Study of 2β decays of ^{150}Nd

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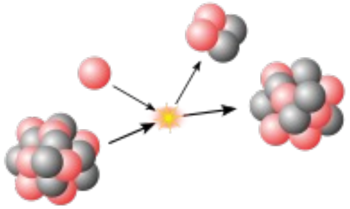
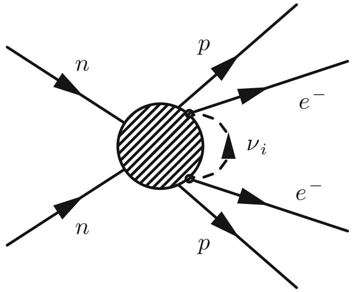


The 2β decay

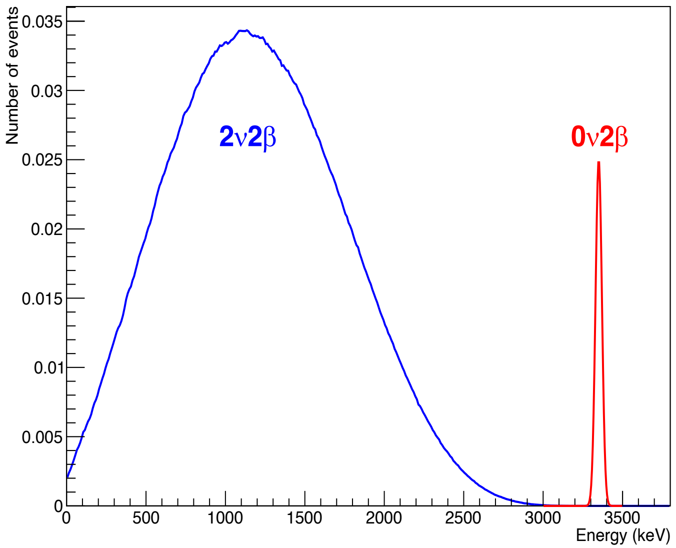


(Neutrino oscillations) ↓

- **2ν2β** decay is a rare process allowed in the SM → lepton number L conserved
- **0ν2β**, if observed, could open a new window beyond the SM → L violated ($\Delta L = 2$) → massive Majorana neutrino

$$
\begin{aligned}
2\nu2\beta^- &: \quad {}^A_Z X \rightarrow {}^A_{Z+2}Y + 2e^- + 2\bar{\nu}_e \\
2\nu2\beta^+ &: \quad {}^A_Z X \rightarrow {}^A_{Z-2}Y + 2e^+ + 2\nu_e \\
2\nu\varepsilon\beta^+ &: \quad e^- + {}^A_Z X \rightarrow {}^A_{Z-2}Y + e^+ + 2\nu_e \\
2\nu2\varepsilon &: \quad 2e^- + {}^A_Z X \rightarrow {}^A_{Z-2}Y + 2\nu_e
\end{aligned}
$$

$$
\begin{aligned}
0\nu2\beta^- &: \quad {}^A_Z X \rightarrow {}^A_{Z+2}Y + 2e^- \\
0\nu2\beta^+ &: \quad {}^A_Z X \rightarrow {}^A_{Z-2}Y + 2e^+ \\
0\nu\varepsilon\beta^+ &: \quad e^- + {}^A_Z X \rightarrow {}^A_{Z-2}Y + e^+ \\
0\nu2\varepsilon &: \quad 2e^- + {}^A_Z X \rightarrow {}^A_{Z-2}Y + \gamma
\end{aligned}
$$

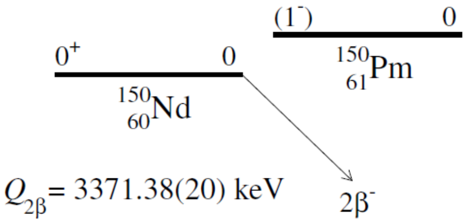


Current sensitivity for **2ν2β⁻** decay: $T_{1/2} \sim 10^{18}$-10^{24} yr; for **0ν2β⁻** : $T_{1/2} > 10^{24}$ - 10^{26} yr

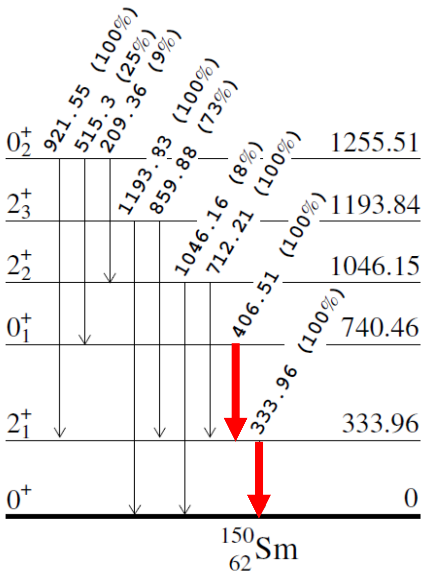
$$
(T^{0\nu}_{1/2})^{-1} = g_A^4 G^{0\nu}(Q,Z) \left| M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2} M^{0\nu}_F \right|^2 |m_{\beta\beta}|^2
$$

