Study of Double Beta Decays of ^{150}Nd

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ICNFP 2023
21/07/2023

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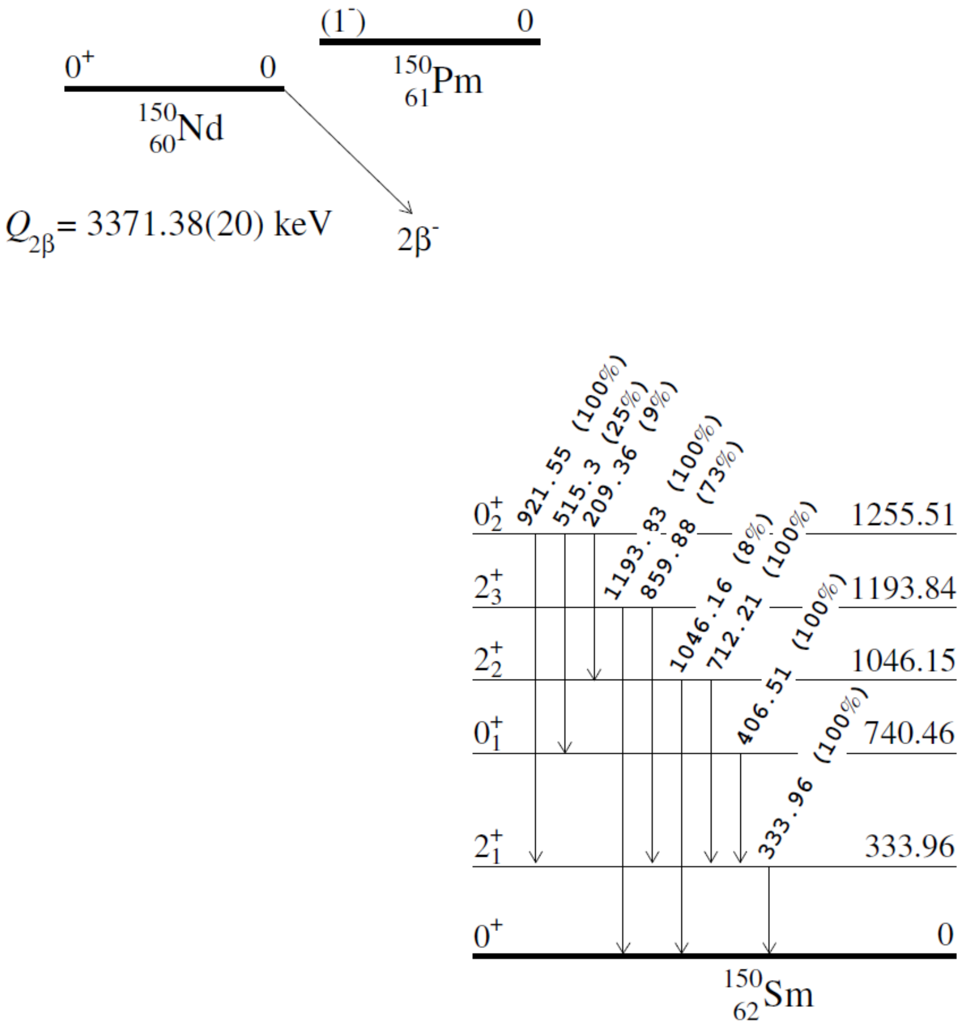
Introduction



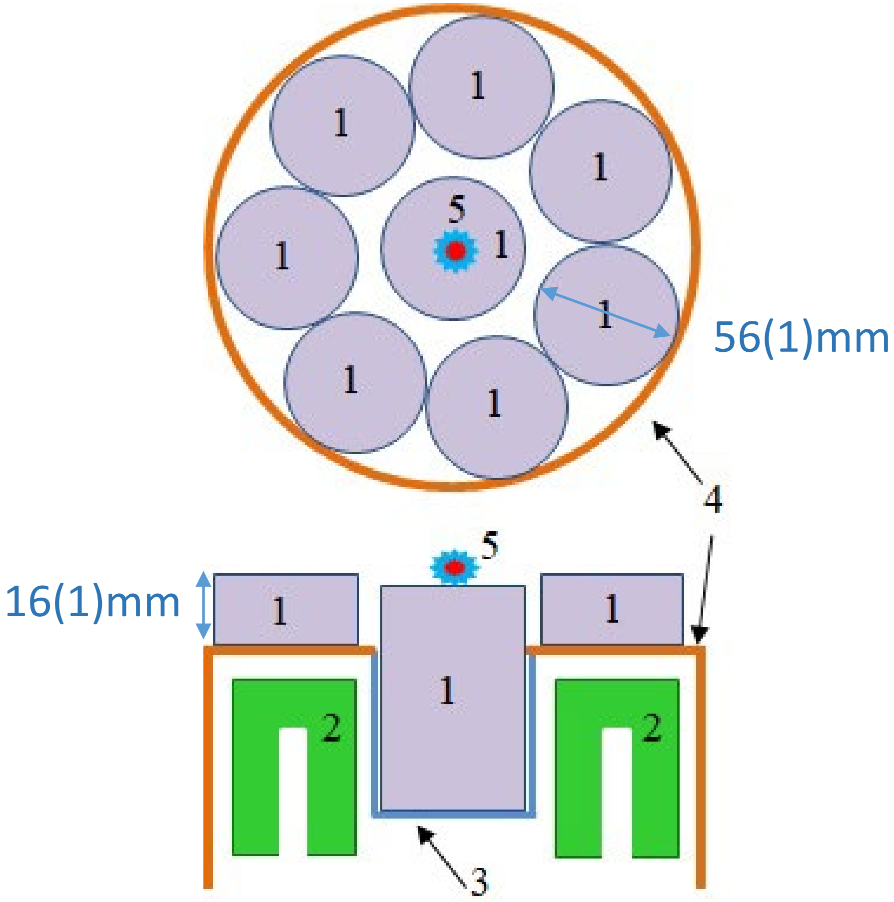
^{150}Nd natural abundance: δ = 5.638 %

Experimental results for ^{150}Nd → ^{150}Sm (0^+_1, 740.46 keV)

