Double beta decay of ^{150}Nd to the excited levels of ^{150}Sm

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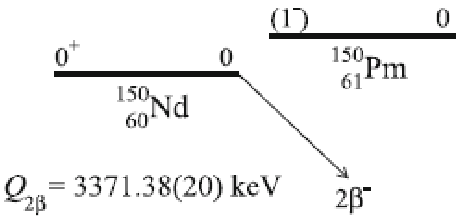
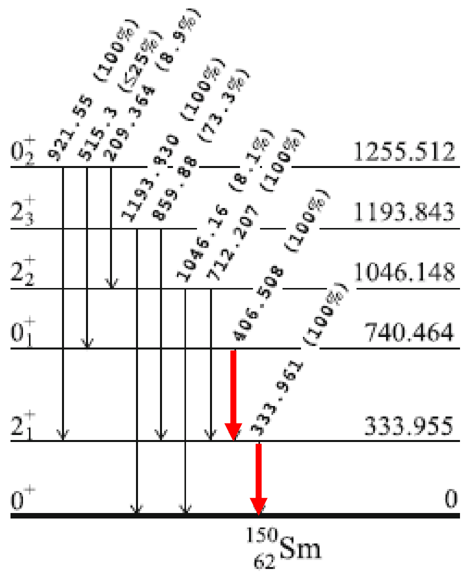
2β decay of ^{150}Nd



δ=5.638(28)%



$T_{1/2}^{2\nu 2\beta \to \text{g.s.}} = 0.93(7) \times 10^{19}$ yr [1]

$T_{1/2}^{2\nu 2\beta \to \text{g.s.}} = 1.16(37) \times 10^{19}$ yr [2]

} 3 experiments

$2\nu 2\beta \to 0_1^+$

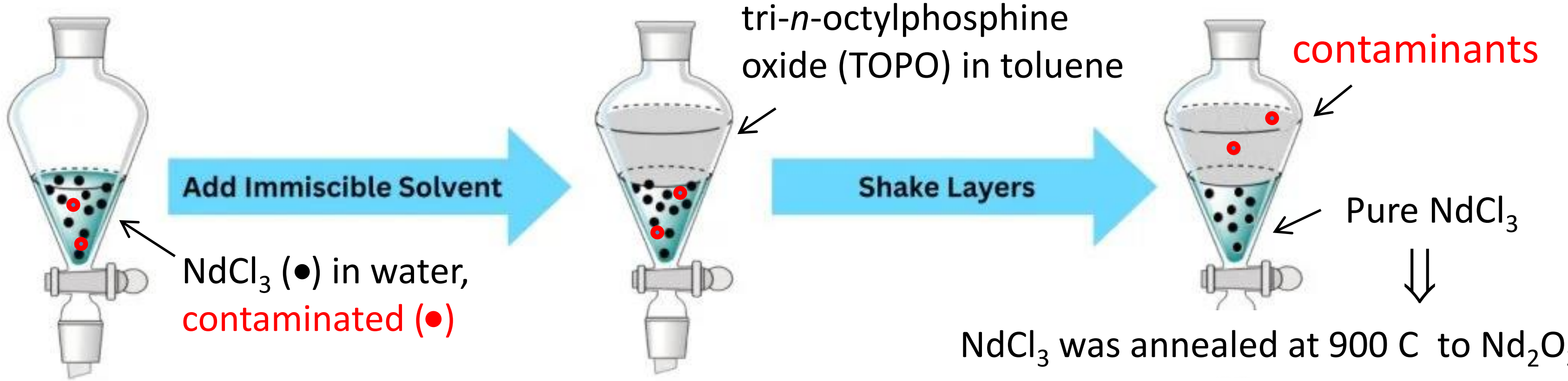
Experiment	$T_{1/2}$ $\times 10^{20}$ yr	Year [Ref]
3.05 kg of Nd_2O_3, HPGe 400cm^3, 1.29 yr	$1.4^{+0.5}_{-0.4}$	2004 [3]
Re-estimation of [3]	$1.33^{+0.45}_{-0.26}$	2009 [4]
50 g of $^{150}Nd_2O_3$ (93.6%) 2 HPGe (304 cm^3 each), 1.76 yr	$1.07^{+0.46}_{-0.26}$	2014 [5]
46.6 g of $^{150}Nd_2O_3$ (91.0%) NEMO-3, 5.25 yr	$1.11^{+0.26}_{-0.21}$	2023 [6]
2.38 kg of Nd_2O_3, 4 HPGe (≈225 cm^3 each), 5.85 yr	$1.03^{+0.38}_{-0.29}$	2025 [7]

[1] A. Barabash, Precise Half-life values for two-neutrino double-b decay: 2020 Review, Universe 6 (2020) 159
[2] B. Pritychenko, V.I. Tretyak, Comprehensive review of 2β decay half-lives, At. Data Nucl. Data Tables. 161 (2025) 101694
[3] A.S. Barabash et al., Double-beta decay of ^{150}Nd to the first 0^+ excited state of ^{150}Sm. JETP Lett. 79, 10 (2004) 52
[4] A.S. Barabash et al., Investigation of $\beta\beta$ decay in ^{150}Nd and ^{148}Nd to the excited states of daughter nuclei. Phys. Rev. C 79 (2009) 045501
[5] M.F. Kidd et al., Two-neutrino double-β decay of ^{150}Nd to excited final states in ^{150}Sm. Phys. Rev. C 90 (2014) 055501 (2014)
[6] X. Aguerre et al., Measurement of the double-β decay of ^{150}Nd to the 0^+_1 excited state of ^{150}Sm in NEMO-3. Eur. Phys. J. C 83 (2023) 1117
[7] A.S. Barabash et al., Double-beta decay of ^{150}Nd to excited levels of ^{150}Sm, Eur. Phys. J. C 85 (2025) 174

Purification of Nd-containing sample

≈3 kg of Nd_2O_3 used in the previous measurements [1] was additionally purified with liquid-liquid extraction. First, the Nd_2O_3 was converted to chloride and dissolved in water:

$$Nd_2O_3 + 6HCl \rightarrow 2NdCl_3 + 3H_2O$$



The yield of recovery of the Nd-containing material after purification and annealing was ≈ 90%

Several analytical methods have been used to measure the concentration of Nd and the presence of elements other than Nd_2O_3: thermogravimetric analysis, coulometric Karl Fischer titration method, ICP-MS, Energy Dispersive X-ray Fluorescence spectrometry, Ion Chromatography, Complexometric titration, and Inductively Coupled Plasma Optical Emission Spectrometry

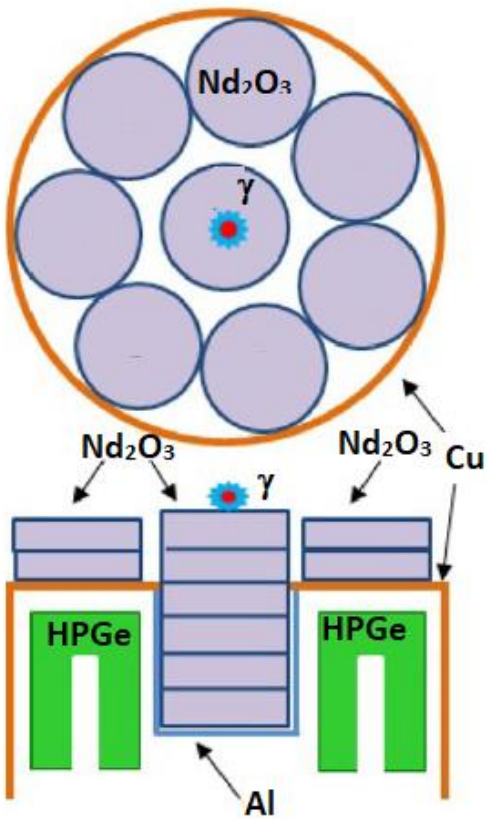
The concentration of Nd is (73.1 ±1.2)% 85.7353(12)% in stoichiometric Nd_2O_3

The sample also contains H_2O, Cl and CO_2 (few %)

The concentration of Eu is <5 ppb

[1] A.S. Barabash et al., Double-beta decay of ^{150}Nd to the first 0^+ excited state of ^{150}Sm. JETP Lett. 79, 10 (2004) 52

