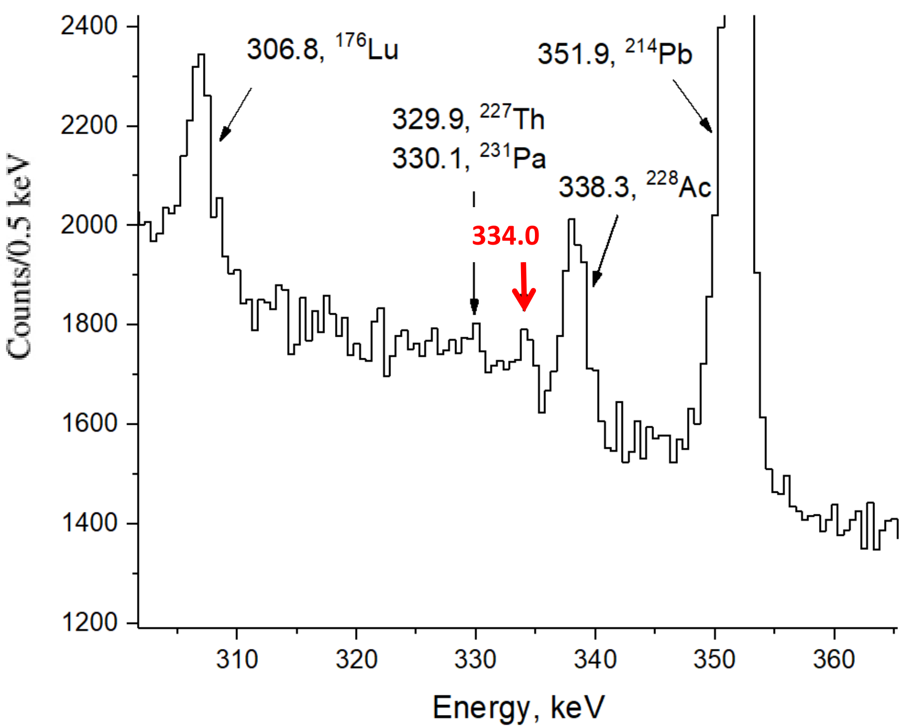
^{176}Lu: 0.29(4) mBq/kg

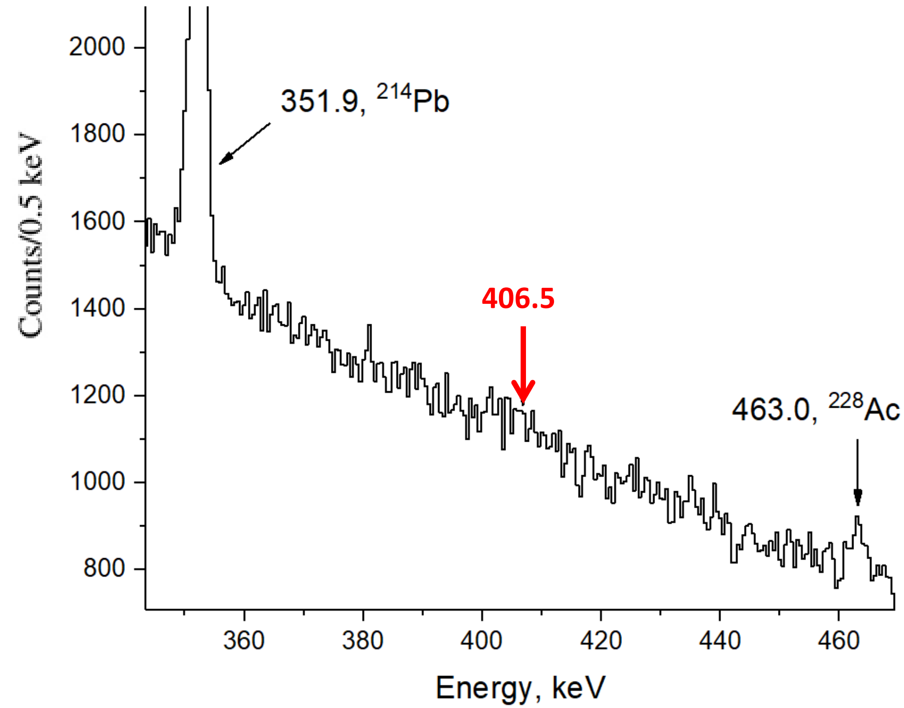
Radioactive contamination of the sample

Chain	Nuclei	Activity, mBq/kg	
		Before purification	After purification
	^{40}K	16(8)	**≤ 1.8**
	^{137}Cs	≤ 0.8	≤ 0.04
	^{138}La	–	**0.057(9)**
	^{176}Lu	1.1(4)	**0.29(4)**
^{232}Th	^{228}Ra	≤ 2.1	≤ 0.3
	^{228}Th	≤ 1.3	≤ 0.4
^{235}U	^{235}U	≤ 1.7	≤ 1.3
