Study of double-β decay of ^{150}Nd to the first 0^+ excited level of ^{150}Sm

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2β processes

β decay: $(A,Z) \rightarrow (A,Z+1) + e^- + \tilde{\nu}_e$

Two neutrino (2ν) double β decay: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\tilde{\nu}_e$

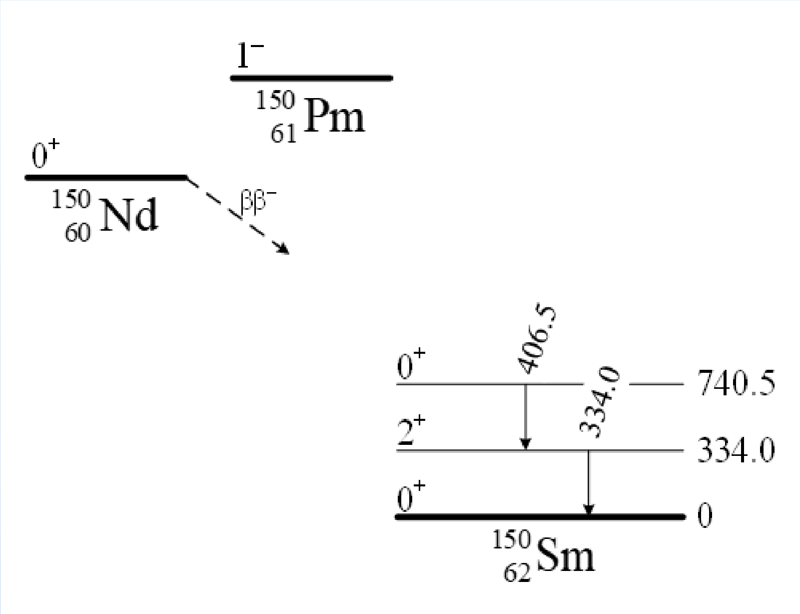
Neutrinoless (0ν) double β decay: $(A,Z) \rightarrow (A,Z+2) + 2e^-$

2ν2β – allowed in SM (observed for 11 isotopes $T_{1/2} \simeq 10^{18} - 10^{24}$ y)

0ν2β – forbidden in SM (due to lepton number violation ΔL=2; $T_{1/2} \geq 10^{24} - 10^{26}$ y; predicted by many SM extensions).

Observation of 0ν2β decay may allow us to test the nature of neutrino, the lepton number violation, an absolute scale of neutrino mass and neutrino mass hierarchy.

2β decay of ^{150}Nd



^{150}Nd 2β decay scheme

^{150}Nd is one of the most prospective isotopes for investigation of 2β decay:

- Energy release

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

- Natural isotopic abundance

  δ = 5.638(28)% [2];

- Possibility to investigate the decay to excited levels of ^{150}Sm with high energy resolution (HP Ge spectrometry).

[1] V.S. Kolhinen et al., Phys. Rev. C 82 (2010) 022501.

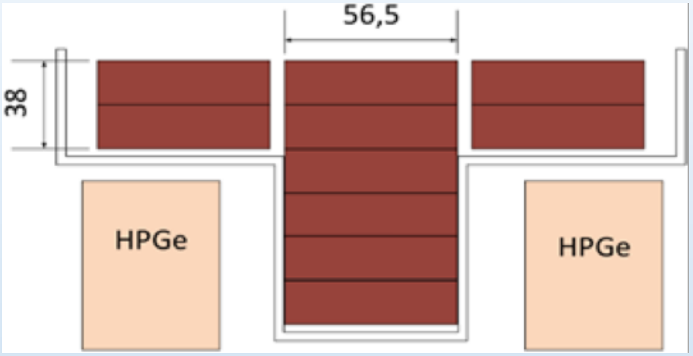
[2] J. Meija et al., Pure Appl. Chem. 88 (2016) 293.

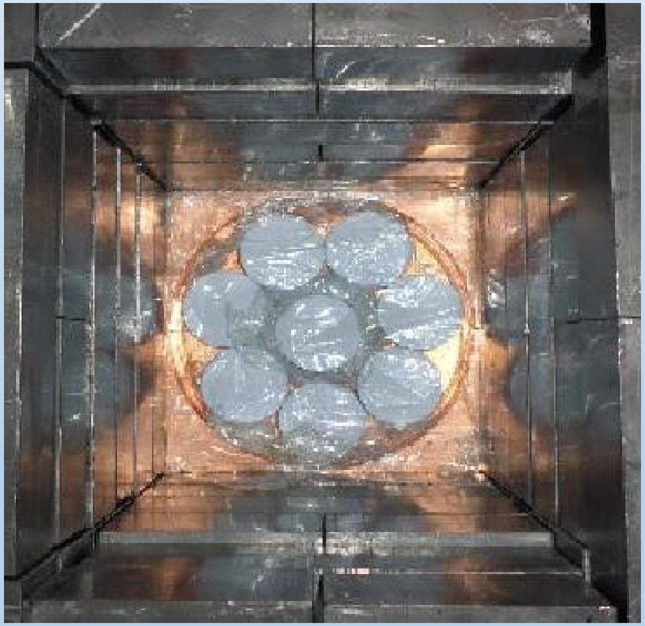
Experimental results for $^{150}Nd \rightarrow ^{150}Sm$ (0^+, 740.5 keV)

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]	$\mathbf{13.3^{+4.5}_{-2.6}}$	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, 2 HP Ge (~304 cm^3 each one), 50 g $^{150}Nd_2O_3$ (δ = 93.6%), 15427 h, coincidence spectrum	$\mathbf{10.7^{+4.6}_{-2.6}}$	2014 [4]
This experiment (previous result)	$4.7^{+4.7}_{-1.9}$	2018 [5]

[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.
[5] A.S. Barabash et al., Nucl. Phys. At. Energy 19 (2018) 95.