Experimental setup

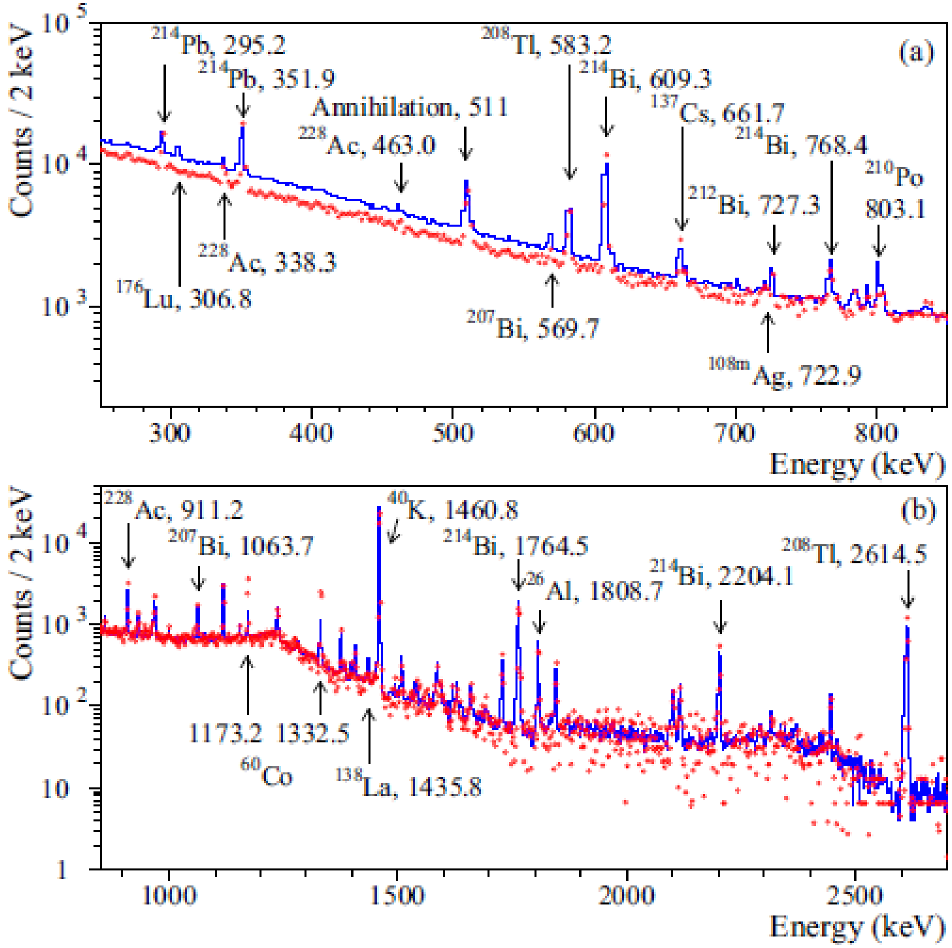


GeMulti detector system
with 4 HPGe ≈225 cm^3 each

2.381 kg of Nd-containing material ⇒
1.74 kg of Nd ⇒
98 g of ^{150}Nd, 4.10 × 10^{23} nuclei of ^{150}Nd

10 cm of high purity copper and a 20-cm-thick layer of lead, enclosed in a Plexiglas box continuously flushed by high-purity nitrogen gas; the STELLA laboratory of the Gran Sasso underground laboratory of INFN (Italy) ~ 3.8 km of water equivalent

Spectrum with the Nd-containing sample and background

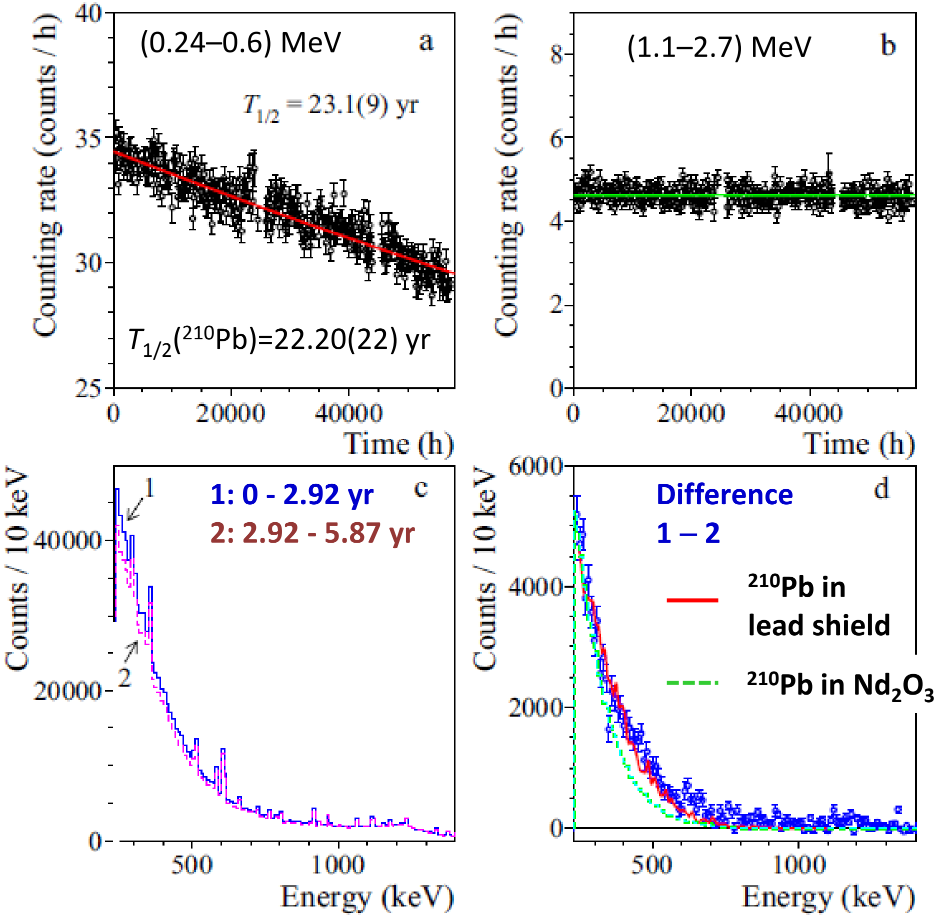


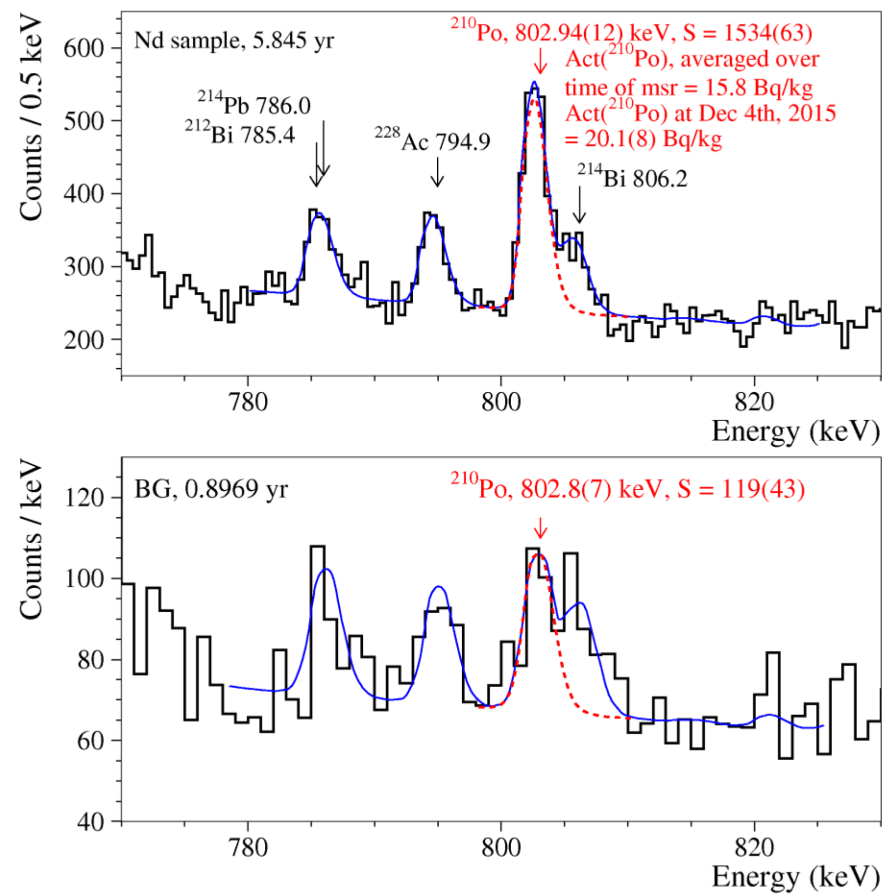
Energy spectra measured with the Nd-containing sample over 5.845 year (solid histogram) and without sample for 0.897 year (normalized to 5.845 year)

^{40}K and nuclides of the ^{232}Th and ^{238}U decay chains. In addition, ^{26}Al, ^{60}Co, ^{108m}Ag, ^{137}Cs, ^{207}Bi γ–ray peaks are observed in both spectra. In the data taken with the sample there are also γ peaks of ^{138}La, ^{176}Lu and some daughters of the ^{235}U decay chain.