where: $m_{\beta\beta} = \sum_i U^2_{ei} m_i$

2β decay of ^{150}Nd



δ= 5.638 %



Experiments to search for $2\nu2\beta \rightarrow 0_1^+$	$T_{1/2}$,× 10^{20} yr	Year [Ref.]
Modane underground laboratory (4800 m w.e.), HPGe 400 cm^3, 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 HPGe (~304 cm^3 each one), 50 g $^{150}Nd_2O_3$ (δ = 93.6%), 1.76 yr, coincidence spectrum	$1.07^{+0.46}_{-0.26}$	2014 [3]
Modane underground laboratory (4800 m w.e.), NEMO-3 detector, 47 g foil of $^{150}Nd_2O_3$ (δ = 91.0 %), 5.25 yr, tracking-calorimetry	$1.11^{+0.26}_{-0.21}$	2023 [4]
LNGS, 2.38 kg of Nd_2O_3, 4 HPGe (≈225 cm^3 each), 5.85 yr	$\mathbf{1.03^{+0.38}_{-0.29}}$	**2025 [5]**

$$\mathbf{2\nu2\beta \rightarrow g.s.:}\ T_{1/2} = 0.93(7)\times10^{19}\ \text{yr}\ \ [6]$$
$$T_{1/2} = 1.16(37)\times10^{19}\ \text{yr}\ \ [7]$$

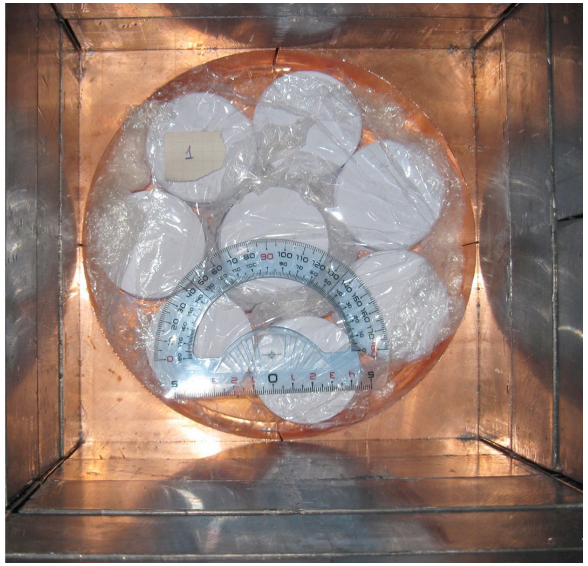
} 3 experiments

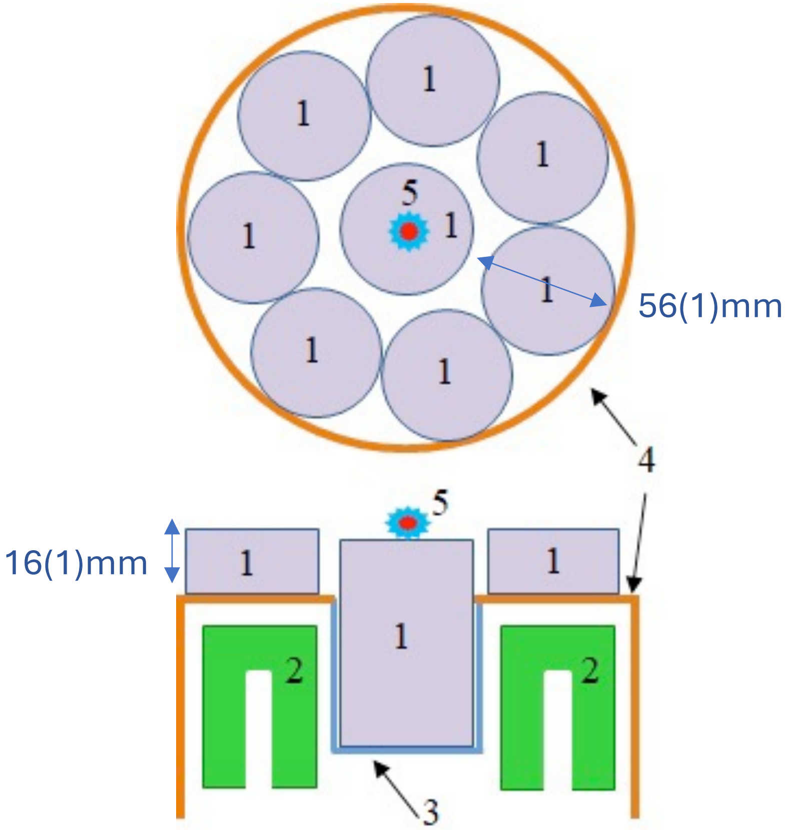
[1] A.S. Barabash et al., Phys. Atom. Nucl. 67 (2004) 1216.
[2] A.S. Barabash et al., Phys. Rev. C 79 (2009) 045501.
[3] M.F. Kidd et al., Phys. Rev. C 90 (2014) 055501.
[4] X. Aguerre et al., Eur. Phys. J. C 83 (2023) 1117.
[5] **A.S. Barabash et al., Eur. Phys. J. C 85 (2025) 174.**
[6] A. Barabash, Universe 6 (2020) 159.
[7] B. Pritychenko, V.I. Tretyak, At. Data Nucl. Data Tables. 161 (2025) 101694.

Eur. Phys. J. C 85 (2025) 174

Experimental Setup

- **2.381 kg Nd_2O_3** sample (average density ~2.84 g/cm^3), used in previous experiment [1], additionally purified [2].
- **4 HPGe** detectors (≃225 cm^3 each) in a cryostat with cylindrical well in the center. In **STELLA laboratory of Gran Sasso National Laboratory (LNGS), Italy.**
- **Shield**: high-purity copper (10 cm), lead (20 cm).
- **Plexiglas container** flushed with high-purity nitrogen gas to remove radon.