^{238}U	^{234}Th	≤ 28	≤ 5.4
	^{226}Ra	1.5(8)	≤ 1.9

γ peaks of ^{40}K, ^{137}Cs, U/Th daughters were observed both in the spectrum with Nd_2O_3 sample and in the background spectrum, which allows to set upper limits on the radioactive contamination of the sample

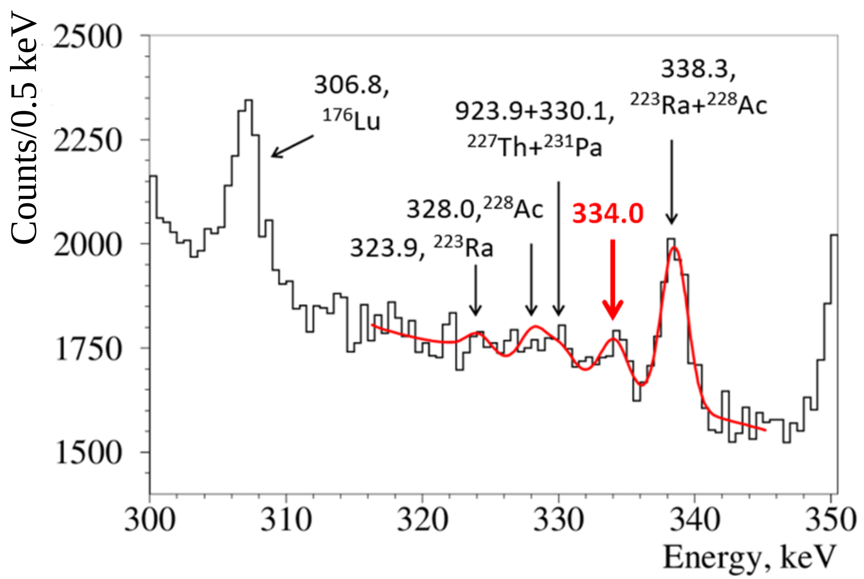
1-dimentional energy spectrum over 34174 h in the regions of interest