Short description	$T_{1/2}$, 10^{20} y	Year [Ref.]
Modane underground laboratory (4800 m w.e.), HP Ge 400 cm3, 3046 g of Nd_2O_3 (δ = 5.638%), 1,29 y, 1-d spectrum	$1.4^{+0.5}_{-0.4}$	2004 [1]
Re-estimation of the measurement in [1]	$1.33^{+0.45}_{-0.26}$	2009 [2]
Kimballton Underground Research Facility, USA (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	$1.07^{+0.46}_{-0.26}$	2014 [3]
Modane underground laboratory (4800 m w.e.), NEMO-3 detector, foil of $^{150}Nd_2O_3$ (δ = 91.0 %).	$1.11^{+0.26}_{-0.21}$	2021 [3]

[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] M.F. Kidd et al., Phys. Rev. C 90 (2014) 055501.
[4] V. Tretyak (on behalf of NEMO-3 collaboration), abstract of LXXI International conference "NUCLEUS-2021.

Experimental Setup



Schematic view of the set-up with Nd-containing source samples (1) installed in the HPGe detector system: (2) coaxial HPGe detectors, (3) aluminium cup of the detector system endcap, (4) copper part of the endcap, (5) position of radioactive γ sources during the calibration campaign.

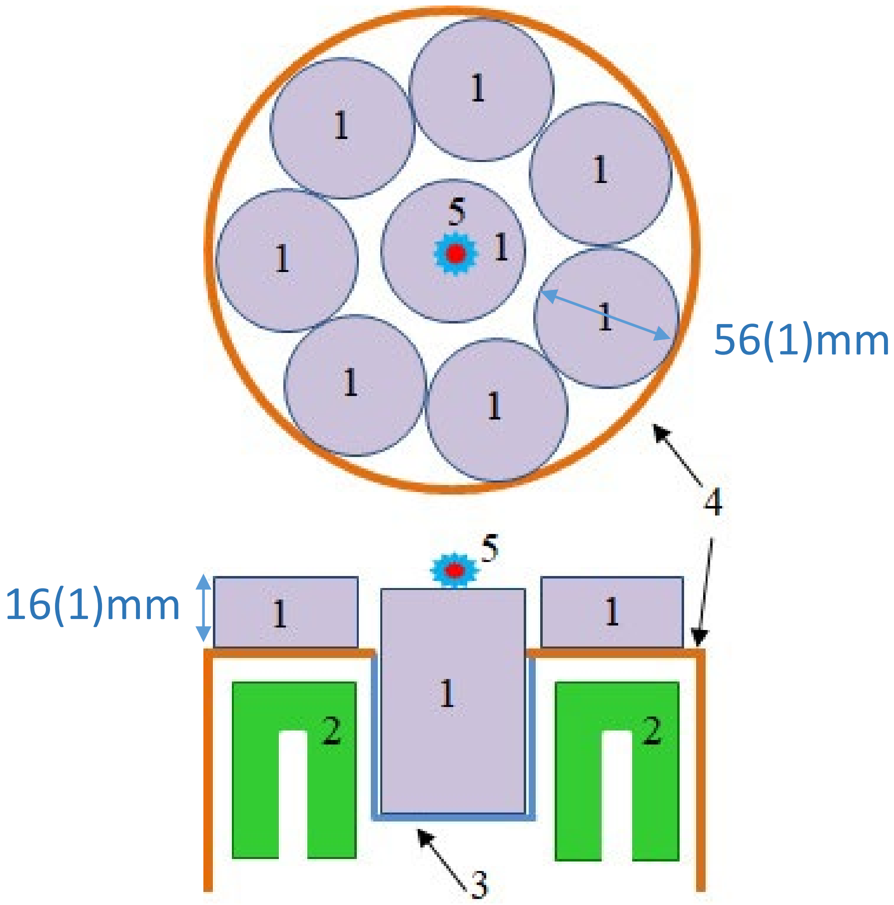
Experimental Setup

- **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 HPGe** 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)

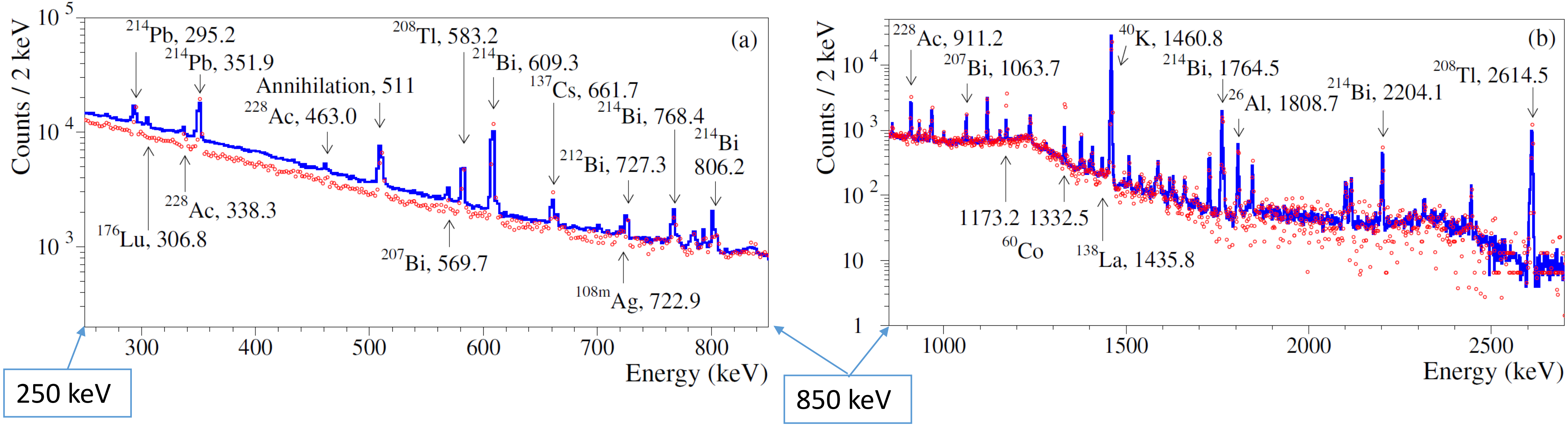
- **Plexiglas container** flushed with high-purity nitrogen gas (to remove the radon)