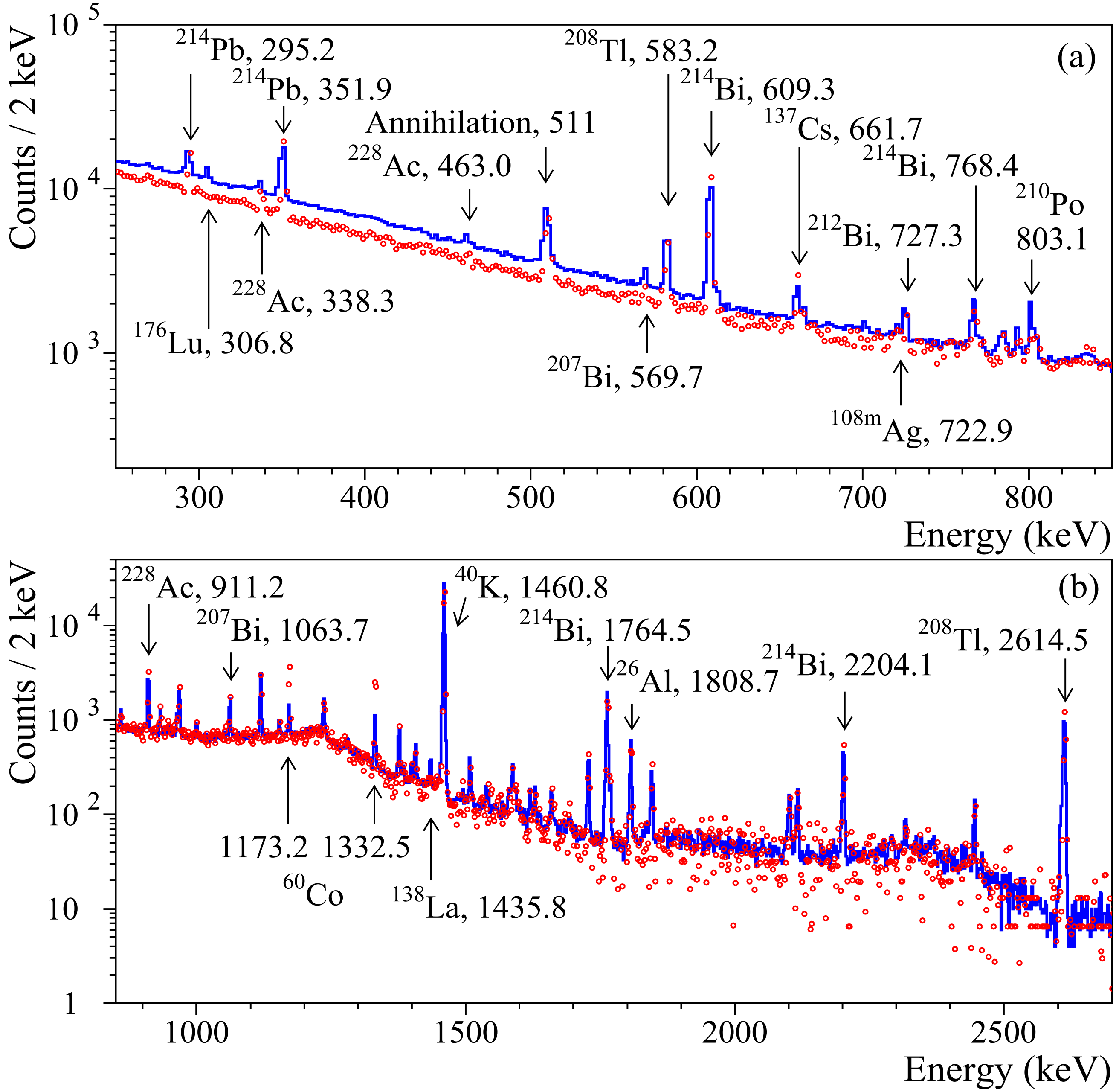


Schematic view of the set-up with Nd-containing source samples (1) installed in the HPGe detector system: (2) coaxial HPGe detectors, (3) aluminium cup of the detector system endcap, (4) copper part of the endcap, (5) position of radioactive γ sources during the calibration campaign.

[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 yr (blue)** and **without sample** for 0.8969 yr (normalized to 5.845 yr, **red**) by the low-background **HPGe-detector system**. The energy of the γ peaks is in keV.



Radioactive contamination of the Nd_2O_3 sample

- The peaks in the spectra 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 both in the data with and without sample.

- Also, γ peaks of lanthanides ^{176}Lu (306.8 keV) and ^{138}La (1435.8 keV) were observed in the spectrum with the Nd_2O_3 sample.