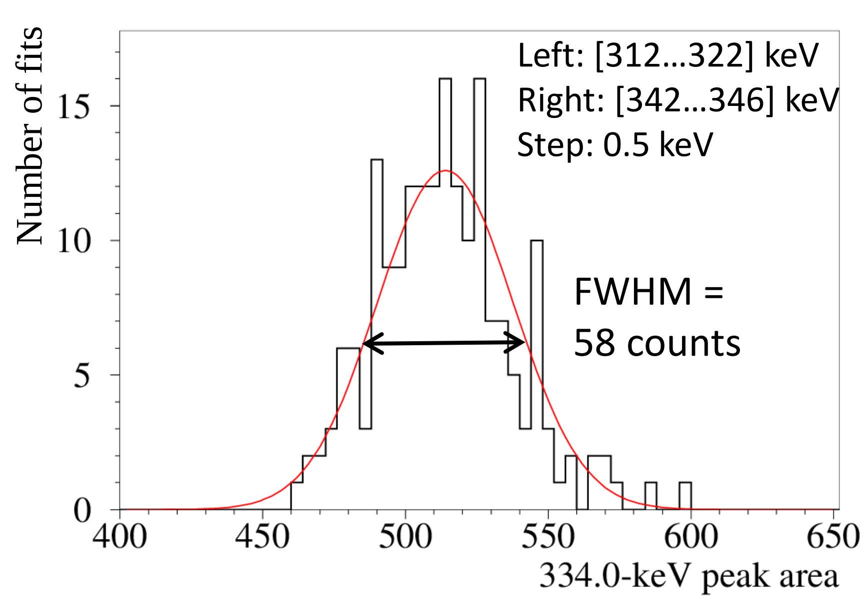




334.0 keV and 406.5 keV γ quanta in cascade, expected in the decay $^{150}Nd \rightarrow {}^{150}Sm\ (0_1^+)$

Analysis of the 1-dimensional spectrum (334.0 keV)



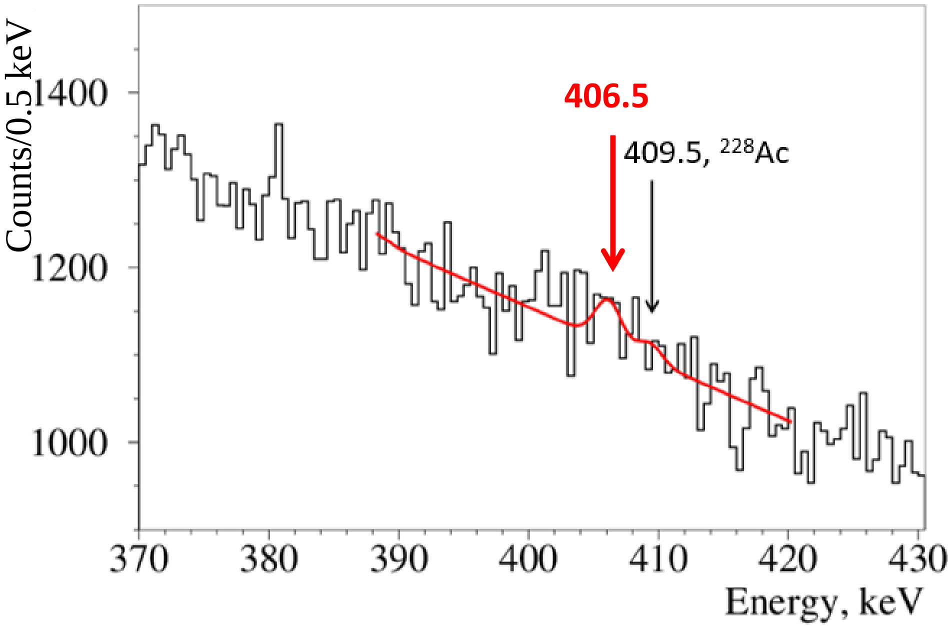


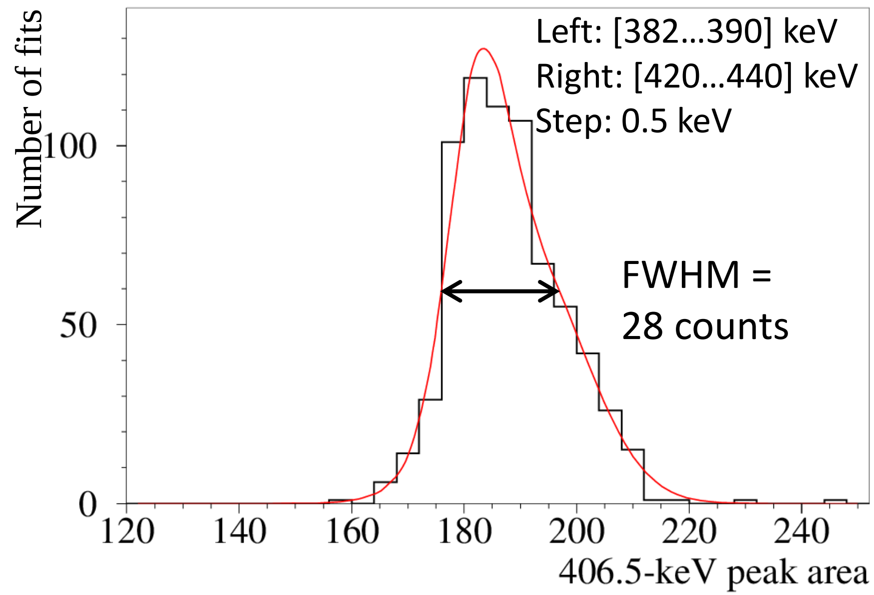
Frequency distribution of S_{334} with different fit intervals