The detector-system spectrometric characteristics: energy scale, resolution, and stability were carefully analyzed by using data of 3 calibrations with γ-ray sources and background γ peaks

Detector is sensitive to ^{210}Pb in the lead shield
(despite the low-active lead, and 10-cm layer of copper)





Bremsstrahlung from ^{210}Bi explains the background rate decrease below ~ 1 MeV. Activity of ^{210}Pb in the near layer of the lead shield is 132(2) Bq/kg

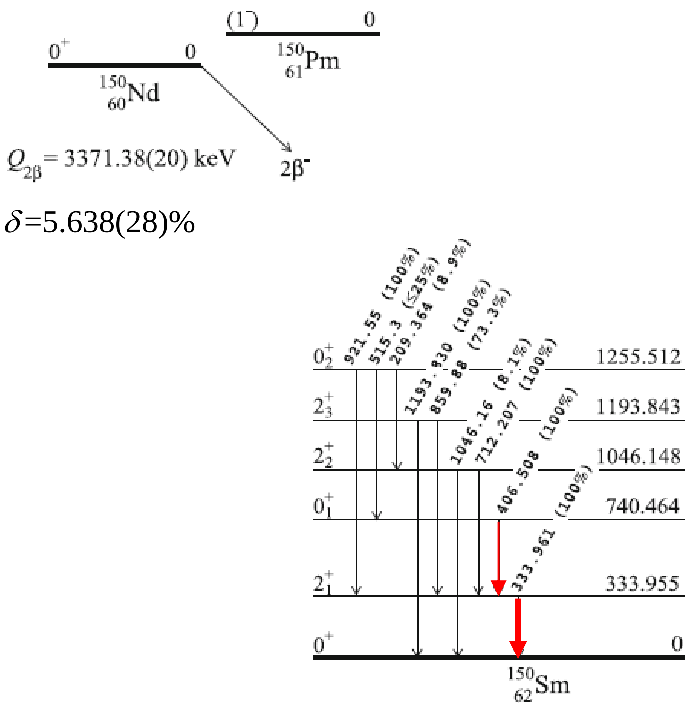
γ peak at 803 keV from *α* decays of ^{210}Po to the first excited level of ^{206}Pb with the absolute intensity 0.00103*(6)*% was detected too

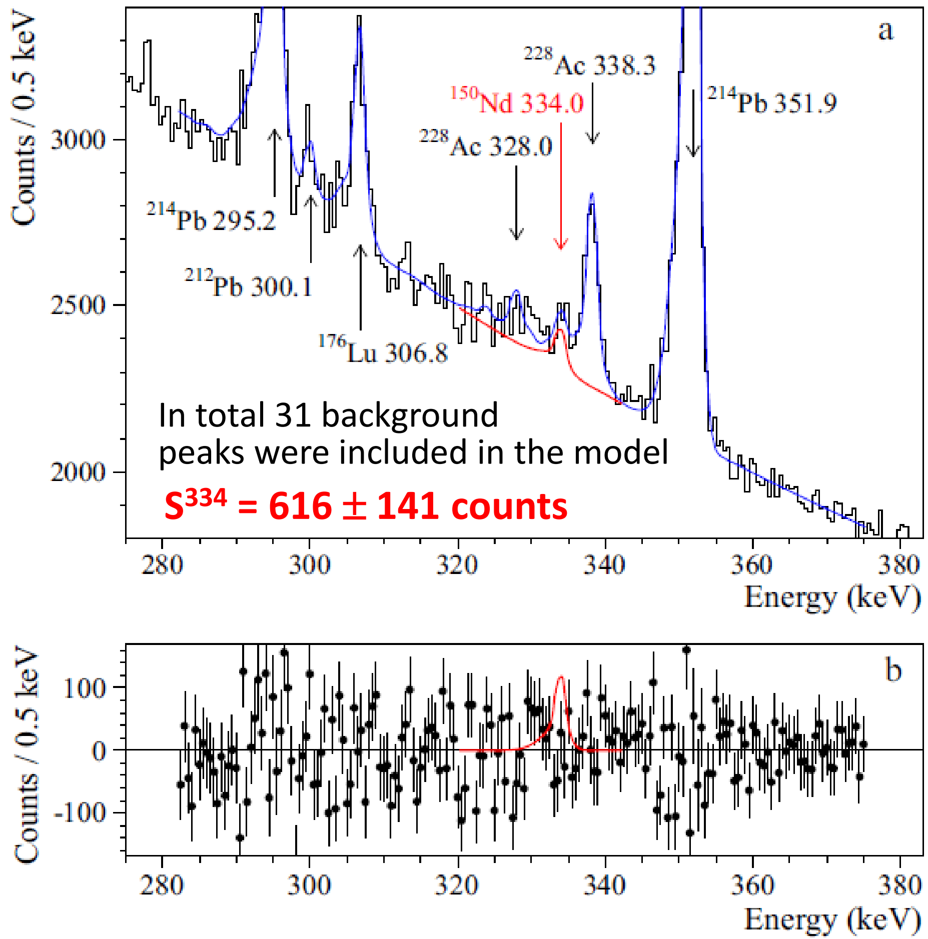
Radioactive contamination of the Nd-containing sample

Chain	Nuclide	Activity (mBq/kg)	
		Before purification	After purification
	^{40}K	16 ± 8	3.4 ± 0.7
	^{138}La		0.095 ± 0.007
	^{150}Eu		≤ 0.037
	^{176}Lu	1.1 ± 0.4	0.30 ± 0.02
^{232}Th	^{228}Ra	≤ 2.1	0.13 ± 0.08
	^{228}Th	≤ 1.3	0.37 ± 0.06
^{235}U	^{235}U	≤ 1.7	0.8 ± 0.2
	^{231}Pa		≤ 0.29
	^{227}Ac		0.46 ± 0.08
^{238}U	^{238}U	≤ 28	≤ 3.8
	^{226}Ra	15 ± 0.8	≤ 0.18
	^{210}Pb		≤ 178

Potassium and Lutetium were reduced by a factor 5, Radium by 80 times

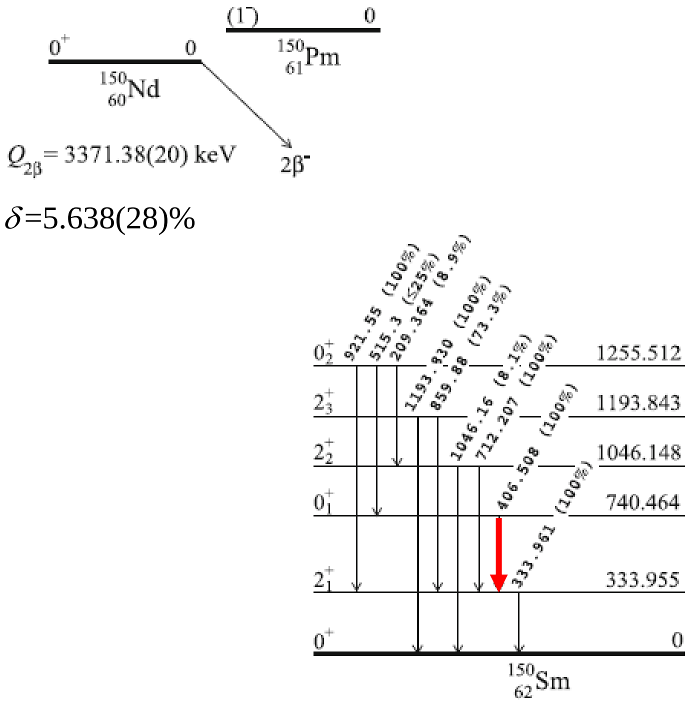
γ peak at 334 keV is clearly observed in 1-dimensional data