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

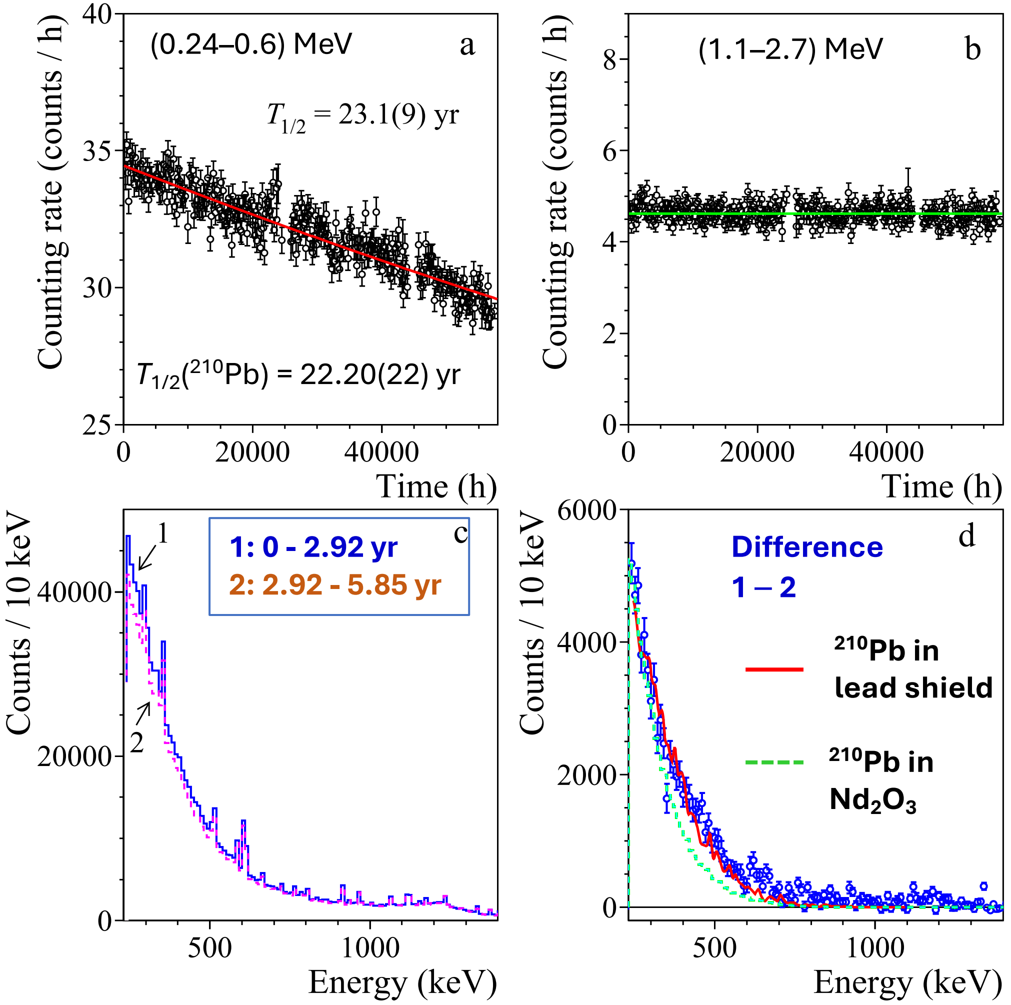
^{138}La: 0.095(7) mBq/kg
^{176}Lu: 0.30(2) mBq/kg

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

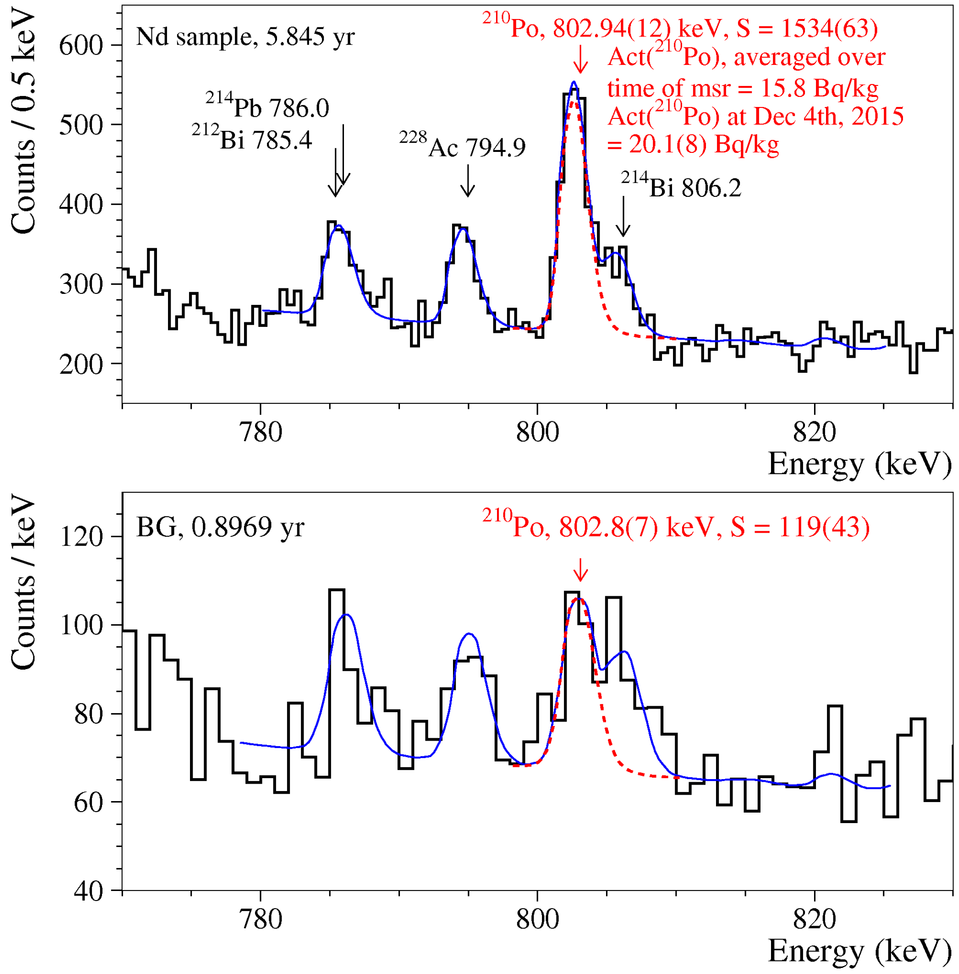
K and Lu were reduced by a factor 5, Ra by 80 times.