Experimental setup



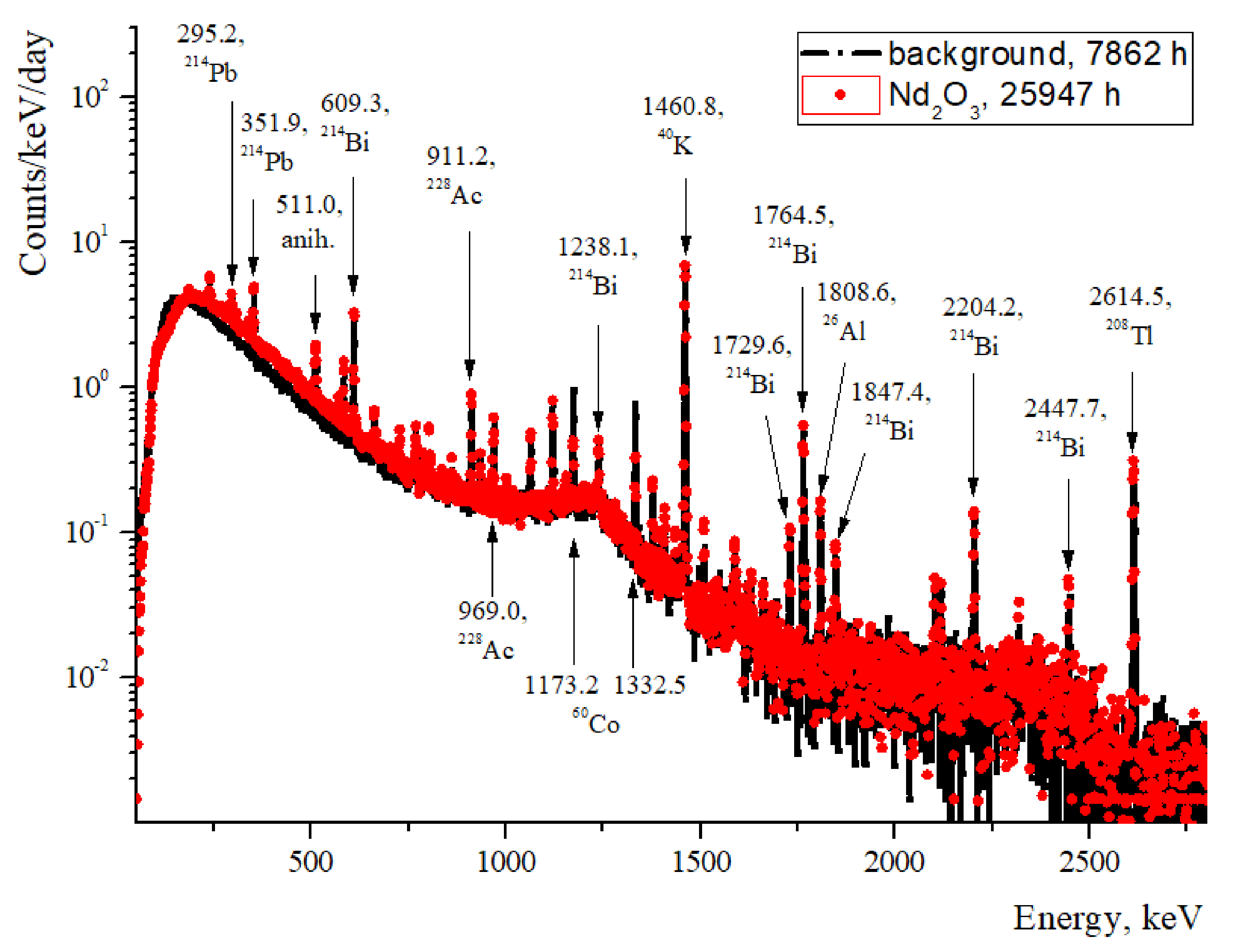


- 2381-g Nd_2O_3 sample (average density ~2.84 g/cm^3), used in previous experiment [1] and additionally purified before the measurements [2].
- 4 HP Ge detectors (≃225 cm^3 each) in a cryostat with cylindrical well in the center
- Shield: copper (10 cm), lead (20 cm)
- Plexiglas container flushed with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

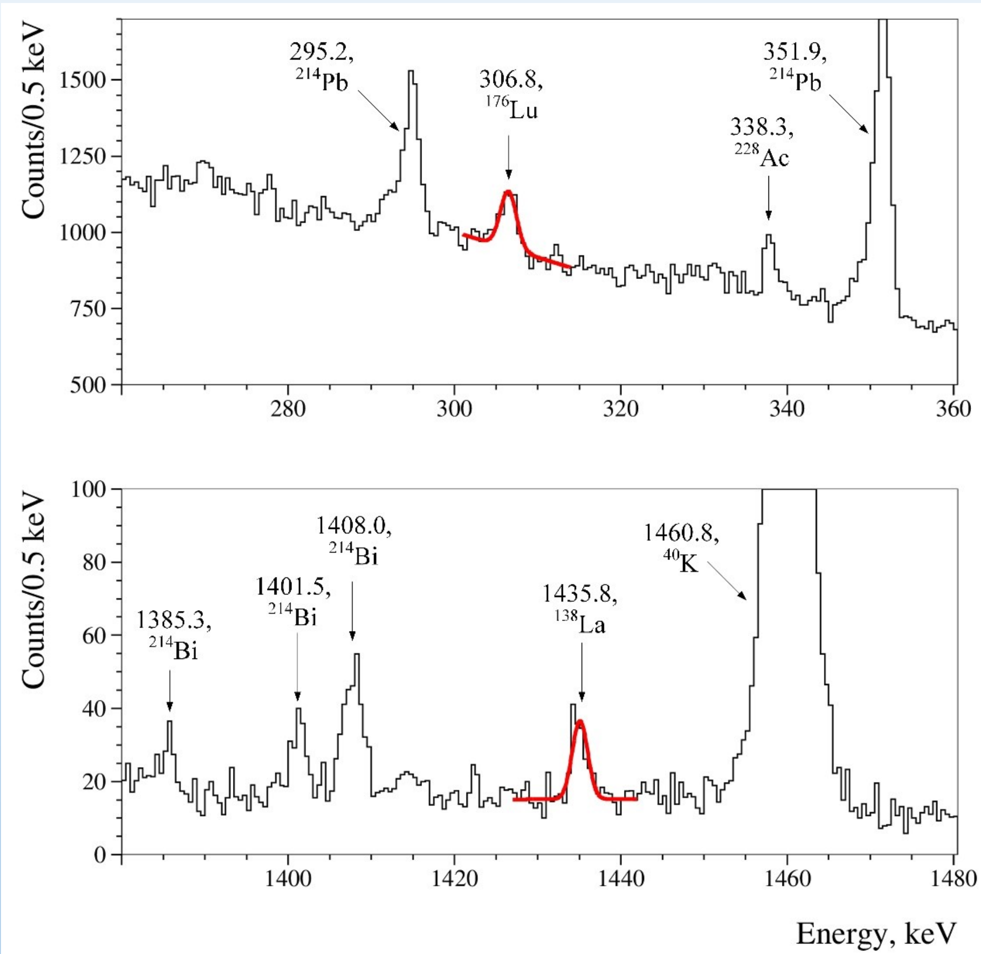
No. of detector	FWHM, keV (1333 keV, ^{60}Co calibrztion source)
1	2.36(2)
2	2.01(2)
3	2.06(2)
4	4.01(4)