$$\boldsymbol{S_{334}} = \mathbf{492} \pm \mathbf{110}(\text{stat})^{+60}_{-237}(\text{syst}) \text{ counts}$$

$$\boldsymbol{T^{334}_{1/2}} = \left[\mathbf{5.7}^{+1.6}_{-1.1}(\text{stat})^{+5.3}_{-0.7}(\text{syst})\right] \cdot \mathbf{10^{19} y}$$

Analysis of the 1-dimensional spectrum (406.5 keV)



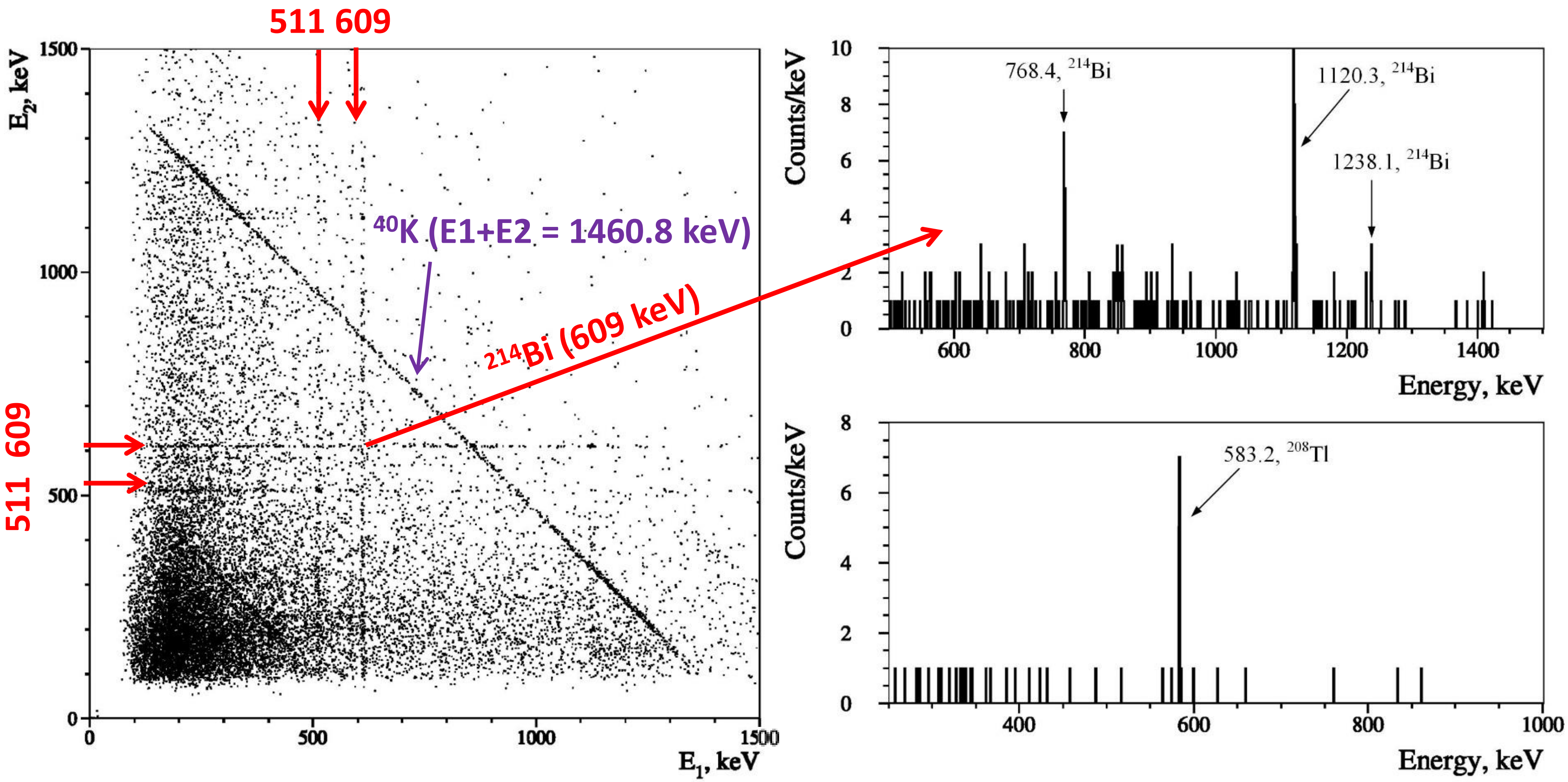


Frequency distribution of S_{406} with different fit intervals

$$\boldsymbol{S_{406}} = \mathbf{203} \pm \mathbf{93}(\text{stat}) \pm \mathbf{25}(\text{syst})\text{ counts}$$