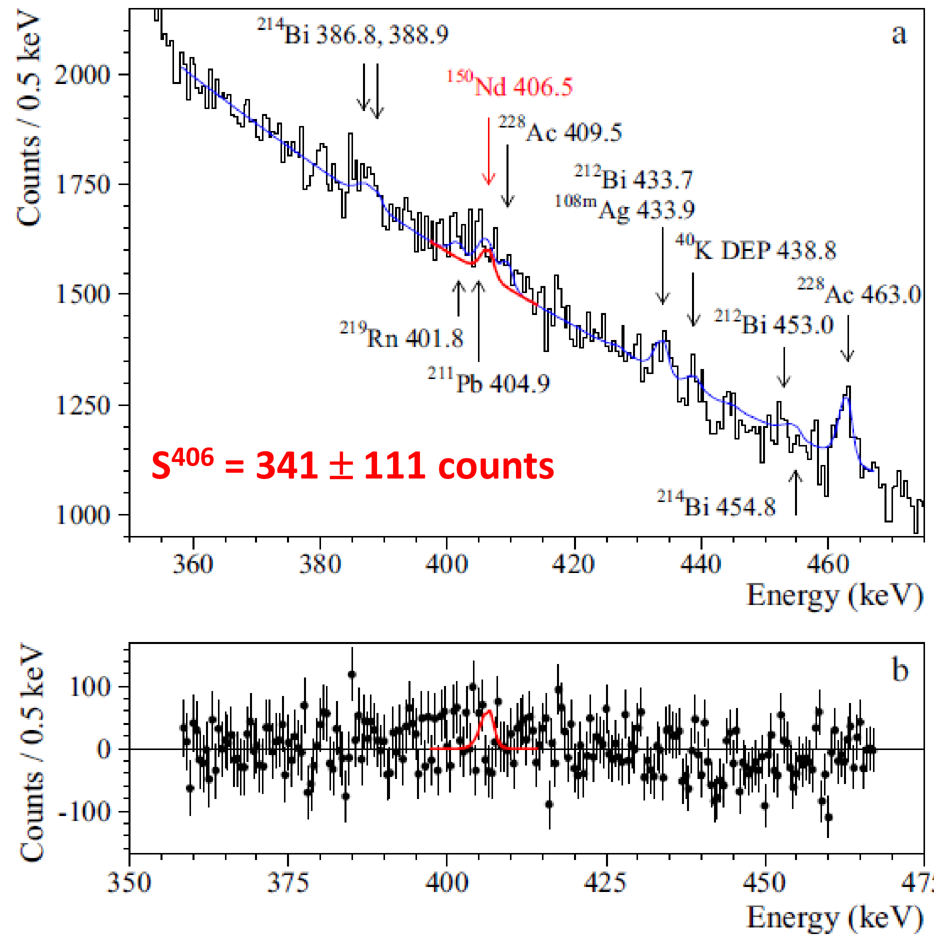




$$T_{1/2}^{334}(\rightarrow 0_1^+) = [0.57^{+0.17}_{-0.11}(\mathrm{stat})^{+0.07}_{-0.08}(\mathrm{syst})]\times 10^{20}\ \mathrm{yr}$$

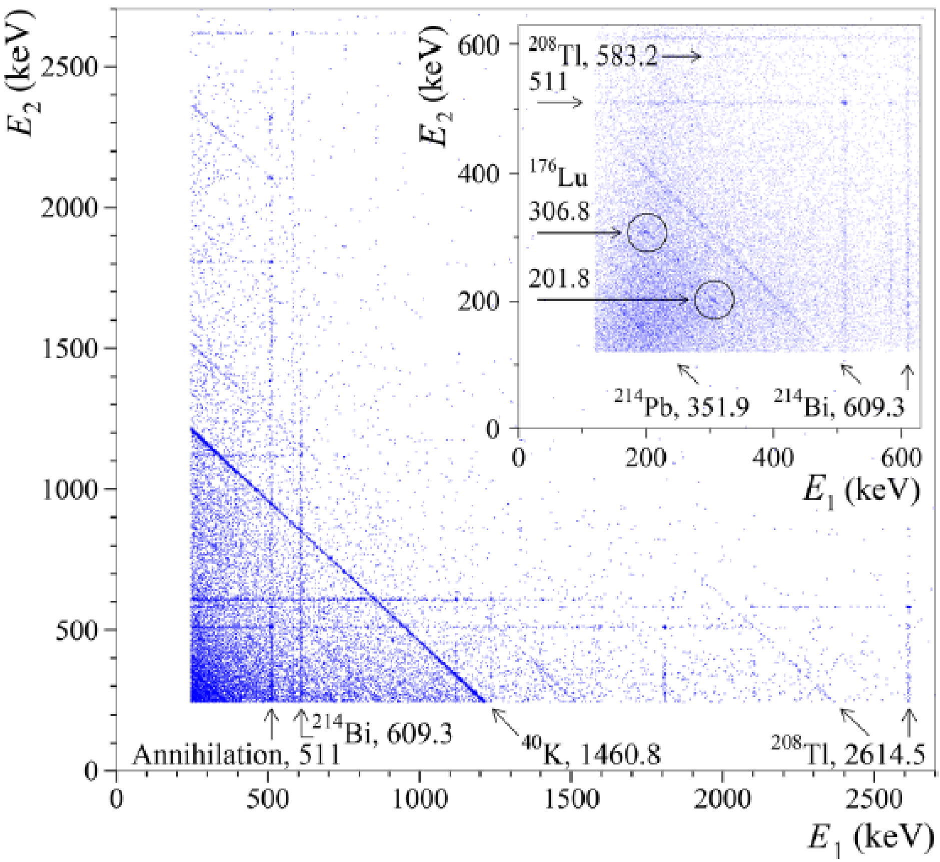
γ peak at 406 keV



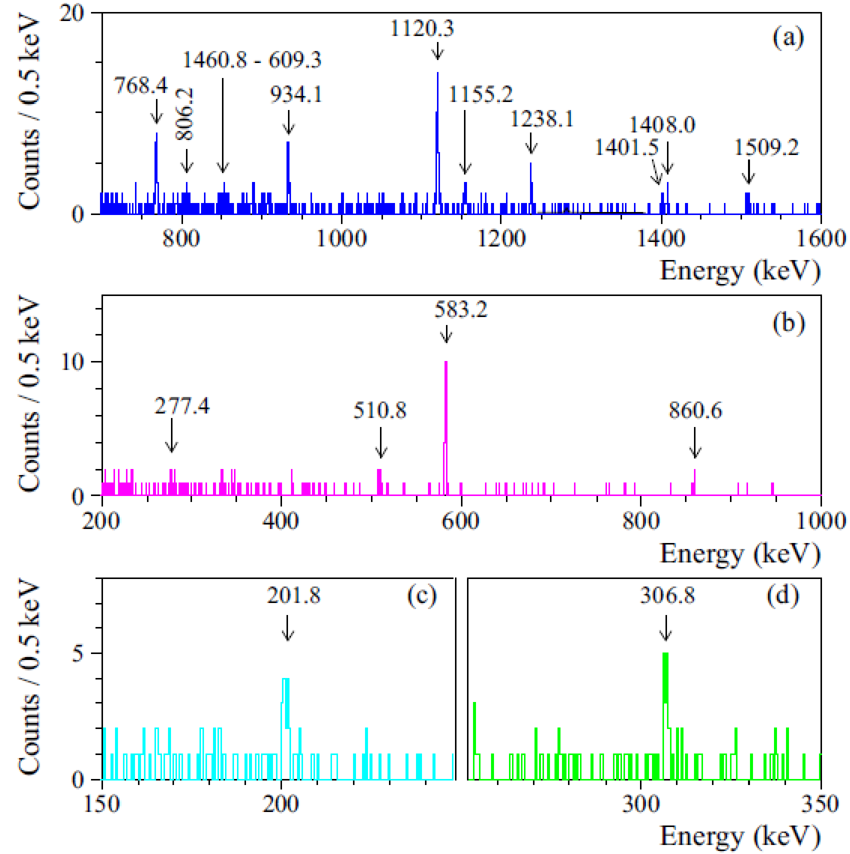


$$T_{1/2}^{406}(\rightarrow 0_1^+) = [1.06_{-0.26}^{+0.51}(\mathrm{stat})_{-0.20}^{+0.10}(\mathrm{syst})]\times 10^{20}\ \mathrm{yr}$$

2-D spectra of events in coincidence



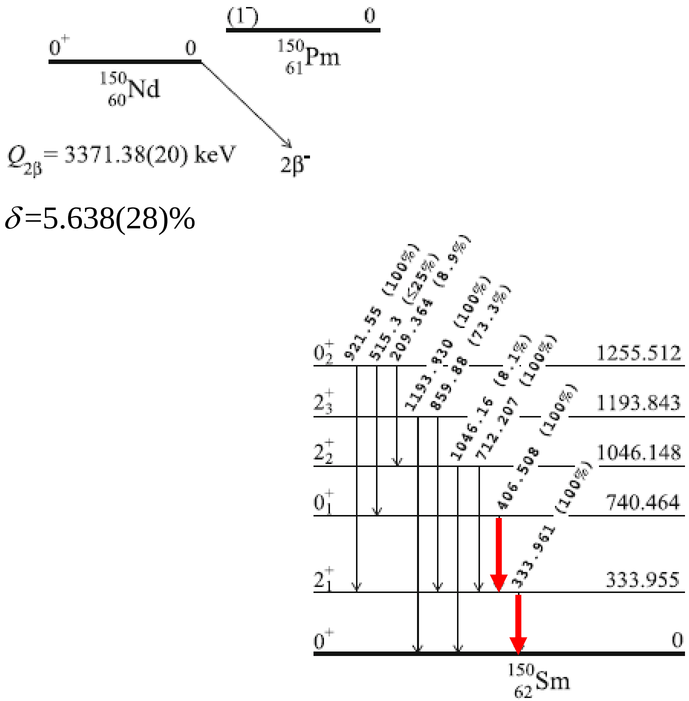
The two-D energy spectrum of events with multiplicity 2 registered in coincidence mode by the HPGe detector system of the Nd-containing sample over 5.845 year