[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 Nd_2O_3 sample



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 and are absent in the background spectrum of the GeMulti setup. The radioactive contamination of the sample have been estimated as:

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

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

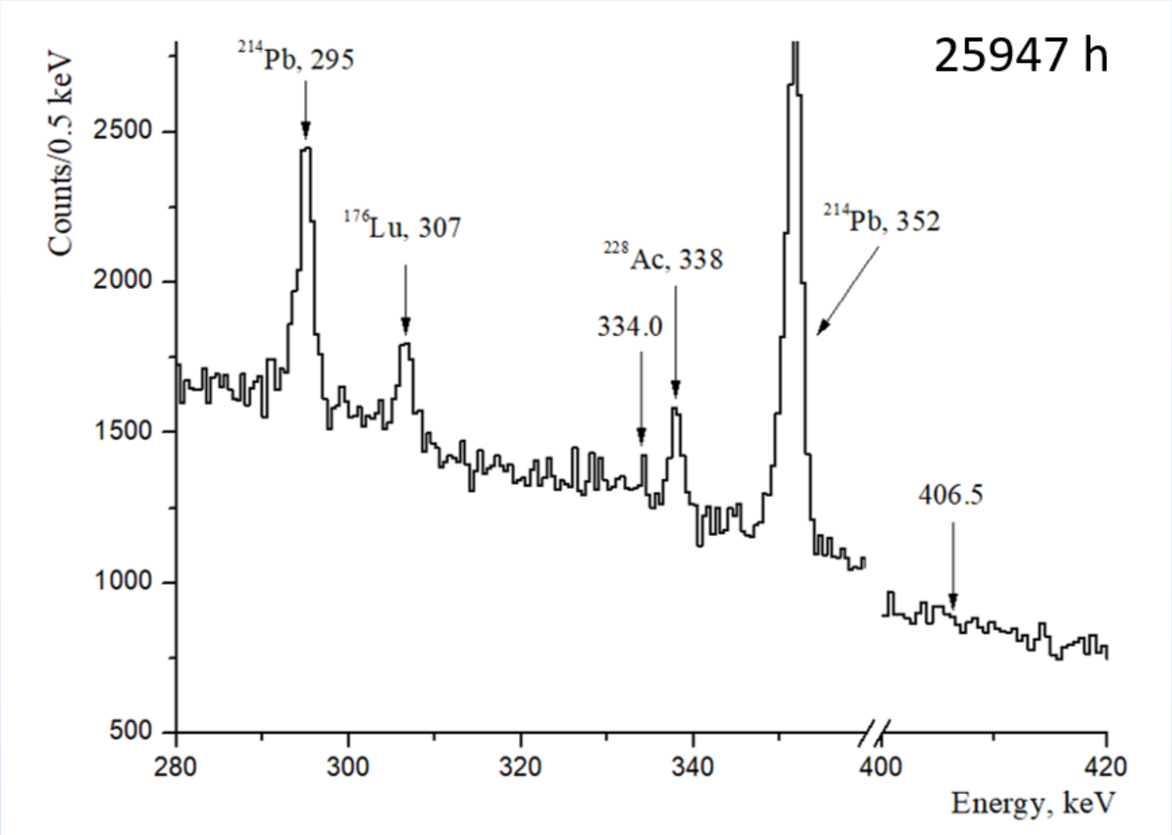
Radioactive contamination of the sample

Chain	Nuclei	Activity, mBq/kg		
		Previous experiment [1]	Before purification	After purification
	^{40}K	46	16(8)	**≤ 1.8**
	^{137}Cs	0.09	≤ 0.8	**≤ 0.04**
	^{138}La	0.07	–	**0.057(9)**
	^{176}Lu	0.5	1.1(4)	**0.29(4)**
^{232}Th	^{228}Ra	0.9	≤ 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	1.2	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.