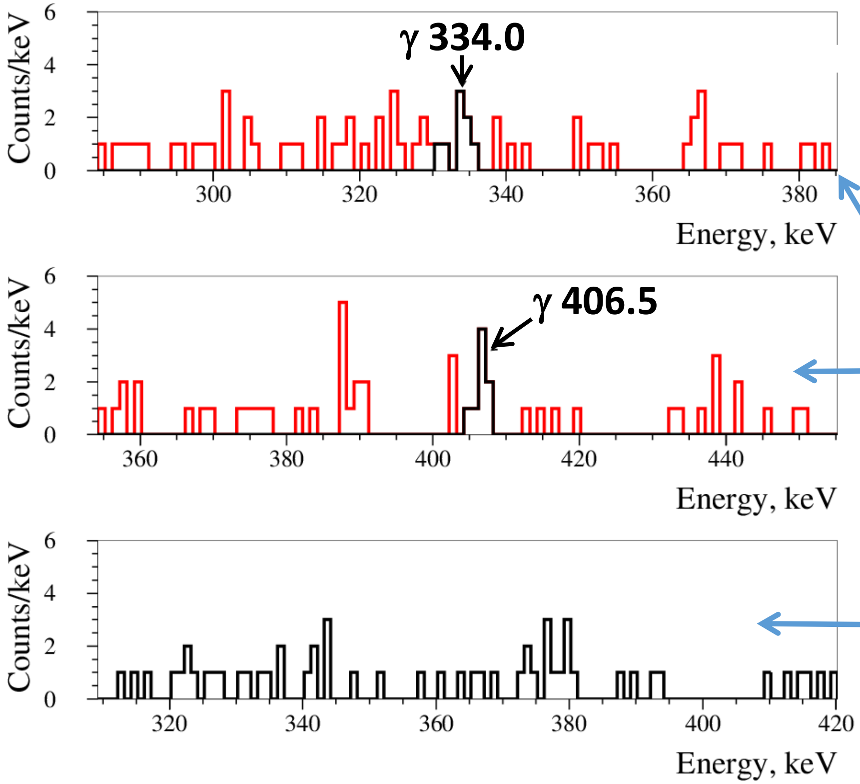
$$\boldsymbol{T_{1/2}^{406}} = \left[\mathbf{15.1}^{+\mathbf{12.8}}_{-\mathbf{4.8}}(\text{stat})^{+\mathbf{2.2}}_{-\mathbf{1.7}}(\text{syst})\right] \cdot \mathbf{10^{19}y}$$

Coincidence spectrum over 34174 h



- The two-dimensional energy spectrum of coincidences allows us to observe γ quanta emitted in the cascade (*left diagram*);
- The spectrum when the energy in one detector is fixed as (609 ± 5) keV (^{214}Bi, *top right*).
- The energy of one detector is fixed as (2615 ± 5) keV (^{208}Tl, *bottom right*).