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

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



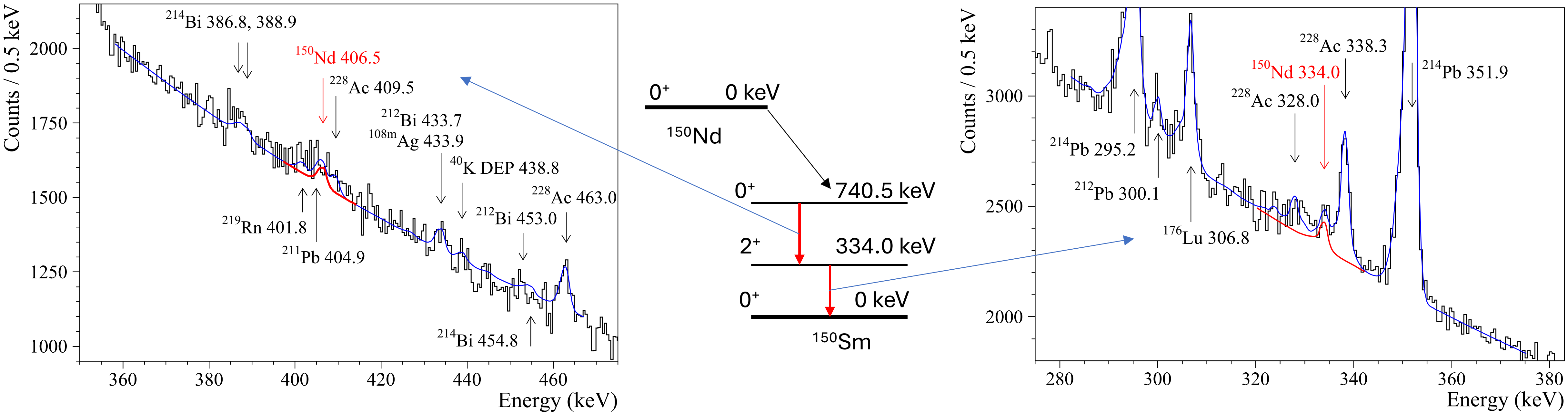
Bremsstrahlung from ^{210}Bi explains the background rate decrease below ~ 1 MeV. Activity of ^{210}Pb in the near layer of the lead shield is 132(2) Bq/kg.



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.