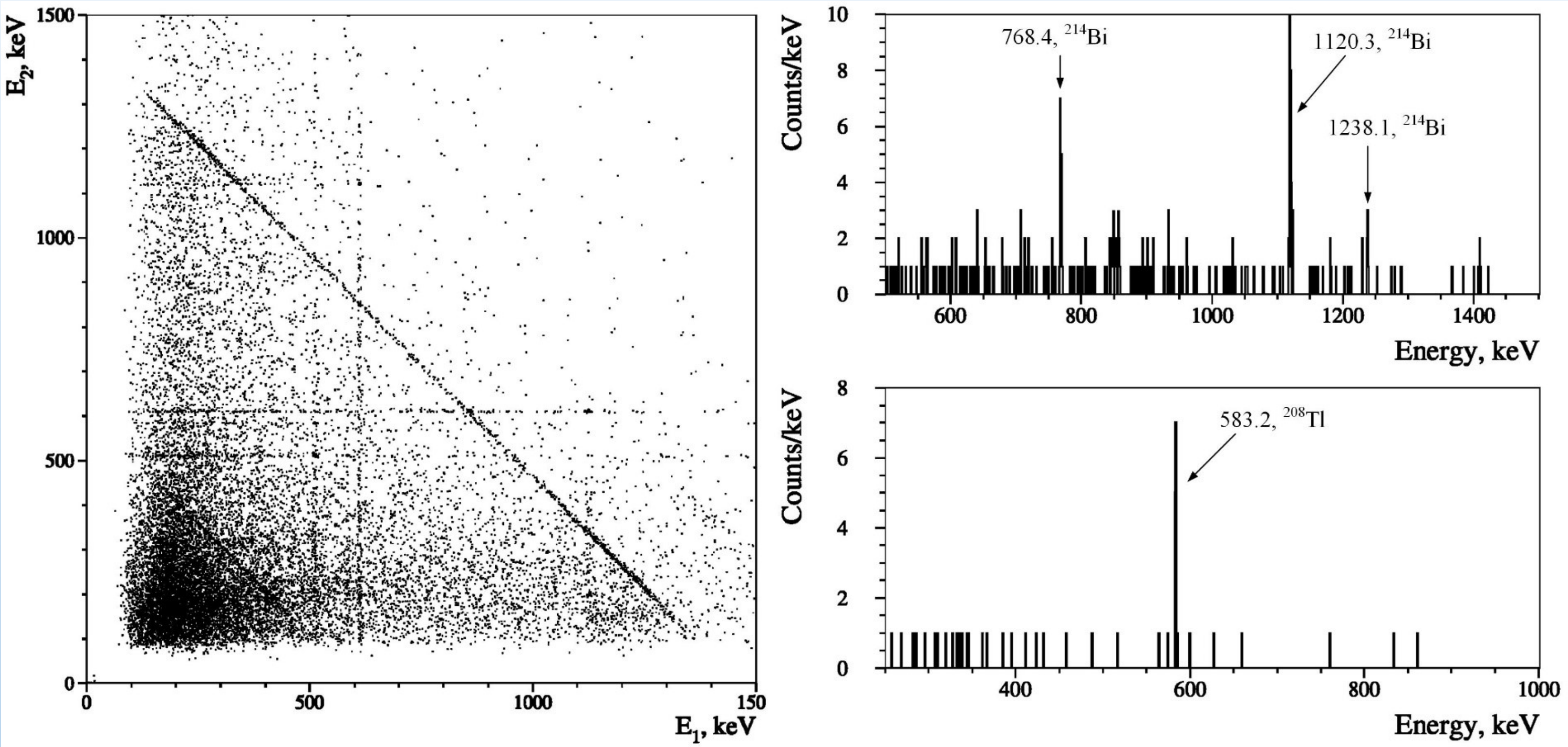
[1] A.S. Barabash et al., Phys. Rev. C 79 (2009) 045501.

1-d spectrum



334.0 keV and 406.5 keV γ quanta in cascade, expected in the decay ^{150}Nd → ^{150}Sm (0_1^+), are not observed in the 1-dimensional spectrum (due to a quite big background).

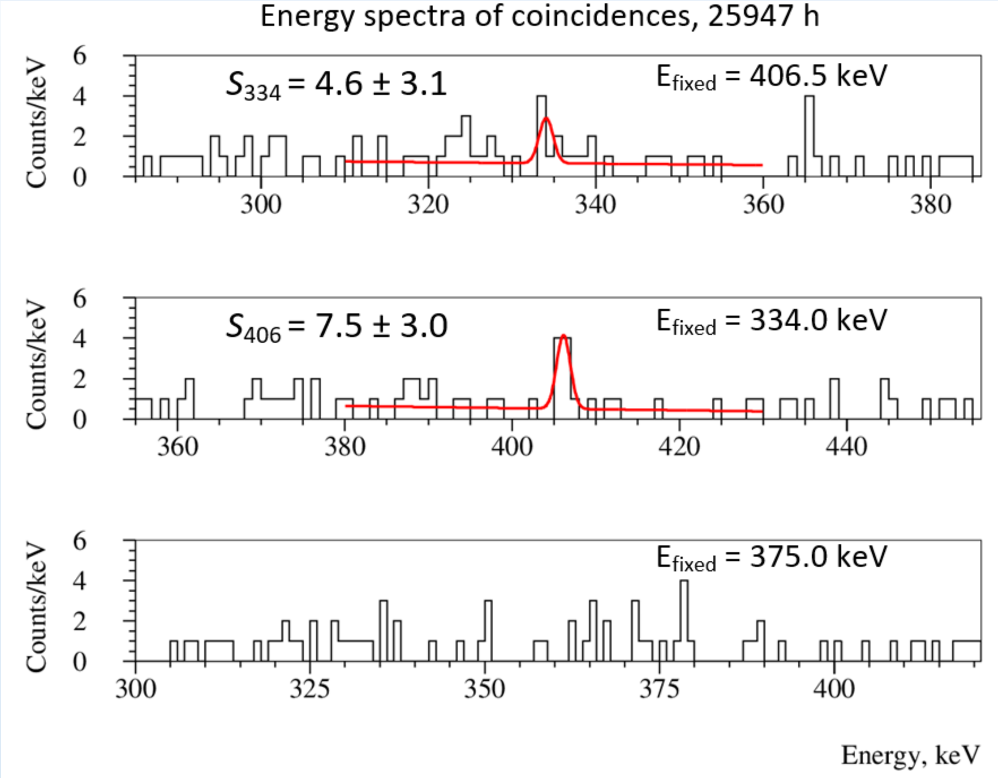
Analysis of coincidence spectra



The two-dimensional energy spectrum of coincidences allows us to observe γ quanta emitted in the same cascade;