Analysis of coincidence spectra



The energy in one detector is fixed to the energy interval where γ quanta from the $^{150}Nd \rightarrow ^{150}Sm$ (0^+, 740.5 keV) decay are expected:
406.5 keV ± 1.4×FWHM
334.0 keV ± 1.4×FWHM

A random coincidence background when energy of events in one of the detectors was taken as
375 keV ± 1.4×FWHM

$$S_{CC} = 6.0^{+3.3}_{-2.7}(\text{stat}) \pm 0.9(\text{syst}) \text{ counts}$$

$$T^{CC}_{1/2} = \left[8.7^{+7.2}_{-3.1}(\text{stat})^{+1.6}_{-1.1}(\text{syst})\right] \cdot 10^{19}\text{y}$$

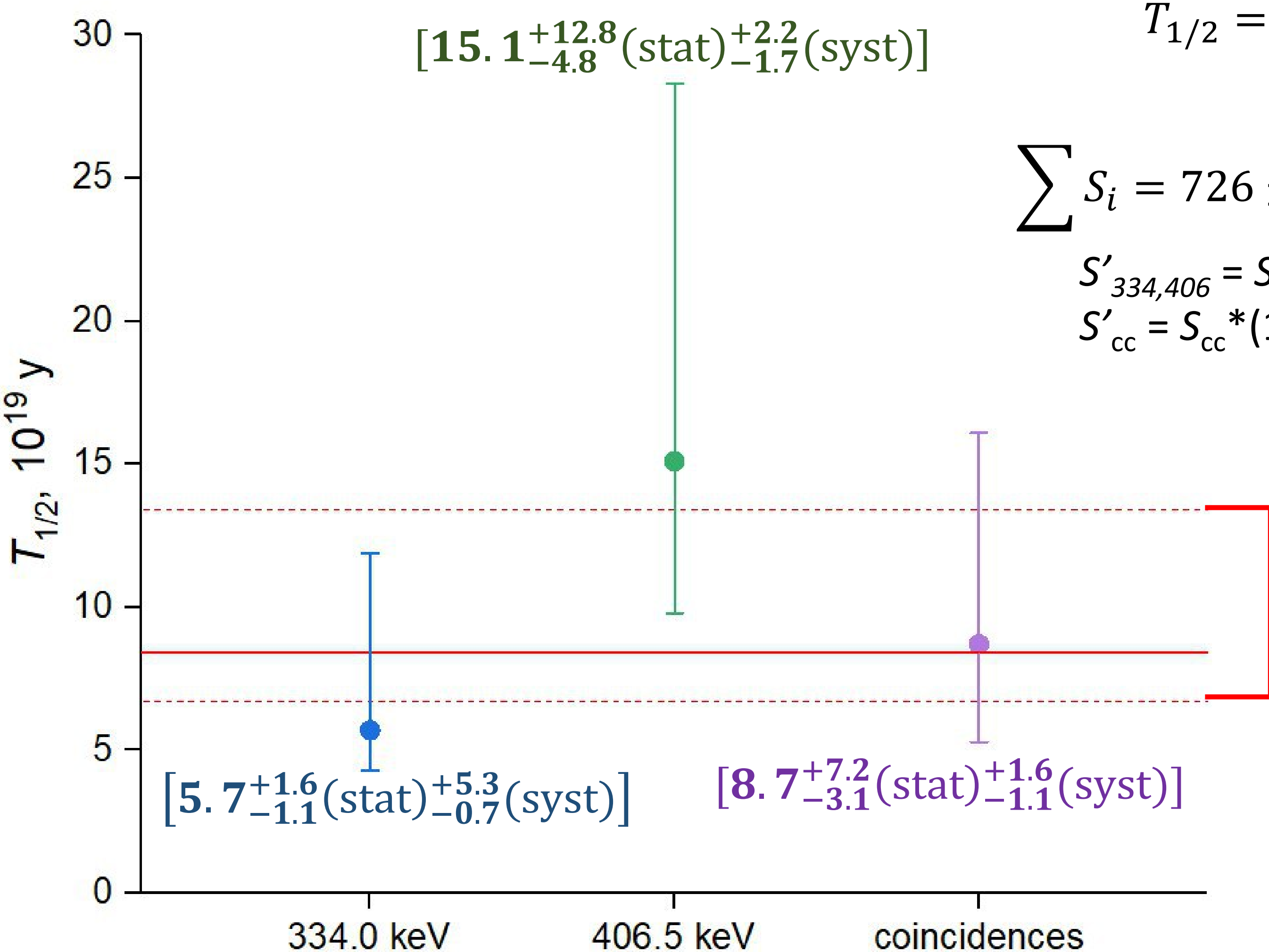
The half-life of ^{150}Nd relative to the 2ν2β decay to the first excited 0^+ level of ^{150}Sm