Schematic view of the set-up with Nd-containing source samples (1) installed in the HPGe detector system: (2) coaxial HPGe detectors, (3) aluminium cup of the detector system endcap, (4) copper part of the endcap, (5) position of radioactive γ sources during the calibration campaign.

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

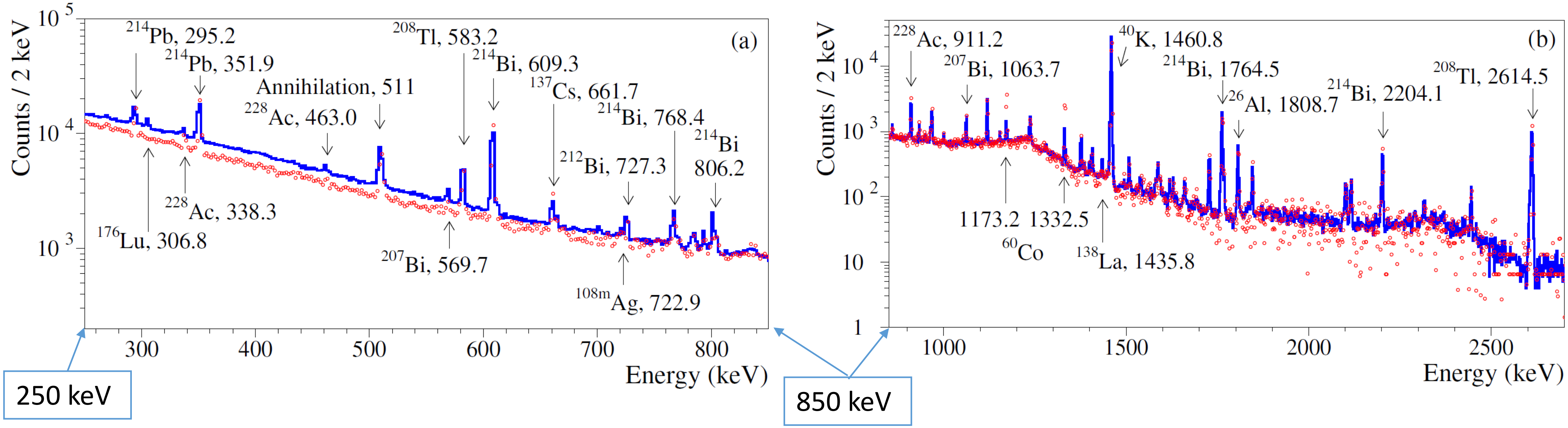
Energy Spectra



Energy spectra measured **with the Nd_2O_3** sample over **5.845 y** (**blue**) and **without sample** for 0.8969 y (normalized to 5.845 y, **red**) by the low-background **HPGe-detector system**. The energy of the γ peaks is in keV.

HPGe detector	Energy resolution for γ peaks, FWHM (keV)			
	295.2 keV (^{214}Pb)	**351.9 keV (^{214}Pb)**	**609.3 keV (^{214}Bi)**	**1460.8 keV (^{40}K)**
1	1.83(8)	1.81(5)	2.03(4)	2.375(8)
2	1.56(8)	1.54(5)	1.80(4)	2.18(4)
3	3.11(9)	3.06(10)	2.42(13)	2.64(3)
4	3.49(18)	3.39(20)	2.80(5)	3.84(2)

Radioactive Contamination of the Nd_2O_3 Sample



The peaks in the spectra presented in Figs. can be assigned to γ quanta of ^{40}K and nuclides of the ^{232}Th and ^{238}U chains. In addition, ^{26}Al, ^{60}Co, ^{108m}Ag, ^{137}Cs, ^{207}Bi γ peaks are observed in the both spectra.

$$A = (S_{sample}/t_{sample} - S_{bg}/t_{bg})/(\eta\ \varepsilon\ m)$$

S_{sample} (S_{bg}) = area of a peak;
t_{sample} (t_{bg}) = time of measurement;
η = γ-ray emission absolute intensity in the transition;
ε = full energy peak detection efficiency;
m = sample mass.

Radioactive Contamination of the Nd_2O_3 Sample

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.