- 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



$$T_{1/2} = \frac{\ln 2 * N * \varepsilon * t}{S},$$

S is a peak area;

t = 25947 h – time of measurement;

N = 4.8×10^{23} – number of ^{150}Nd nuclei in the sample

ε = 4.3×10^{-4} is a full absorption peak detection efficiency (in coincidence), obtained in EGSnrc;

Average area: $S = 6.1 \pm 2.2$ counts

$$T_{1/2} = 6.9^{+4.0}_{-1.9}(\text{stat.}) \times 10^{19}\ \text{y (preliminary)}$$

Systematic uncertainties of $T_{1/2}$

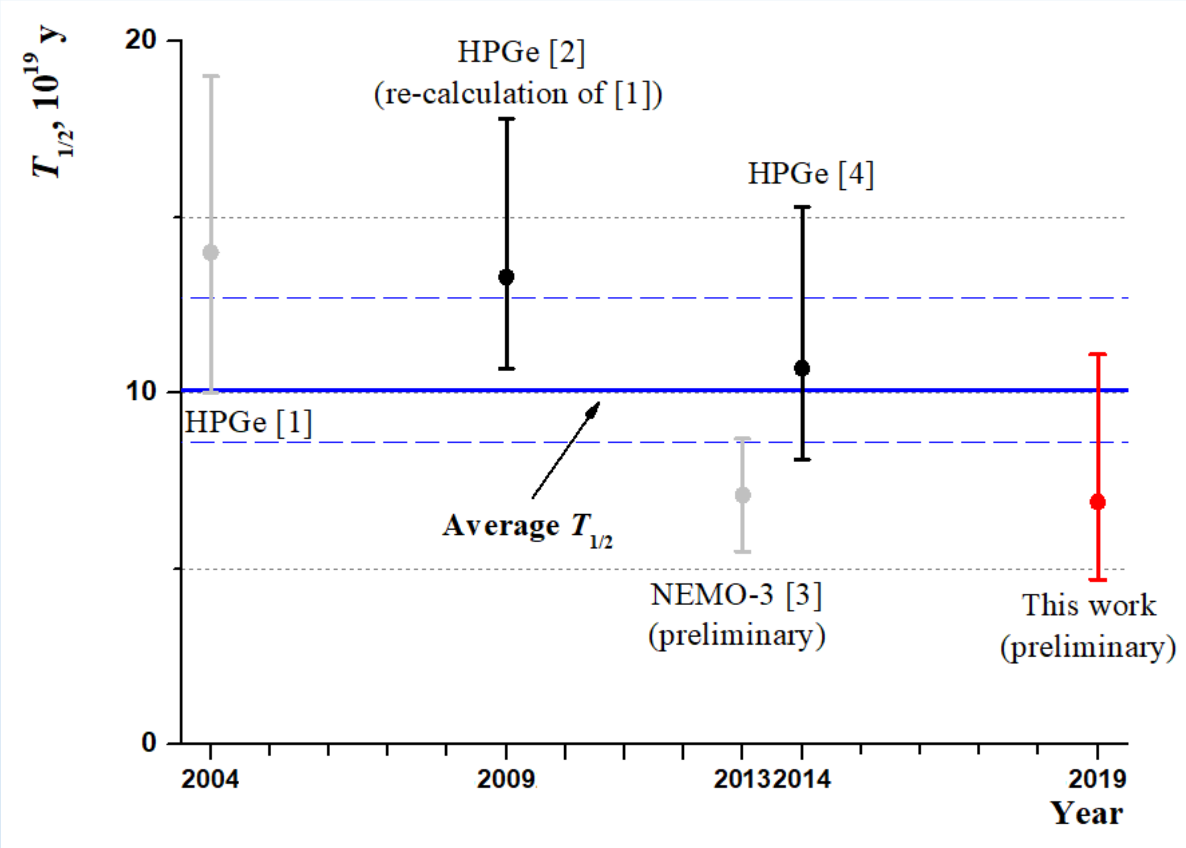
Source of the error	Contribution, %
Number of ^{150}Nd nuclei	± 0.04%
Detection efficiency calculation	± 15%
Interval of the fit	± 6%
Total	± 16%

$$T_{1/2} = [6.9^{+4.0}_{-1.9}(\text{stat.}) \pm 1.1(\text{syst.})] \times 10^{19}\ \text{y}$$

Possible additional source of systematic errors: presence of neodymium (oxy)chlorides → number of ^{150}Nd nuclei (analysis of the sample should be done after the measurement);

- Experimental check of the Monte Carlo simulations is foreseen at the end of the experiment (to reduce the error).

Comparison with previous results



Average $T_{1/2}$:

$$T_{1/2} = 10.1^{+2.6}_{-1.5} \times 10^{19}$$ y ([2], [4], and the present result)

[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 calculation

$$(T_{1/2})^{-1} = G^{2\nu}|M_{2\nu,eff}|^2;\ M_{2\nu,eff} = g_A^2 \cdot M_{2\nu}$$
$$T_{1/2} = 10.1^{+2.6}_{-1.5} \times 10^{19}\ \text{y}$$

Year [Ref.]	G^{2v}, 10^{-19} y^{-1}	$M^{exp}_{2\nu,eff}$
1995 [1]	58.3	0.041 ± 0.004
1998 [2]	48.5	0.045 ± 0.005
2012 [3]	43.3	0.047 ± 0.005
2015 [4]	41.2	0.049 ± 0.006

$M^{th.}_{2\nu,eff}$: $0.167 \cdot g_A^2$ [2] – s.p. estimations of double Gamov-Teller NME
$0.012 \cdot g_A^2$ [3,5] – microscopic interacting boson model (IBM-2, CA);

$\sim 0.21 \cdot g_A^2$ – approximate value in SSD (estimated by J. Kotila)
$\sim$0.056 – by using $g_A^{eff} = 1.269 \cdot A^{-0.18}$

[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 by using low-background 4-crystal HPGe γ-spectrometer at the Gran Sasso UL.
- Gamma quanta expected in the decay have been observed in the coincidence spectra. The area of the effect is 6.1 ± 2.2 counts. The half-life of ^{150}Nd relatively to the 2β decay to the 0_1^+ excited state of ^{150}Sm is estimated (preliminary) as

$$T_{1/2} = [6.9^{+4.0}_{-1.9}(\text{stat.}) \pm 1.1(\text{syst.})] \times 10^{19} \text{ y}$$

- Experiment is in progress to improve the half-life value accuracy. Detection efficiency and chemical compound should be checked at the end of the measurements.