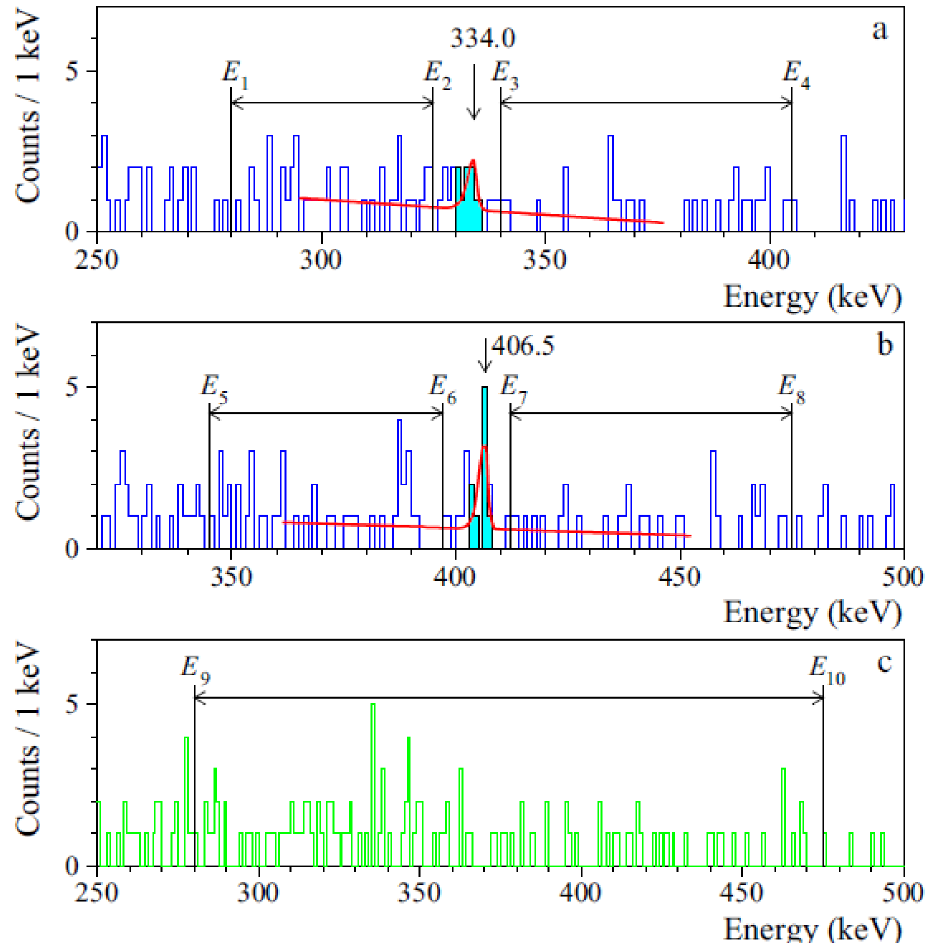


The coincidence spectra when the energy of one detector is $609.3\ \mathrm{keV}\ ^{+3\sigma_R}_{-3\sigma_L}$ [^{214}Bi, (a)], $2165\ \mathrm{keV}\ ^{+3\sigma_R}_{-3\sigma_L}$ [^{208}Tl, (b)], 306.8 keV ± 3σ (c) and $201.8\ \mathrm{keV}\ ^{+3\sigma_R}_{-3\sigma_L}$ (d) [both γ quanta of ^{176}Lu]

The analysis demonstrates the ability of the detector system to detect γ-ray quanta in coincidence

2β decay of ^{150}Nd to 740.5 keV 0_1^+ level of ^{150}Sm





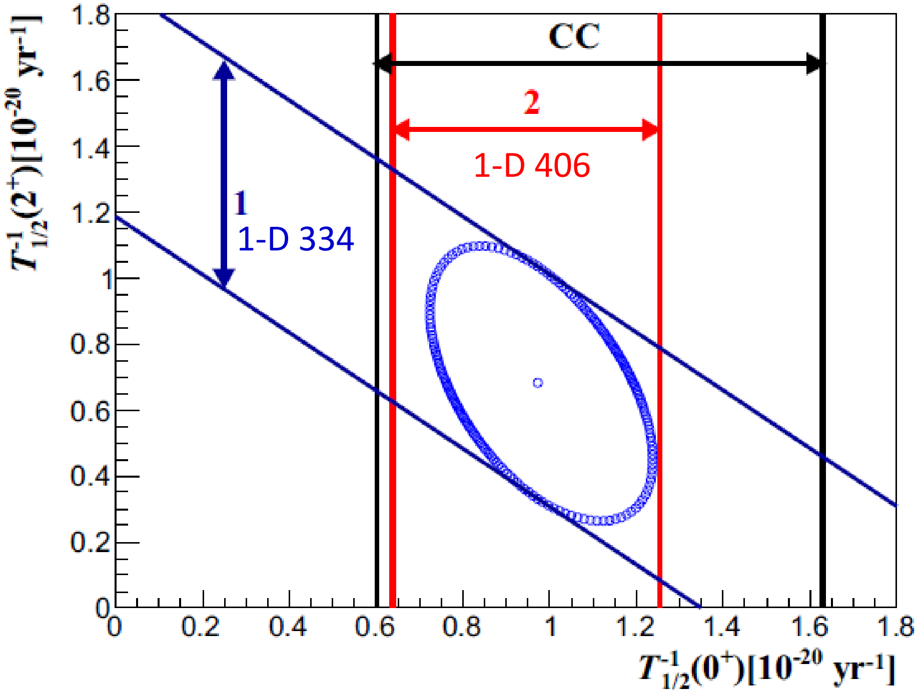
Background: $b = 2.53 \pm 0.21$ counts

Total events observed: $n_0 = 9$ counts

Signal central value: $n_0 - b = 6.47$ counts $\Rightarrow$ $T_{1/2}^{334\&406}(\rightarrow 0_1^+) = [0.98^{+0.69}_{-0.36}(\text{stat})^{+0.13}_{-0.12}(\text{syst})]\times 10^{20}$ yr

Combination of 1-D (334 keV, 406 keV) and CC $\Rightarrow$ $T_{1/2}(\rightarrow 0_1^+) = [0.83^{+0.18}_{-0.13}(\text{stat})^{+0.16}_{-0.19}(\text{syst})]\times 10^{20}$ yr

Maximum likelihood procedure for 1-D and CC, including the possible contribution of the decay to the 2_1^+ level



Assuming the difference S_{334} - S_{406} = 275 ± 179 counts is due to transition to the 2_1^+ level,

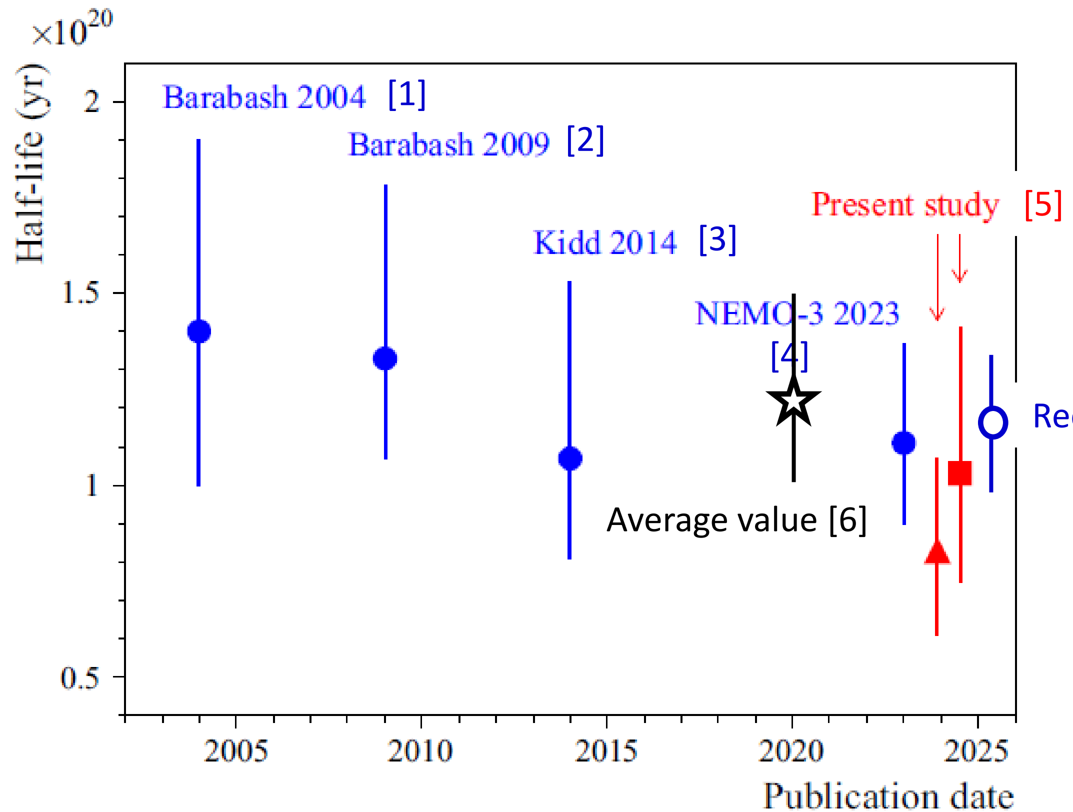
$$T_{1/2}(\rightarrow 2_1^+) = [1.5^{+2.3}_{-0.6}(\text{stat}) \pm 0.4(\text{syst})] \times 10^{20}\ \text{yr},$$