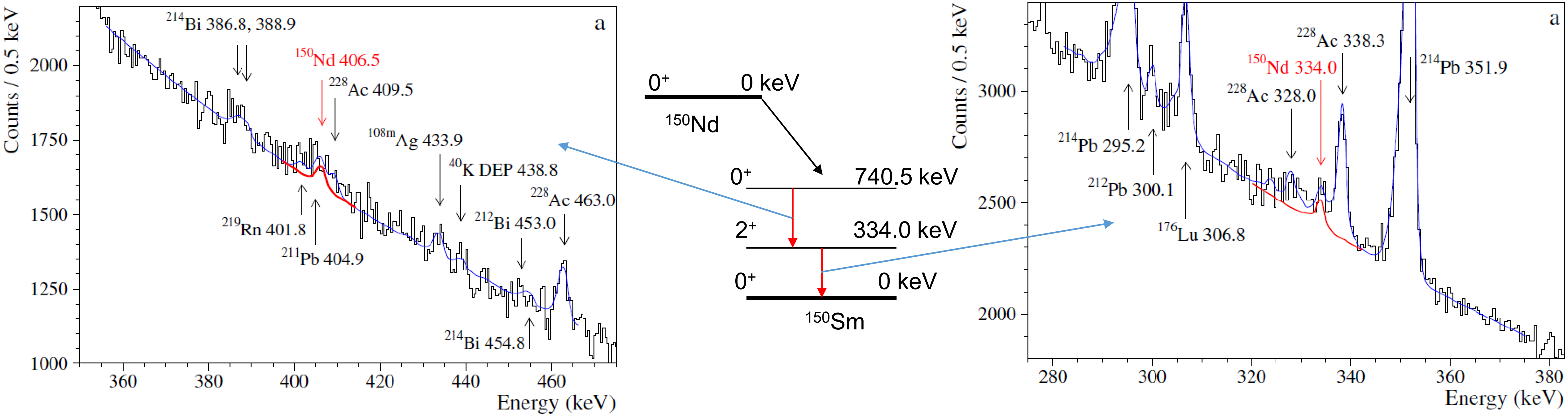
The radioactive contamination of the sample by the lanthanides have been estimated as:

^{138}La: 0.085(7) mBq/kg
^{176}Lu: 0.32(2) mBq/kg

Other estimated contaminants: **^{228}Ra, ^{228}Th, ^{235}U, ^{227}Ac, ^{40}K.**

Chain	Nuclide	Activity (mBq/kg)	
		Before purification [29]	Purified material
	^{40}K	16 ± 8	3.1 ± 0.7
	^{60}Co		≤ 0.03
	^{101}Rh		≤ 0.09
	^{102}Rh		≤ 0.005
	^{108m}Ag		≤ 0.018
	^{121}Te		≤ 0.36
	^{133}Ba		≤ 0.006
	^{137}Cs	≤ 0.8	≤ 0.018
	^{138}La		0.085 ± 0.007
	^{144}Ce		≤ 0.9
	^{150}Eu		≤ 0.033
	^{152}Eu		≤ 0.10
	^{154}Eu		≤ 0.014
	^{176}Lu	1.1 ± 0.4	0.32 ± 0.02
	^{207}Bi		≤ 0.07
^{232}Th	^{228}Ra	≤ 2.1	0.12 ± 0.07
	^{228}Th	≤ 1.3	0.33 ± 0.05
^{235}U	^{235}U	≤ 1.7	1.5 ± 0.4
	^{231}Pa		≤ 0.28
	^{227}Ac		0.47 ± 0.07
^{238}U	^{234m}Pa	≤ 28	≤ 3.4
	^{226}Ra	15 ± 0.8	≤ 0.17
	^{210}Pb		≤ 178

Energy Spectrum in the ROI - 1D Spectra (13,92 kg y)



406.5-keV peak area = 389(121) counts
χ^2/n.d.f. = 222/207 = 1.07

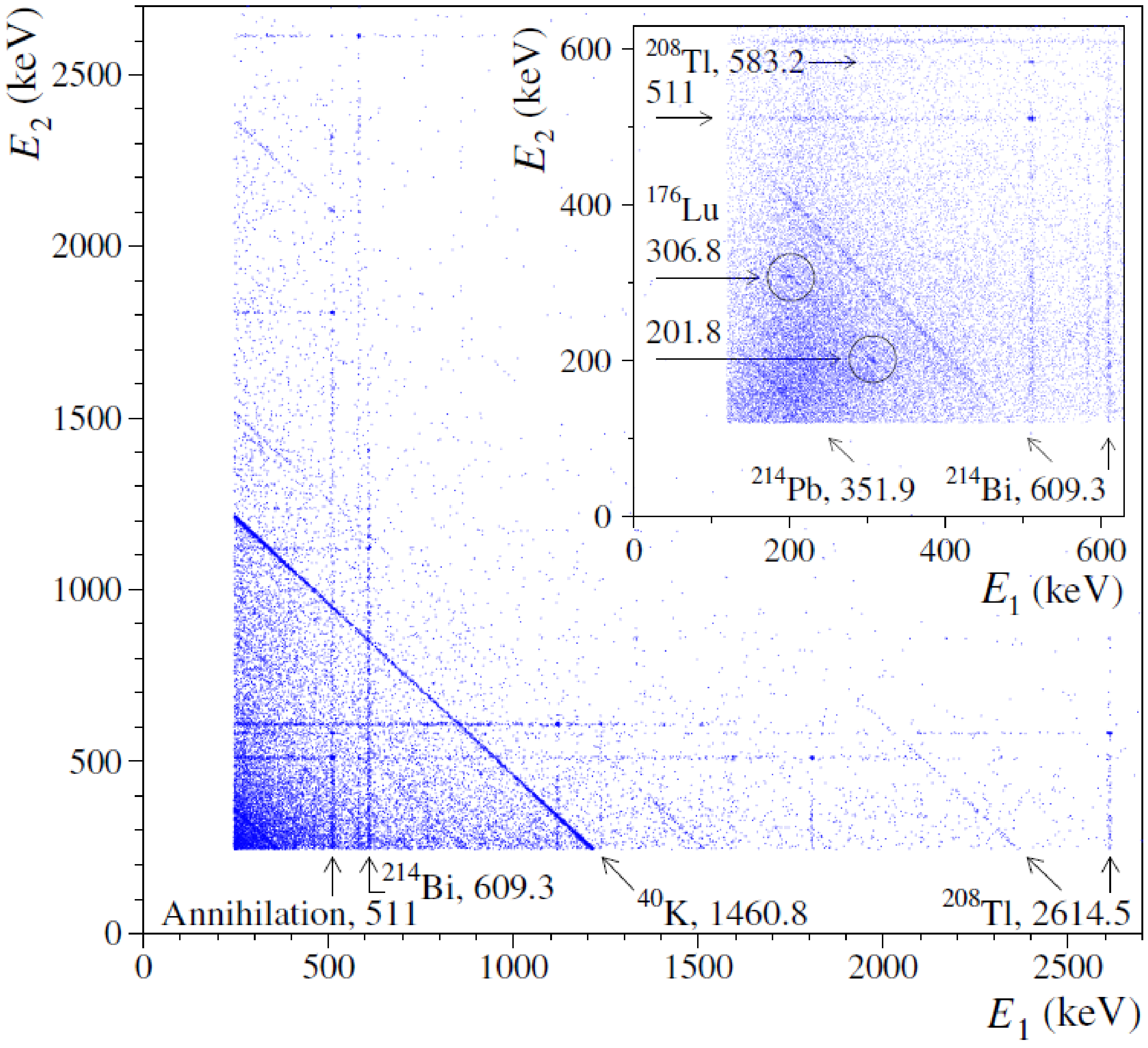
334.0-keV peak area = 615(144) counts
with a reasonable fit quality
χ^2/n.d.f. = 235/175 = 1.34