Back-up slides

Detection efficiency

The full detection efficiencies in the full absorption peak were calculated by Monte-Carlo simulation by using EGSnrc package [1] + DECAY0 event generator:

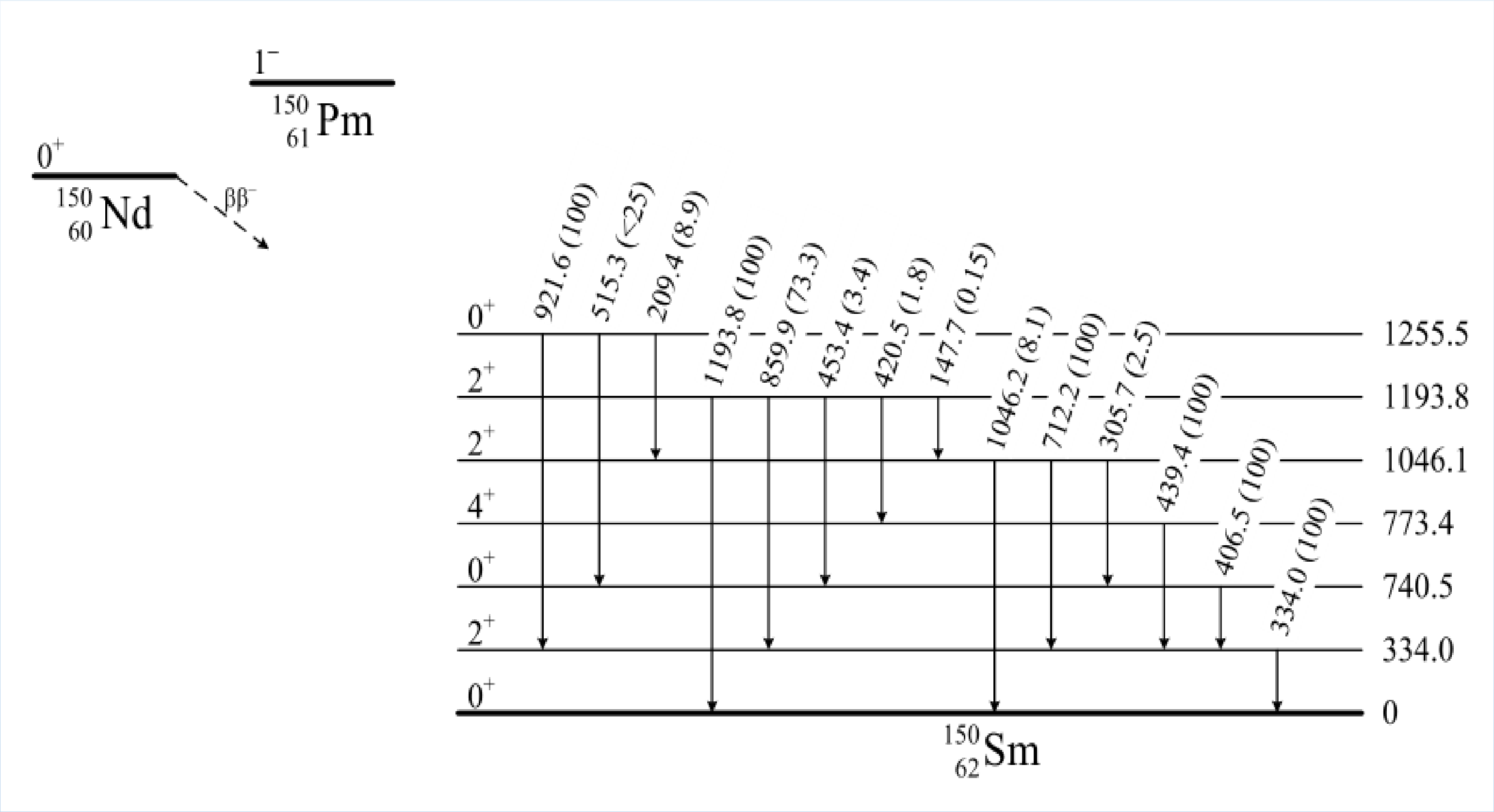
- $\varepsilon_{334} = 2.24\%$
- $\varepsilon_{406} = 2.42\%$
- $\varepsilon_{\text{coinc}} = 4.3 \cdot 10^{-4}$

The $\varepsilon_{\text{coinc}}$ was estimated taking into consideration the angular correlation between two γ quanta in $0^+ \rightarrow 2^+ \rightarrow 0+$ cascade:

$$\rho(\theta) = 1 - 3cos^2(\theta) + 4cos^4(\theta)$$

[1] I. Kawrakow, D.W.O. Rogers, The EGSnrc code system: Monte Carlo simulation of electron and photon transport, NRCC Report PIRS-701, Ottawa, 2003.