The best limit $T_{1/2}$ > 2.42 x 10^{20} yr [1]

$$T_{1/2}(\rightarrow 0_1^+) = [1.03^{+0.35}_{-0.22}(\text{stat})^{+0.16}_{-0.19}(\text{syst})] \times 10^{20}\ \text{yr}.$$

[1] X. Aguerre et al., Measurement of the double-β decay of 150 Nd to the 0 1+ excited state of 150 Sm in NEMO-3, Eur. Phys. J. C 83 (2023) 1117

A historical perspective of the 2ν2β half-life of $^{150}Nd(\rightarrow 0^+_1)$



[1] A.S. Barabash et al., Double-beta decay of ^{150}Nd to the first 0^+ excited state of ^{150}Sm. JETP Lett. 79, 10 (2004) 52
[2] A.S. Barabash et al., Investigation of *ββ* decay in ^{150}Nd and ^{148}Nd to the excited states of daughter nuclei. Phys. Rev. C 79 (2009) 045501
[3] M.F. Kidd et al., Two-neutrino double-*β* decay of ^{150}Nd to excited final states in ^{150}Sm. Phys. Rev. C 90 (2014) 055501 (2014)
[4] X. Aguerre et al., Measurement of the double-*β* decay of ^{150}Nd to the 0^+_1 excited state of ^{150}Sm in NEMO-3. Eur. Phys. J. C 83 (2023) 1117
[5] A.S. Barabash et al., Double-beta decay of ^{150}Nd to excited levels of ^{150}Sm, Eur. Phys. J. C 85 (2025) 174
[6] A. Barabash, Precise Half-life values for two-neutrino double-b decay: 2020 Review, Universe 6 (2020) 159
[7] B. Pritychenko, V.I. Tretyak, Comprehensive review of 2β decay half-lives, At. Data Nucl. Data Tables. 161 (2025) 101694

Theoretical calculations of ^{150}Nd 2β-decay probability

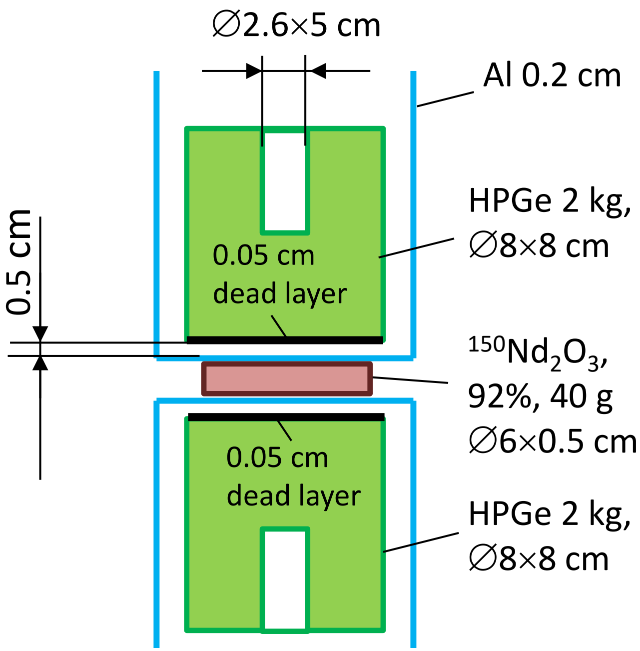
Probabilities of ^{150}Nd 2ν2β-transitions to the 0^+_1 and 2^+_1 excited levels were calculated in the framework of proton-neutron QRPA with isospin restoration combined with like-nucleon QRPA for a description of excited states in the final nuclei.

Transition $^{150}Nd \rightarrow ^{150}Sm$	g_A^{eff}	Theoretical $T_{1/2}$ (yr)	Experiment (yr)
$0^+ \rightarrow 0^+$	1.276	9.34×10^{18}	$9.3(7) \times 10^{18}$ yr [1]
	0.957	9.31×10^{18}	
$0^+ \rightarrow 0^+_1$	1.276	0.43×10^{20}	$1.03^{+0.38}_{-0.29} \times 10^{20}$
	0.957	1.19×10^{20}	
$0^+ \rightarrow 2^+_1$	1.276	1.32×10^{20} *)	$1.5^{+2.3}_{-0.7} \times 10^{20}$
	0.957	4.18×10^{20}	

*) This is an interesting case when theorists calculated their value without knowing the experimental data. January 26, 2023 4:18 PM Dong-Liang Fang wrote to Fedor Simkovic: "*I now finished the calculation for the decay 2+ for Nd with spherical QRPA multiplied by deformed overlap factors. The results are not so good, they are generally too large.*"

[1] X. Aguerre et al., Measurement of the double-β-decay of ^{150}Nd to the 0^+_1 excited state of ^{150}Sm in NEMO-3, Eur. Phys. J. C 83 (2023) 1117.

Improvement of the experimental sensitivity



The detector system is surrounded by copper shield

Detection efficiency to 334 keV and 406 keV γ-ray quanta in the decay to the 740.5 keV 0_1^+ level:

9.9% and 9.7% *)

Detection efficiency to 334 keV and 406 keV γ-ray quanta in the decay to the 740.5 keV 0_1^+ level in coincidence:

1.5% **)

Detection efficiency to 334 keV γ-ray quanta in the decay to the 334.0 keV 2_1^+ level:

19% **)

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*) 2.12% and 2.17% in the present work
**) 0.0426%
***) 2.41%

Assuming a background similar to the GeMulti detector system, the $T_{1/2}(\rightarrow 0_1^+) = 1\times10^{20}$ yr can be measured over 3 year with ~20% precision both in 1-D and CC modes. The decay to the 2_1^+ 334 keV level with $T_{1/2} = 4\times10^{20}$ yr could be observed with 3σ precision.
A similar approach was used previously for ^{100}Mo [1,2], ^{150}Nd [3] (however, 1-D spectra were not analyzed), and ^{96}Zr [4].

[1] L. De Braeckeleer et al., Phys. Rev. Lett. 86 (2001) 3510. [2] M. J. Hornish et al., Phys. Rev. C 74 (2006) 044314. [3] M. F. Kidd et. al., Phys. Rev. C 90 (2014) 055501. [4] S. W. Finch and W. Tornow, Phys. Rev. C 92 (2015) 045501.