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

$$T^{406}_{1/2}(^{150}\mathrm{Nd} \rightarrow \; ^{150}\mathrm{Sm}(0^+_1)) = [1.03^{+0.47}_{-0.24}(\mathrm{stat})] \times 10^{20} \mathrm{~y}$$

$$T^{334}_{1/2}(^{150}\mathrm{Nd} \rightarrow \; ^{150}\mathrm{Sm}(0^+_1)) = [0.60^{+0.18}_{-0.11}(\mathrm{stat})] \times 10^{20} \mathrm{~y}$$

Coincidence in 2 HPGe Detectors (13,92 kg y)

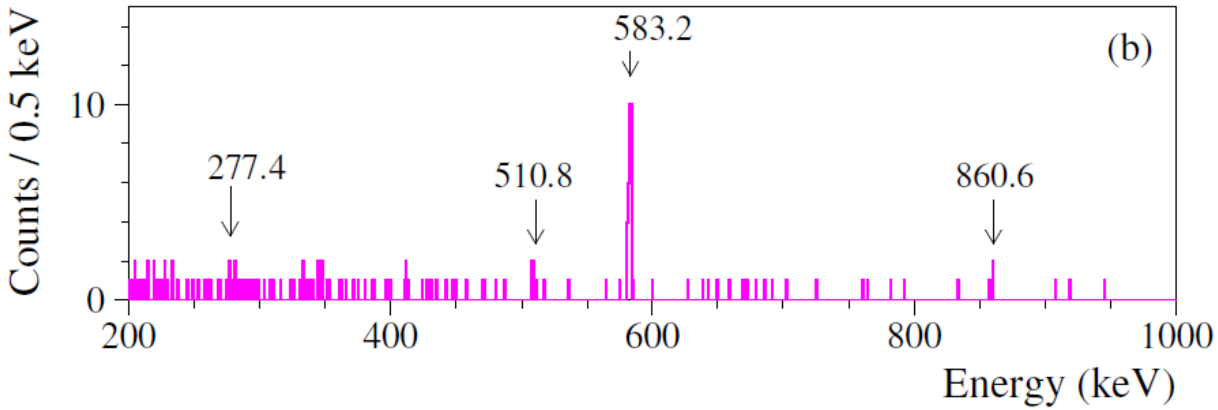


Two γ quanta, 334.0 keV and 406.5 keV, emitted in de-excitation of the 740.5-keV 0^{+1} level of ^{150}Sm, can be detected in coincidence by the HPGe counters of the detector system.

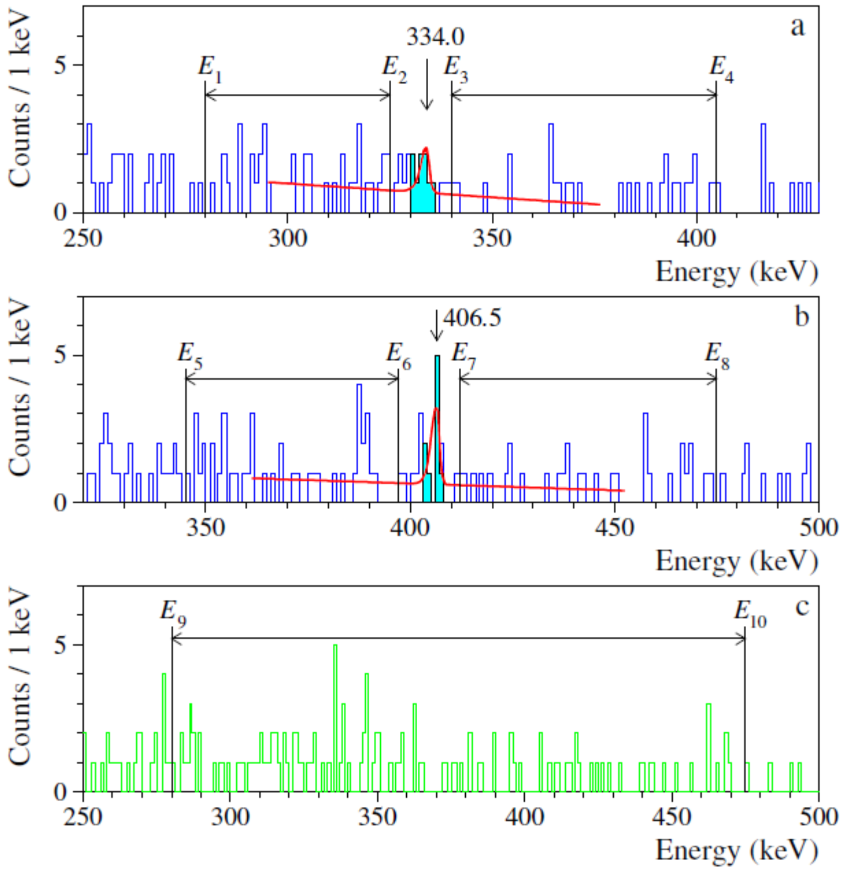
Some peculiarities in the 2D-spectrum:

- Vertical/Horizontal lines: ^{214}Bi, ^{208}Tl, annih. 511
- Diagonal lines: ^{40}K, ^{208}Tl, ^{214}Pb, ^{214}Bi
- Point-like structures: ^{176}Lu

Example:
The energy of one detector is fixed at (2615 ± 3σ) keV (^{208}Tl)



Coincidence in 2 HPGe Detectorsemitted in De-excitation of the 740.5 keV 0^+_1 level of ^{150}Sm (13,92 kg y)



The energy in one detector is fixed to the energy interval where γ quanta from the ^{150}Nd → ^{150}Sm (0^+, 740.5 keV) decay are expected:

(406.5 ± 3σ) keV

(334.0 ± 3σ) keV

A random coincidence background when energy of events in one of the detectors was taken as (375 keV ± 3σ) keV

$S^{334\&406}$ = 3.80 − 10.3 counts (68% C.L.)

$\varepsilon^{334\&406}$ = 0.0004262(23)

$T^{334\&406}_{1/2}$ (^{150}Nd → ^{150}Sm(0^+_1)) = $[0.98^{+0.69}_{-0.36}$(stat)$]\times10^{20}$ y.

Half-life of ^{150}Nd relative to the 2ν2β decay to the 0^+_1 excited level of ^{150}Sm

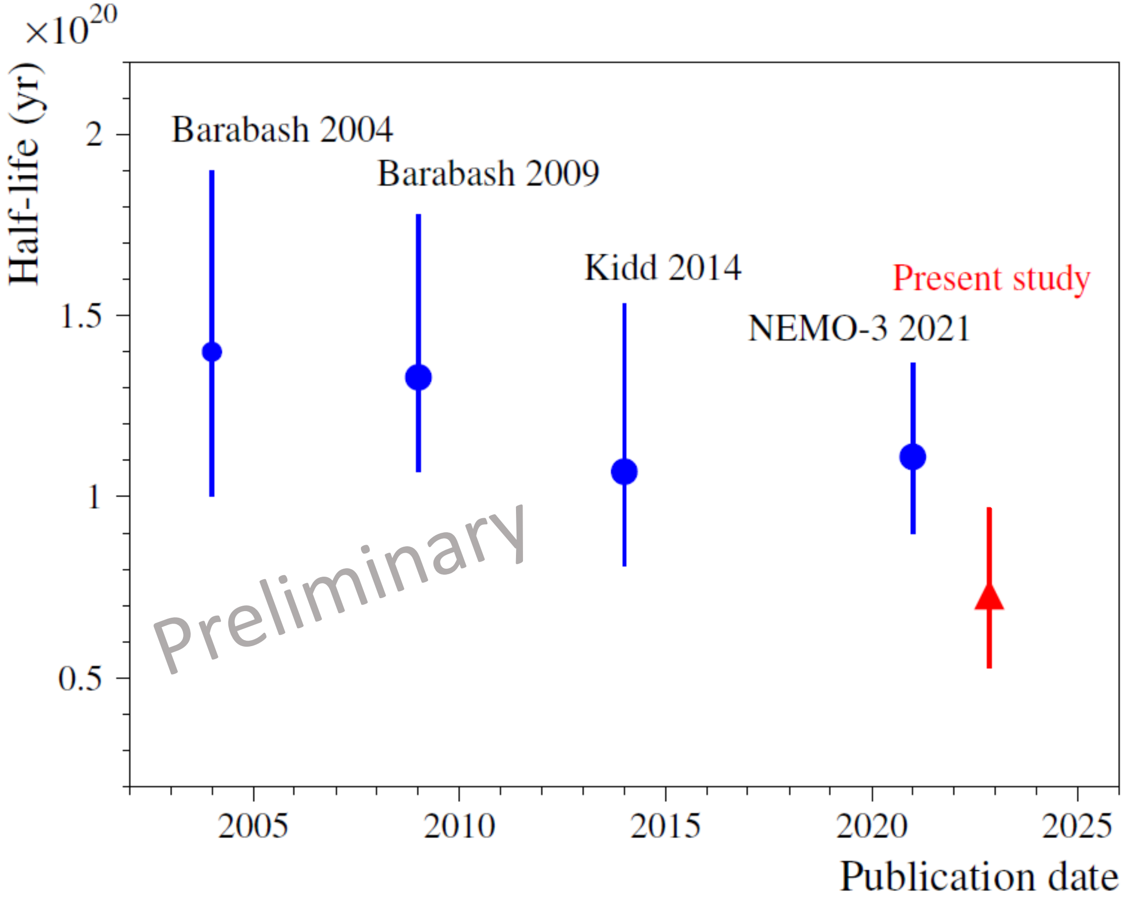
Source of systematic uncertainty	Relative uncertainty (% of $T_{1/2}$)
Number of ^{150}Nd nuclei	± 1.7
Detection efficiency in 1-dimensional data	± 3.2
Interval of fit for 334.0-keV peak	$^{+1.0}_{-1.4}$
Bin of spectrum for 334.0-keV peak fit	$^{+10.6}_{-7.2}$
Energy scale for 334.0-keV peak fit	$+0.8$
Model of background for 334.0-keV peak fit	-0.8
Interval of fit for 406.5-keV peak	$^{+3.7}_{-5.1}$
Bin of spectrum for 406.5-keV peak fit	-12.0
Energy scale for 406.5-keV peak fit	-2.5
Model of background for 406.5-keV peak fit	$^{+5.7}_{-4.2}$
Monte Carlo statistics for CC detection efficiency	± 0.5
Energy interval of events selection to build CC spectra	$^{+11.9}_{-2.8}$
Energy interval of background estimation in CC data	$^{+1.1}_{-4.3}$