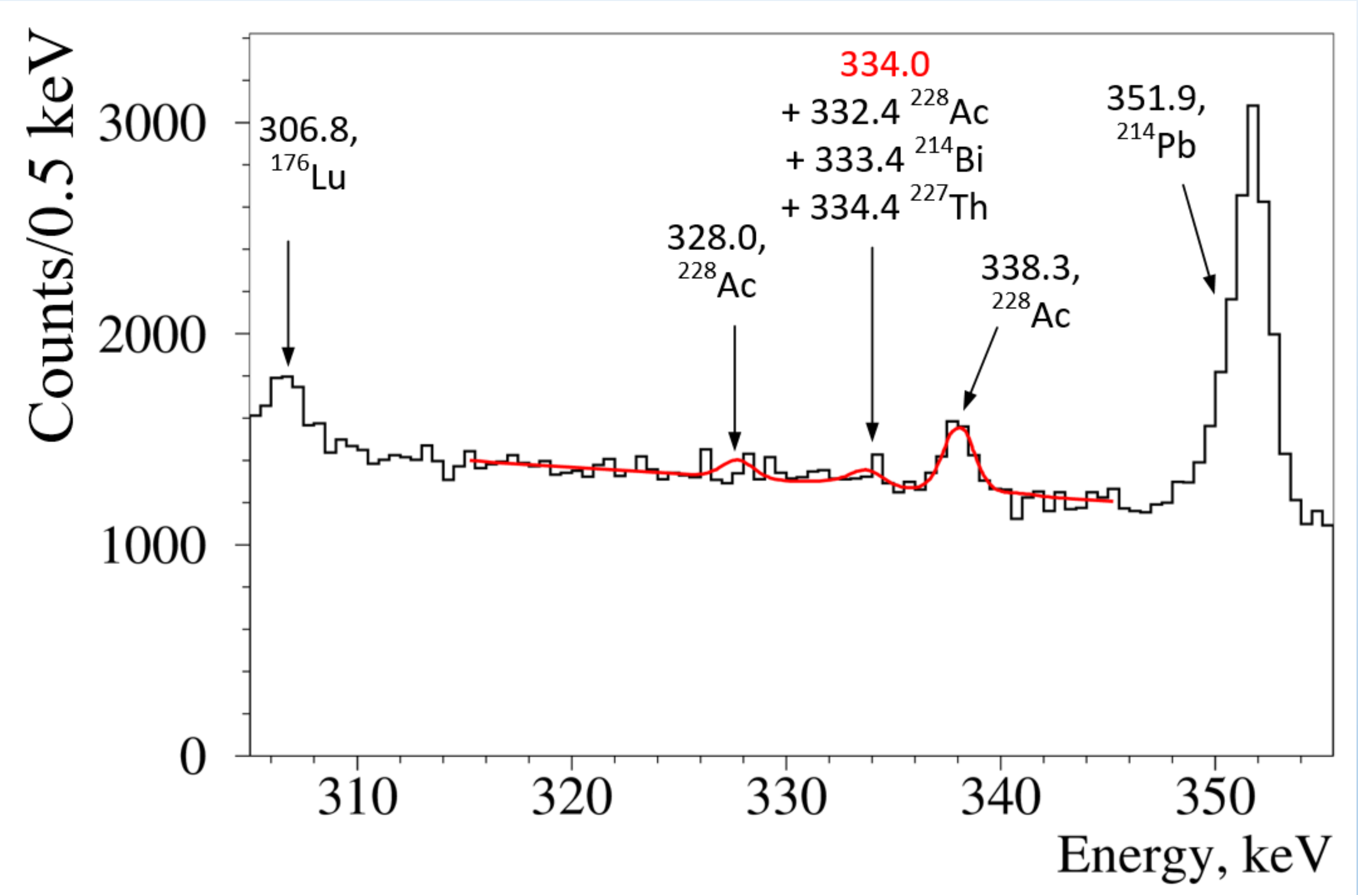
Scheme of DBD of ^{150}Nd



Fit of the 1-dim spectrum

γ from $^{150}Nd \rightarrow$ ^{150}Sm)	E_γ, keV (I, %)		
	^{238}U chain	^{232}Th chain	^{235}U chain
334.0 keV	314.3 (0.078) ^{214}Pb 323.8 (0.029) ^{214}Pb 333.4 (0.065) ^{214}Bi	321.6 (0.226) ^{228}Ac 327.4 (0.12) ^{228}Ac 328.0 (2.95) ^{228}Ac 332.4 (0.4) ^{228}Ac 338.3 (11.27) ^{228}Ac 341.0 (0.369) ^{228}Ac	314.85 (0.66) ^{227}Th 323.9 (3.99) ^{223}Ra 329.9 (4.0) ^{227}Th 330.1 (1.4) ^{231}Pa 334.4 (1.54) ^{227}Th 338.3 (2.84) ^{223}Ra
406.5 keV	386.8 (0.295) ^{214}Bi 388.9 (0.402) ^{214}Bi 405.7 (0.169) ^{214}Bi	409.5 (1.92) ^{228}Ac	401.8 (6.6) ^{219}Rn 404.9 (3.78) ^{211}Pb