Conclusions and prospects

1. The $2\nu2\beta$ decay of ^{150}Nd to the first 740.5 keV 0^+ level of ^{150}Sm was detected in both one-dimensional and coincidence spectra:

$$T_{1/2}^{2\nu2\beta\to0_1^+} = [0.83^{+0.18}_{-0.13}(\text{stat})^{+0.16}_{-0.19}(\text{syst})]\times10^{20}\ \text{yr.}$$

2. Interpreting some excess of the 334.0-keV peak as an indication of the $2\nu2\beta$ transition to the 334.0 keV 2^+ level with the half-life:

$$T_{1/2}^{2\nu2\beta\to2_1^+} = [1.5^{+2.3}_{-0.6}(\text{stat})\pm0.4(\text{syst})]\times10^{20}\ \text{yr,}$$

$$T_{1/2}^{2\nu2\beta\to0_1^+} = [1.03^{+0.35}_{-0.22}(\text{stat})^{+0.16}_{-0.19}(\text{syst})]\times10^{20}\ \text{yr.}$$

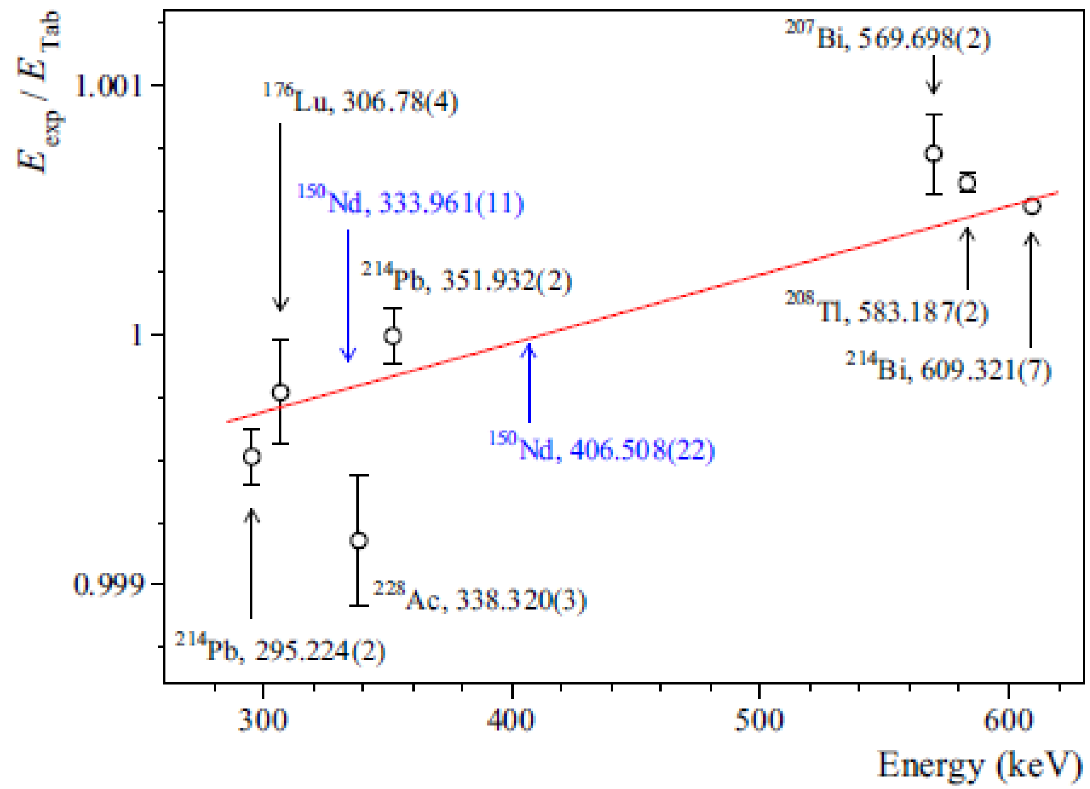
3. The half-lives for the decays to the 0_1^+ and 2_1^+ levels agree with the existing experimental values and limits, and with the half-life range calculated in the framework of proton-neutron QRPA with isospin restoration combined with like-nucleon QRPA for a description of excited states in the final nuclei.
4. The experimental sensitivity can be improved with ~40 g of enriched ^{150}Nd sample between two large volume ultra-low background HPGe detectors.

[1] A.S. Barabash et al., Double-beta decay of ^{150}Nd to excited levels of ^{150}Sm, Eur. Phys. J. C 85 (2025) 174.*)

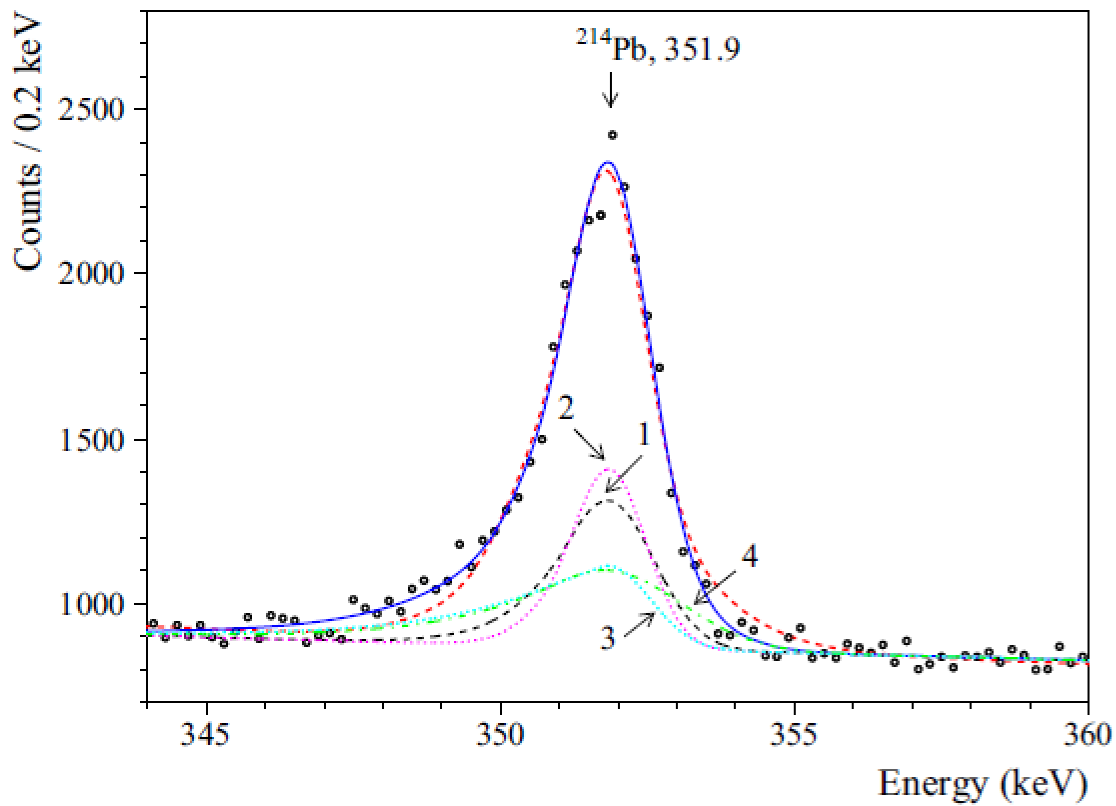
*) The experiment was proposed in 2008; thus, it was a 17-year experiment

Backup slides

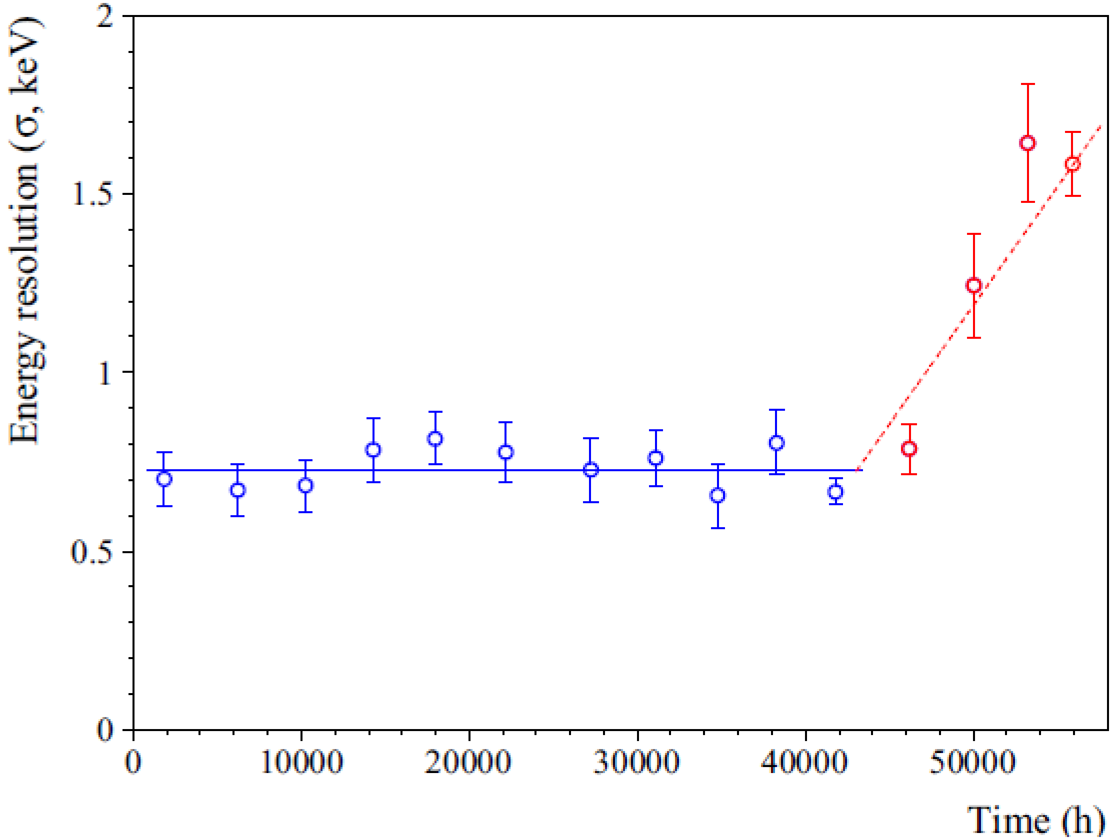
Accuracy of the energy scale over 5.845 yr of data taking