Eur. Phys. J. C 85 (2025) 174

Energy spectrum in the ROI - 1D spectra



406.5-keV peak area = 341(111) counts

χ^2/n.d.f. = 221/205 = 1.08

334.0-keV peak area = 616(141) counts

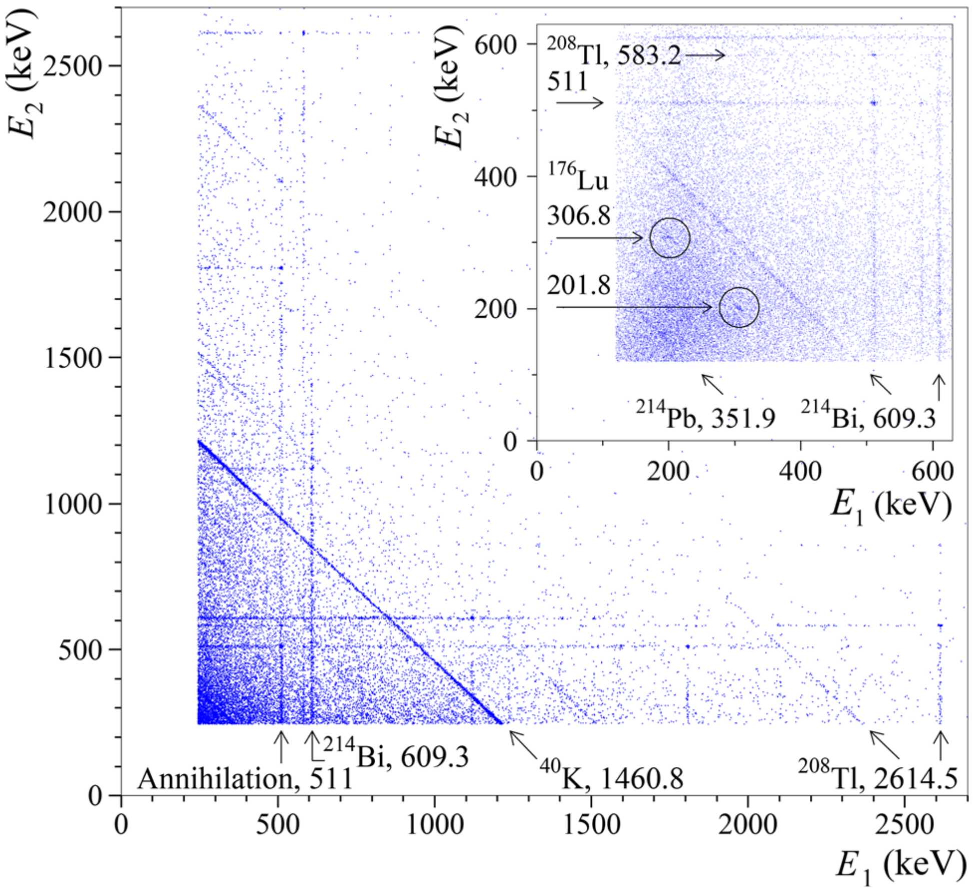
χ^2/n.d.f. = 227/175 = 1.29

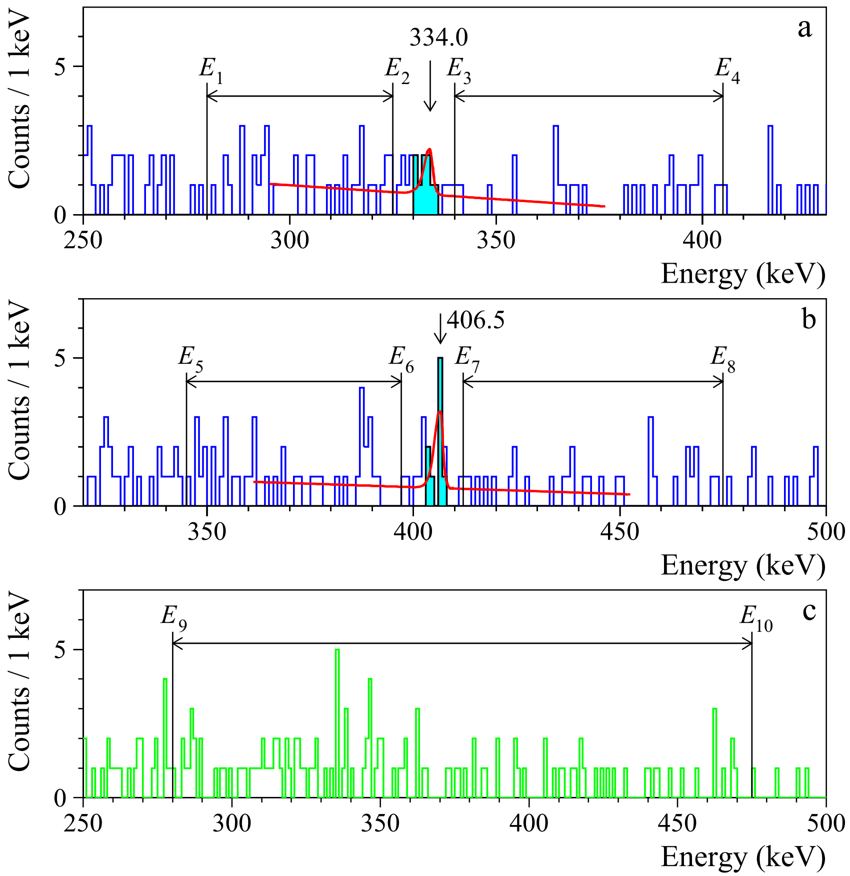
$$T_{1/2}^{406}\left({}^{150}\mathrm{Nd} \rightarrow {}^{150}\mathrm{Sm}(0_1^+)\right) = [1.06^{+0.51}_{-0.26}(\mathrm{stat})^{+0.10}_{-0.20}(\mathrm{syst})]\times 10^{20}\ \mathrm{yr}$$

$$T_{1/2}^{334}\left({}^{150}\mathrm{Nd} \rightarrow {}^{150}\mathrm{Sm}(0_1^+)\right) = [0.57^{+0.17}_{-0.11}(\mathrm{stat})^{+0.07}_{-0.08}(\mathrm{syst})]\times 10^{20}\ \mathrm{yr}$$

Eur. Phys. J. C 85 (2025) 174

Coincidence spectrum in 2 HPGe Detectors





Background:

b = 2.53 ± 0.21 counts

Total events observed:

n_0 = 9 counts

Signal central value:

$n_0 - b$ = 6.47 counts

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.

$$T_{1/2}^{334\&406}\left(^{150}\mathrm{Nd} \rightarrow {}^{150}\mathrm{Sm}(0_1^+)\right) = [0.98^{+0.69}_{-0.36}(\mathrm{stat})^{+0.13}_{-0.12}(\mathrm{syst})] \times 10^{20}\ \mathrm{yr}$$

Combination of 1-D (334 keV, 406 keV) and CC:

$$\boldsymbol{T_{1/2}^{334\&406} = [0.83^{+0.18}_{-0.13}(\mathrm{stat})^{+0.16}_{-0.19}(\mathrm{syst})] \times 10^{20}\ \mathrm{yr}}$$