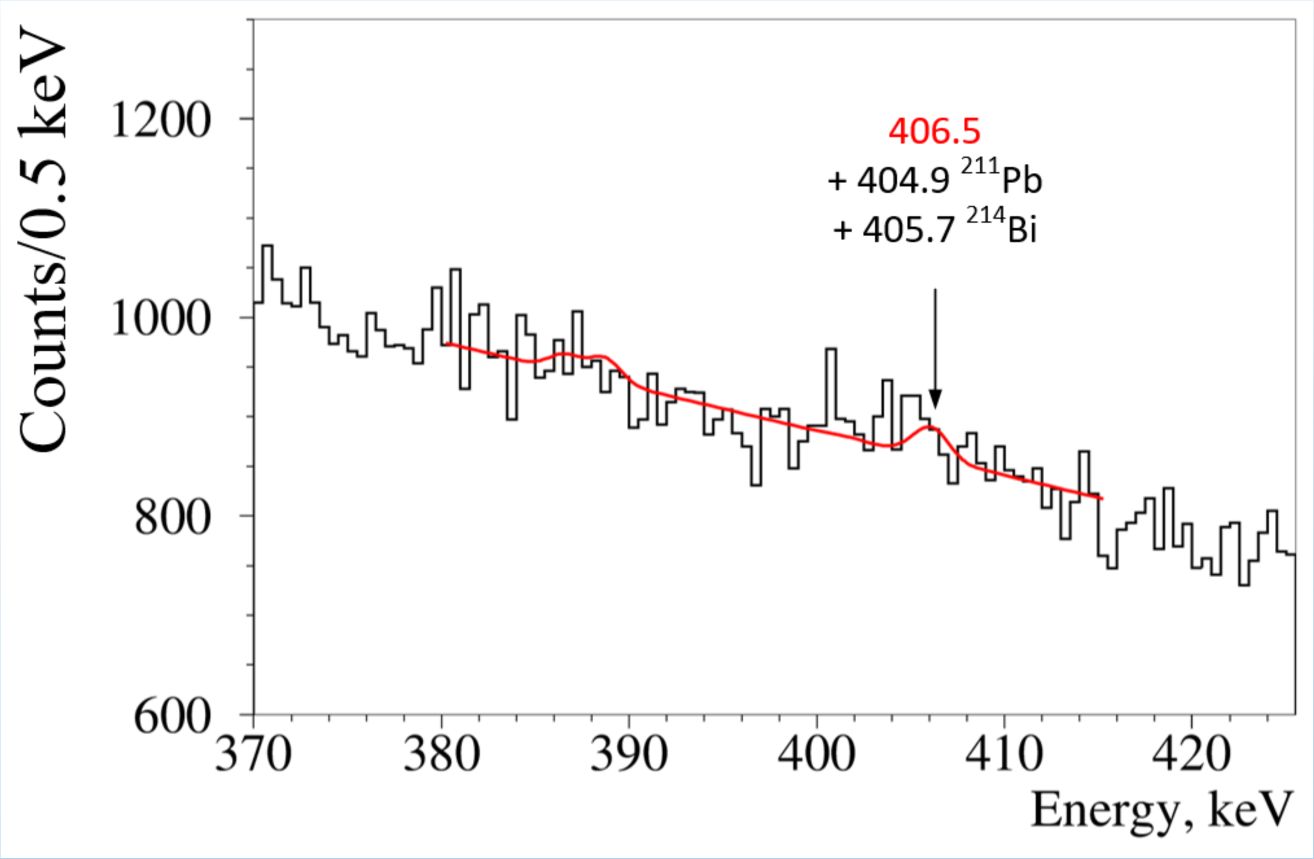
Fit of the 334 keV



S = 238 ± 87 counts → lim S = 381 →

→ lim $T_{1/2} = 5.8 \times 10^{19}$ y

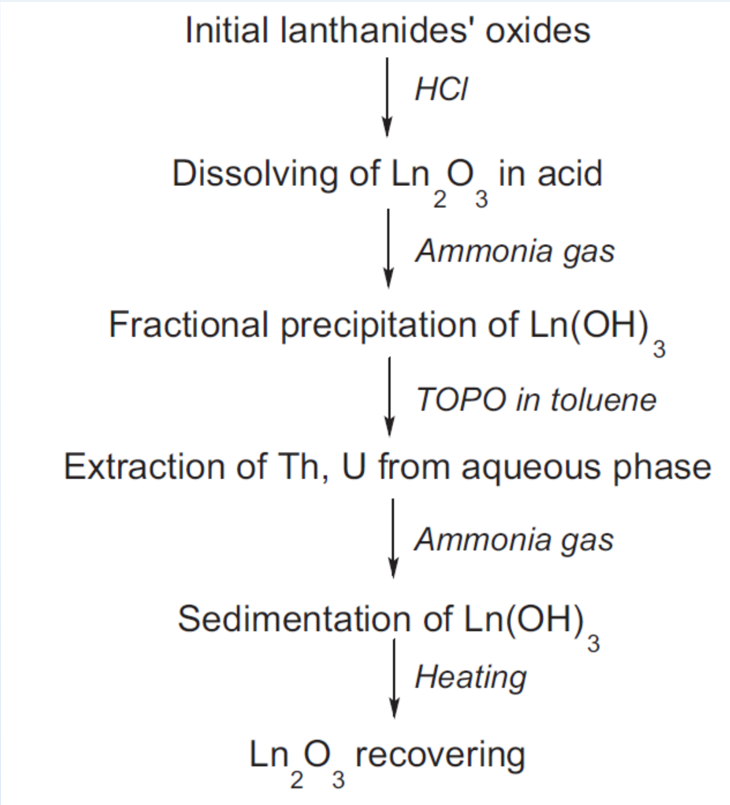
Fit of the 406.5 keV

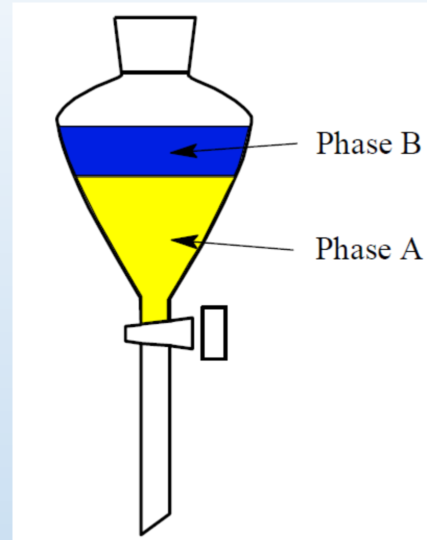


S = 135 ± 74 counts (± 55 syst.) → lim S = 288 →

→ lim $T_{1/2}$ = 7.7 × 10^{19} y

Nd_2O_3 purification





- $Nd_2O_3 + 6HCl \rightarrow 2NdCl_3 + 3H_2O$
- Phase A: $NdCl_3$ in water
- Phase B: tri-*n*-octyl-phosphine oxide (TOPO) in toluene
- Liquid-liquid extraction

$NdCl_3(Th, U)_{(aq)} + nTOPO_{(org)} \rightarrow$

$\rightarrow NdCl_{3(aq)} + [(Th,U)\cdot nTOPO](Cl)_{(org)}$

- $NdCl_3 + 3NH_3 + 3H_2O \rightarrow Nd(OH)_3\downarrow + 3NH_4Cl$
- $Nd(OH)_3$ thermal decomposition to Nd_2O_3.