$$T_{1/2} = \frac{\ln 2 \cdot N \cdot t \cdot \sum \varepsilon_i}{\sum S_i}$$

$$\sum S_i = 726 \pm 150(\text{stat})^{+69}_{-249}(\text{syst})$$

$S'_{334,406} = S_{334,406} * (1+\alpha_{334,406})$

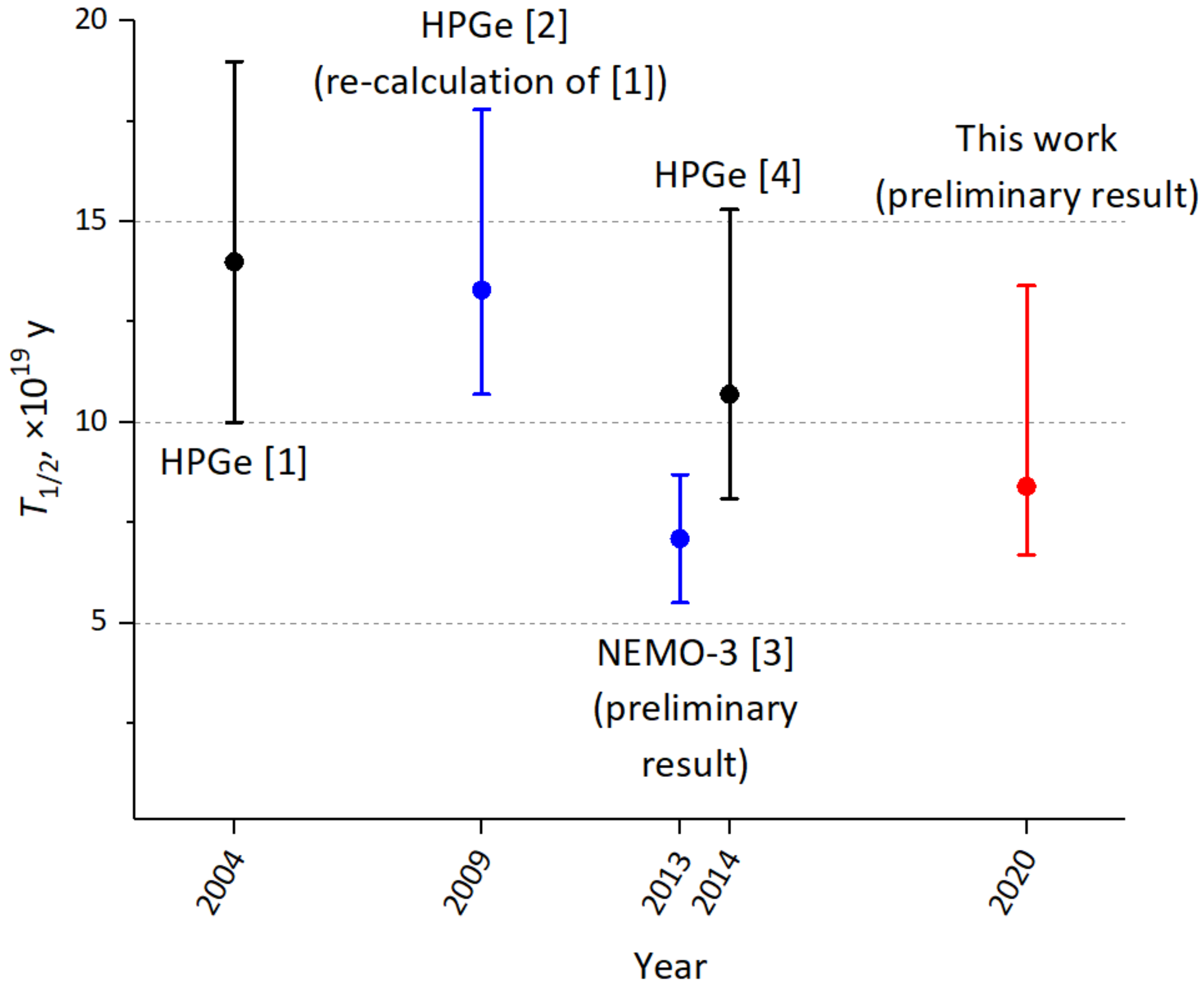
$S'_{cc} = S_{cc} * (1+\alpha_{334}) * (1+\alpha_{406})$