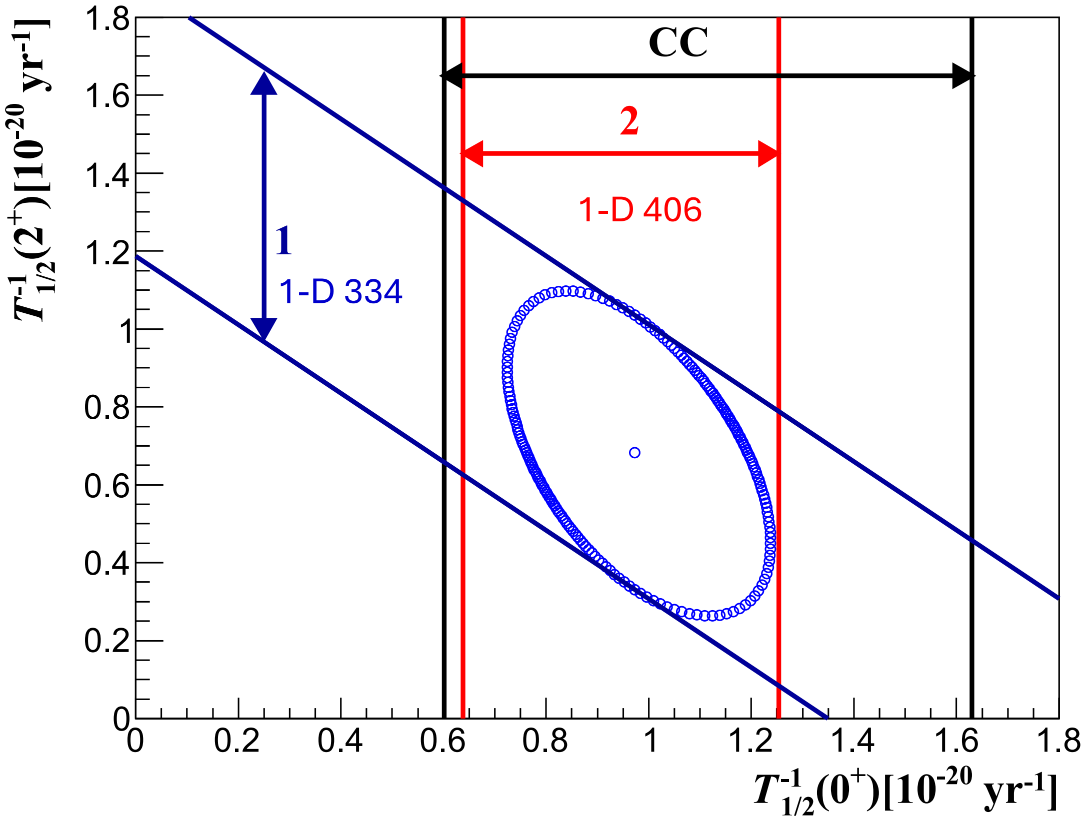
Maximum likelihood procedure for 1-D and CC, including the possible contribution of the decay to the 2_1^+ level

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

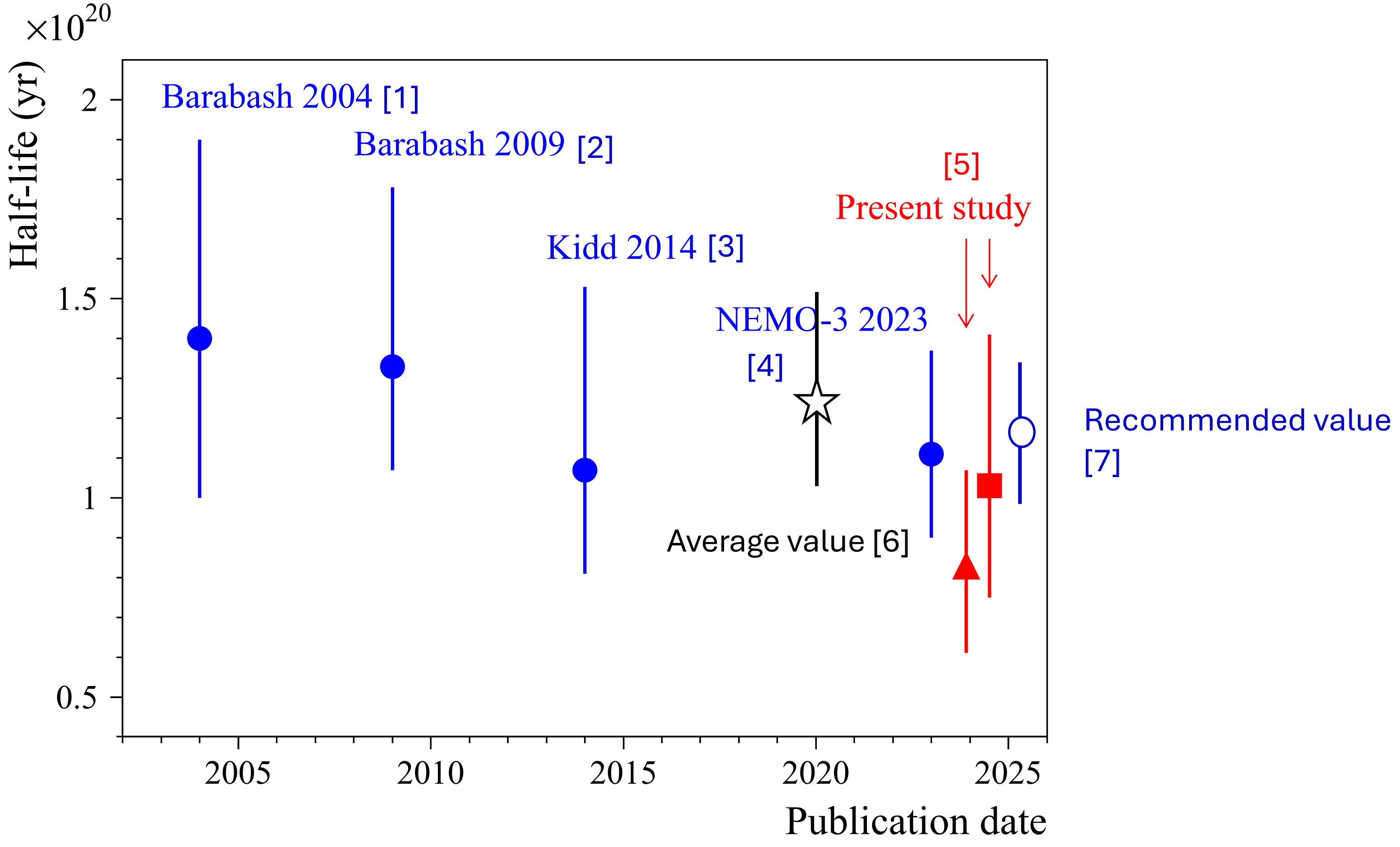
$$T_{1/2}^{2\nu2\beta\to2_1^+} = [1.53^{+2.3}_{-0.6}(\text{stat}) \pm 0.4(\text{syst})]\times 10^{20}\ \text{yr},$$