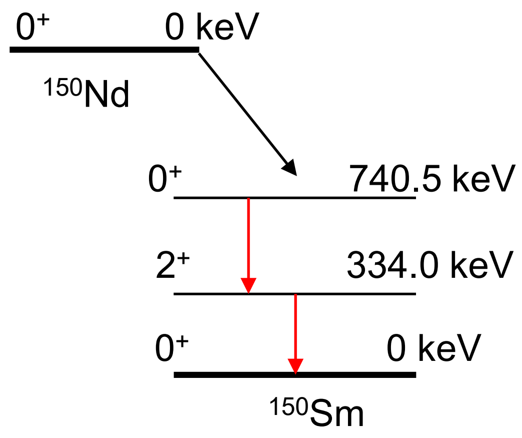
Sources of systematic uncertainties of the half-life of ^{150}Nd relative to the 2ν2β decay to the 740.5 keV 0^+_1 excited level of ^{150}Sm calculated by using the 334.0-keV, 406.5-keV peaks in the 1-dimensional spectrum, and the CC data. The uncertainties are assumed to be independent and added in quadrature.

Half-life of ^{150}Nd relative to the 2ν2β decay to the first 0^+_1 excited level of ^{150}Sm obtained by analysis of the **1-dimensional spectrum**, **coincidence data**, and **their combinations**. "M = 1" denotes the results obtained from the analysis of the 1-dimensional spectrum built under the condition "multiplicity = 1".

Number in order	Method of analysis	Half-life, 10^{20} yr
1	1-Dimensional spectrum, 334.0 keV peak	$0.60^{+0.18}_{-0.11}(\text{stat})^{+0.07}_{-0.05}(\text{syst})$
1a	1-Dimensional spectrum, 334.0 keV peak, $M = 1$	$0.63^{+0.20}_{-0.12}(\text{stat})^{+0.08}_{-0.06}(\text{syst})$
2	1-Dimensional spectrum, 406.5 keV peak	$1.03^{+0.47}_{-0.24}(\text{stat})^{+0.08}_{-0.15}(\text{syst})$
2a	1-Dimensional spectrum, 406.5 keV peak, $M = 1$	$1.02^{+0.49}_{-0.25}(\text{stat})^{+0.08}_{-0.15}(\text{syst})$
3	Combination of 1 and 2	$0.61^{+0.14}_{-0.09}(\text{stat})^{+0.11}_{-0.16}(\text{syst})$
4	Coincidence data (comparison of the events observed with known mean background)	$0.98^{+0.69}_{-0.36}(\text{stat})^{+0.12}_{-0.05}(\text{syst})$
5	Combination of 1a, 2a and 4 (see footnote 4)	$0.73^{+0.18}_{-0.11}(\text{stat})^{+0.16}_{-0.17}(\text{syst})$
6	Combination of 2a and 4 (see footnote 4)	$1.00^{+0.40}_{-0.21}(\text{stat})^{+0.14}_{-0.15}(\text{syst})$

Half-life of ^{150}Nd relative to the 2ν2β decay to the 0^+_1 excited level of ^{150}Sm