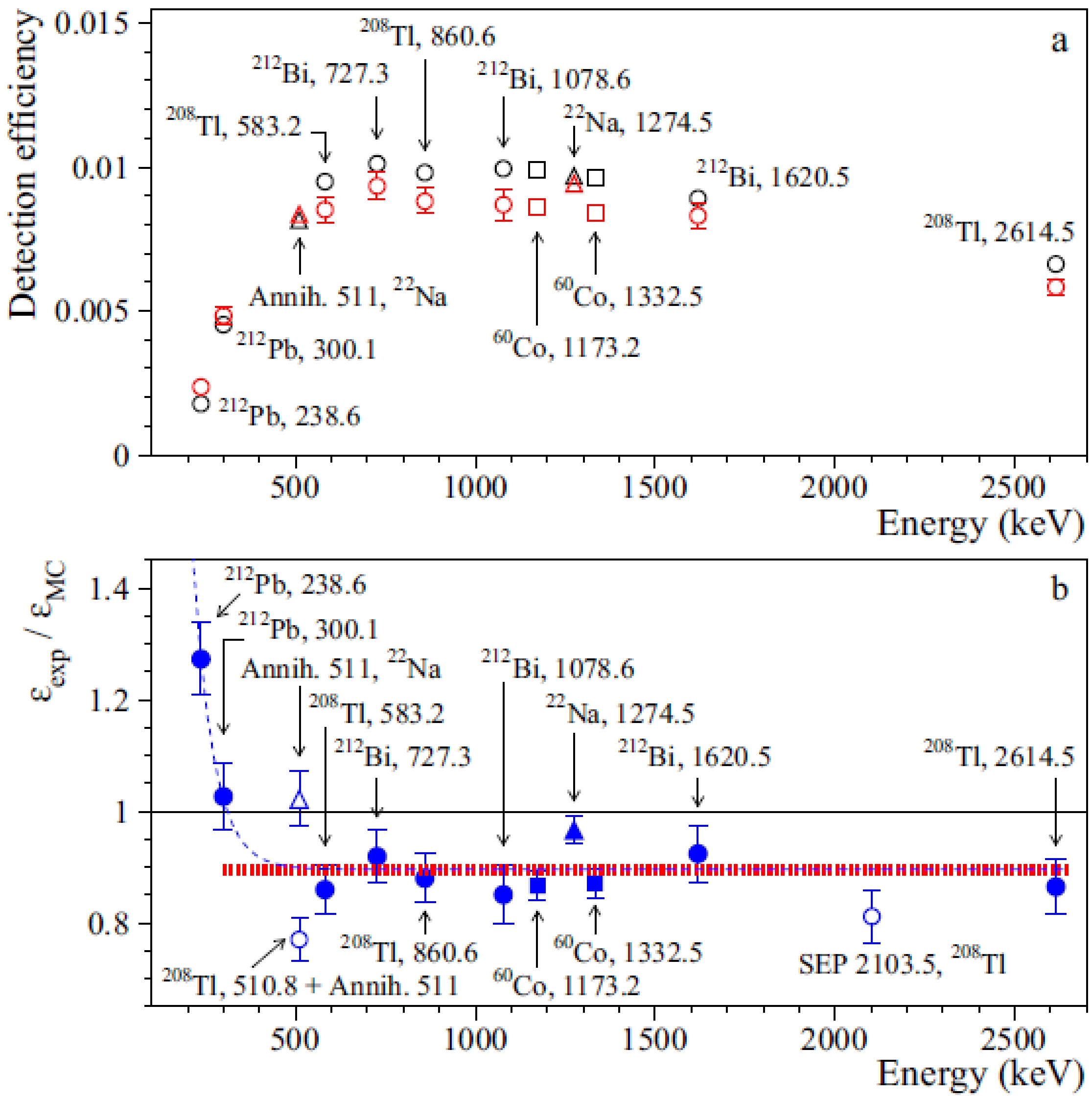
Asymmetry of γ peaks



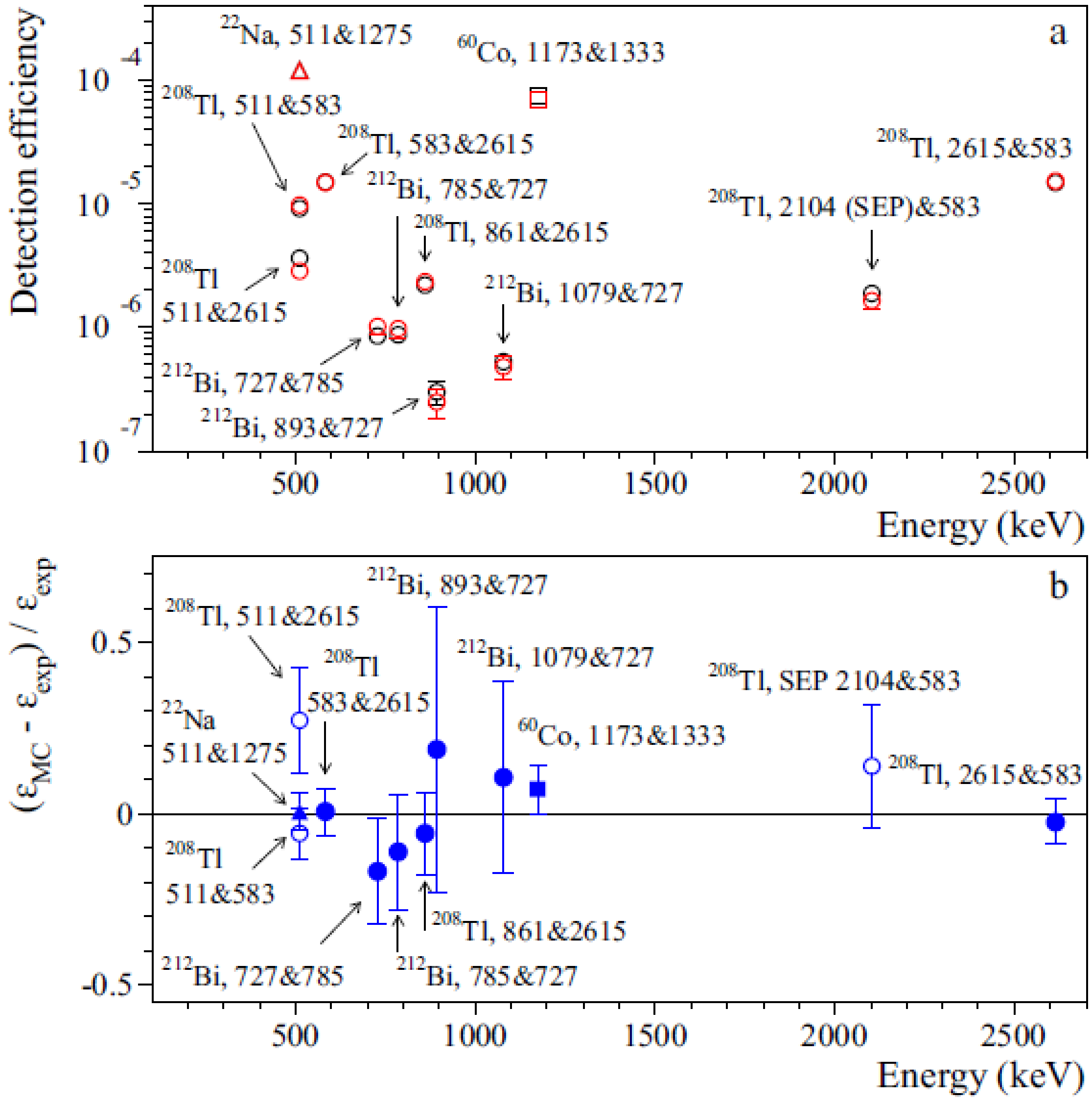
Increase of the energy resolution of one of the detectors



Detection efficiency in 1-D mode



Detection efficiency in coincidence mode



Dependence of $T_{1/2}(\rightarrow 0_1^+)$ on the energy interval of CC selection