Combined $T_{1/2}$
(334.0, 406.5 keV and CC)

$[\mathbf{8.4}^{+2.2}_{-1.4}(\text{stat})^{+4.4}_{-0.8}(\text{syst})]$

Comparison with other results



[1] A.S. Barabash et al., Phys. Atom. Nucl. 67 (2004) 1216.

[2] A.S. Barabash et al., Phys. Rev. C 79 (2009) 045501.

[3] S. Blondel, PhD thesis, LAL, Orsay, France, LAL 13-154 (2013).

[4] M.F. Kidd et al., Phys. Rev. C 90 (2014) 055501.

Matrix element of the decay

$$(T_{1/2})^{-1} = G^{2\nu}|M_{2\nu,eff}|^2;\ M_{2\nu,eff} = g_A^2 \cdot M_{2\nu}$$
$$T_{1/2} = 8.4^{+5.0}_{-1.7} \times 10^{19}\text{y}$$

Year [Ref.]	$G^{2\nu}$, 10^{-19} y^{-1}	$M_{2\nu,eff}^{exp}$
1995 [1]	58.3	$0.045^{+0.007}_{-0.011}$
1998 [2]	48.5	$0.050^{+0.007}_{-0.012}$
2012 [3]	43.3	$0.052^{+0.008}_{-0.012}$
2015 [4]	41.2	$0.054^{+0.008}_{-0.013}$

$M_{2\nu,eff}^{th.}$: 0.269 [2] – s.p. estimations of double Gamov-Teller NME
0.019 [3,5] – microscopic interacting boson model (IBM-2, HSD)

G_A = 1,27

[1] J.G. Hirsch et al., Nucl. Phys. A 589 (1995) 445.
[2] J. Suhonen, O. Civitarese, Phys. Rep. 300 (1998) 123.
[3] J. Kotila, F. Iachello, Phys. Rev. C 85 (2012) 034316.
[4] M. Mirea, T. Pahomi, S. Stoica, Rom. Rep. Phys. 67 (2015) 872.
[5] J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 91 (2015) 034304.

Conclusions

- Experimental investigation of 2β decay of ^{150}Nd to the first 0^+ excited state of ^{150}Sm is in progress with chemically purified 2381-g Nd_2O_3 sample by using low-background 4-crystal HPGe γ-spectrometer at the LNGS.
- Two γ quanta with energies 334.0 keV and 406.5 keV emitted after deexcitation of the 0^+_1 excited level of ^{150}Sm have been observed in the data after 34174 h of measurements. The half-life of ^{150}Nd relatively to the $2\beta^-$ decay to the 0_1^+ excited state of ^{150}Sm is

$$\boldsymbol{T_{1/2}} = \left[\mathbf{8.4}^{+2.2}_{-1.4}(\text{stat})^{+4.4}_{-0.8}(\text{syst})\right] \times \mathbf{10^{19}}\text{y}$$

- The data on 2ν mode probability is important both for theoretical and experimental studies of the 2β decay of ^{150}Nd
- Experiment is running to improve the half-life value accuracy. Precise estimation of the Nd concentration and of the detection efficiency are in progress.