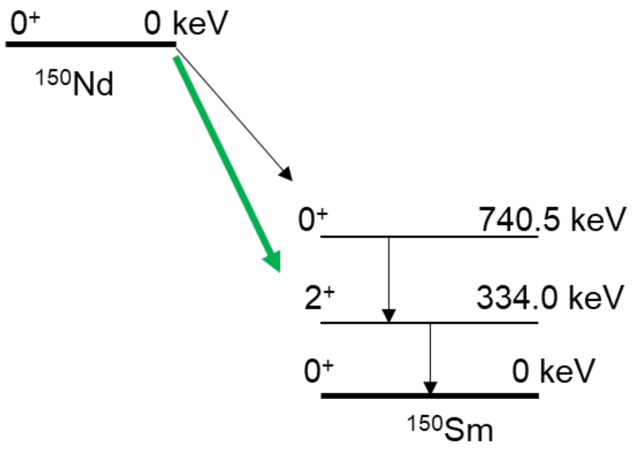


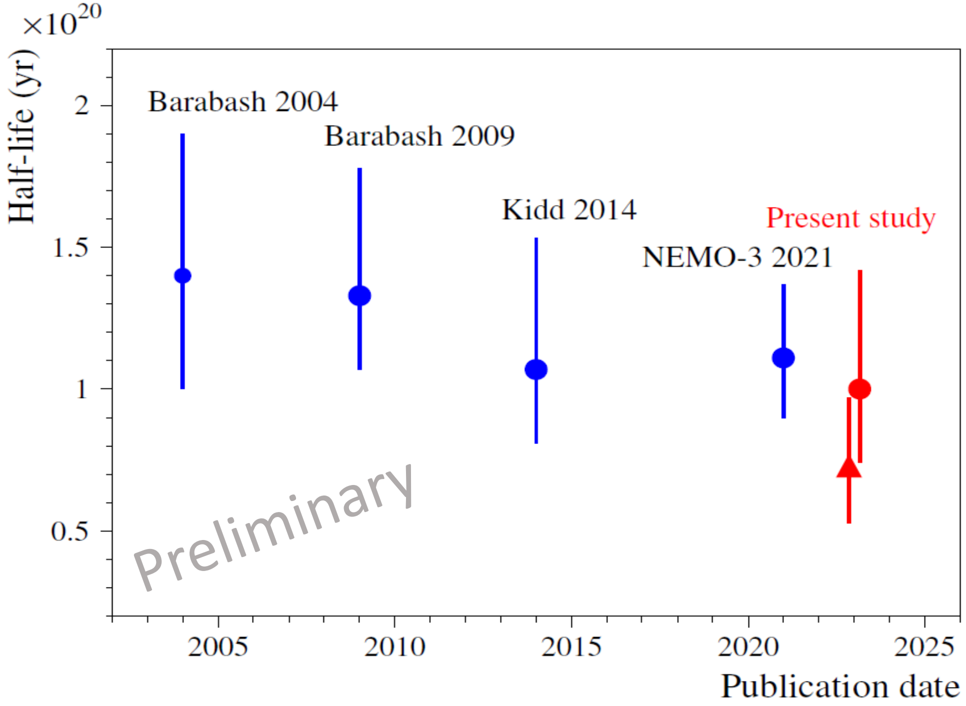


Preliminary

$$T_{1/2}(^{150}\mathrm{Nd} \rightarrow \ ^{150}\mathrm{Sm}(0_1^+)) = [0.73^{+0.18}_{-0.11}(\mathrm{stat})^{+0.16}_{-0.17}(\mathrm{syst})] \times 10^{20}\ \mathrm{y}$$

Indication of 2ν2β decay of ^{150}Nd to the 2^+_1 excited level of ^{150}Sm





$$T_{1/2}(^{150}\mathrm{Nd} \rightarrow\ ^{150}\mathrm{Sm}(0_1^+)) \sim 1 \times 10^{20}\ y$$

406.5-keV peak area = 389(121) counts
334.0-keV peak area = 615(144) counts

$$T_{1/2}(^{150}\mathrm{Nd} \rightarrow\ ^{150}\mathrm{Sm}(2_1^+)) \sim 2 \times 10^{20}\ y$$

More statistics is needed

Conclusions

Double-β transitions of ^{150}Nd to excited levels of ^{150}Sm were studied with the help of low-background HPGe γ spectrometry at the **Gran Sasso underground laboratory** of the INFN (Italy).

A **highly purified neodymium-containing** sample with a mass of **2.381 kg** was measured over **5.845 y** in a closed geometry by a **four-crystal HPGe detector system**, that allowed to detect γ quanta with energies 334.0 keV and 406.5 keV, emitted in the 2ν2β decay of ^{150}Nd to the 740.5 keV 0^+_1 excited level of ^{150}Sm both in the 1-dimensional energy spectrum and in coincidence. By analysis of the 334.0-keV and 406.5-keV peaks, and of the coincidences between the γ quanta, the half-life of ^{150}Nd was calculated as:

$$T_{1/2}(^{150}\mathrm{Nd} \rightarrow \ ^{150}\mathrm{Sm}(0_1^+)) = [0.73^{+0.18}_{-0.11}(\mathrm{stat})^{+0.16}_{-0.17}(\mathrm{syst})] \times 10^{20}\ \mathrm{y}$$

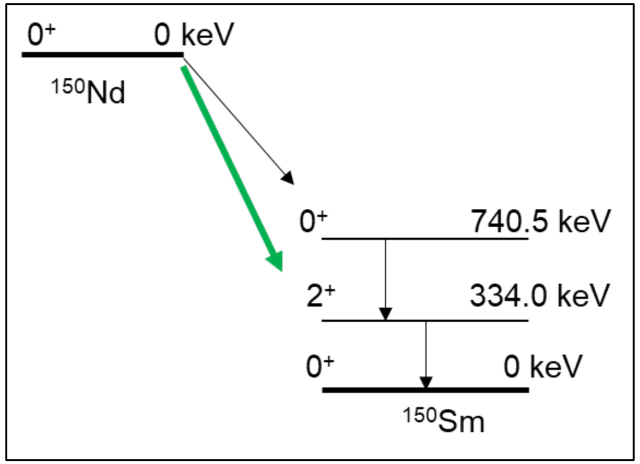
Preliminary

However, **taking into account the excess of events in the 334.0-keV peak**:

$$T_{1/2}(^{150}\mathrm{Nd} \rightarrow \ ^{150}\mathrm{Sm}(0_1^+)) \sim 1 \times 10^{20}\ y$$

$$T_{1/2}(^{150}\mathrm{Nd} \rightarrow \ ^{150}\mathrm{Sm}(2_1^+)) \sim 2 \times 10^{20}\ y$$

More statistics is needed



The theoretical calculations of the ^{150}Nd decay probability are in progress.

Preliminary calculations in the framework of the spherical QRPA multiplied by deformed overlap factors agree the hint