$$T_{1/2}^{2\nu2\beta\to0_1^+} = [1.03^{+0.35}_{-0.22}(\text{stat})^{+0.16}_{-0.19}(\text{syst})]\times 10^{20}\ \text{yr}$$

The best limit: $T_{1/2}$ > 2.42 x 10^{20} yr [*X. Aguerre et al., Eur. Phys. J. C 83 (2023) 1117*].



A historical perspective of the $2\nu2\beta$ half-life of $^{150}Nd(\rightarrow 0_1^+)$



[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] X. Aguerre et al., Eur. Phys. J. C 83 (2023) 1117.
[5] A.S. Barabash et al., Eur. Phys. J. C 85 (2025) 174.
[6] A. Barabash, Universe 6 (2020) 159.
[7] B. Pritychenko, V.I. Tretyak, At. Data Nucl. Data Tables. 161 (2025) 101694.

Eur. Phys. J. C 85 (2025) 174

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

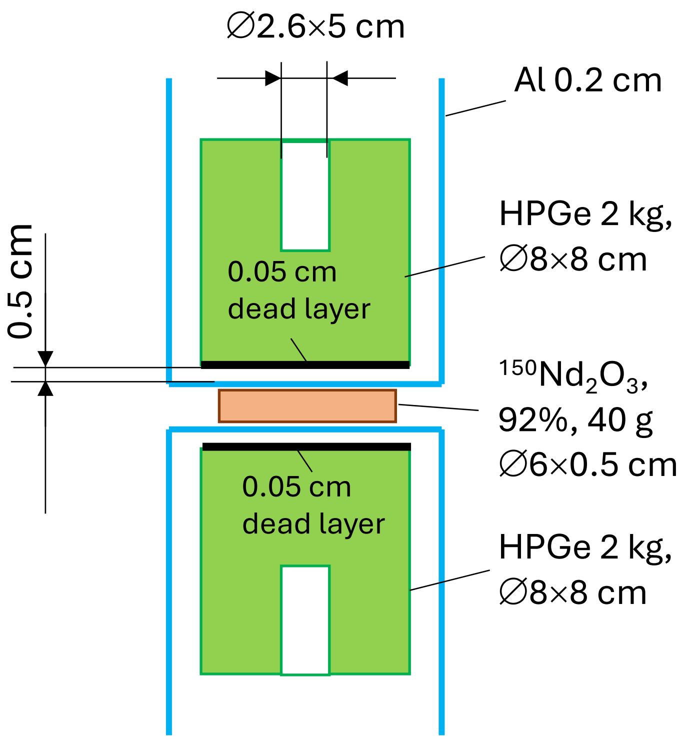
Probabilities of ^{150}Nd 2ν2β-transitions to the 0_1^+ and 2_1^+ excited levels were calculated in the framework of proton-neutron QRPA with isospin restoration combined with like-nucleon QRPA for a description of excited states in the final nuclei.

Transition ^{150}Nd → ^{150}Sm	g_A^{eff}	Theoretical $T_{1/2}$ (yr)	Experimental $T_{1/2}$ (yr)
$0^+ \to 0^+$	1.276	9.34×10^{18}	$9.3(7)\times10^{18}$ [1]
	0.957	9.31×10^{18}	
$0^+ \to 0_1^+$	1.276	0.43×10^{20}	$1.03^{+0.38}_{-0.29}\times10^{20}$
	0.957	1.19×10^{20}	
$0^+ \to 2_1^+$	1.276	1.32×10^{20} *)	$1.5^{+2.3}_{-0.7}\times10^{20}$
	0.957	4.18×10^{20}	

[1] X. Aguerre et al., Eur. Phys. J. C 83 (2023) 1117.

*) 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.*"

Improvement of the experimental sensitivity



- 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% **)

*) 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

- 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:

$$T_{1/2}^{2\nu2\beta\to0_1^+} = [0.83^{+0.18}_{-0.13}(\mathrm{stat})^{+0.16}_{-0.19}(\mathrm{syst})]\times 10^{20}\ \mathrm{yr}$$

- 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:

$$T_{1/2}^{2\nu2\beta\to2_1^+} = [1.53^{+2.3}_{-0.6}(\mathrm{stat}) \pm 0.4(\mathrm{syst})]\times 10^{20}\ \mathrm{yr,}$$

$$T_{1/2}^{2\nu2\beta\to0_1^+} = [1.03^{+0.35}_{-0.22}(\mathrm{stat})^{+0.16}_{-0.19}(\mathrm{syst})]\times 10^{20}\ \mathrm{yr,}$$

- 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.

- The experimental sensitivity can be improved with ~40 g of enriched ^{150}Nd sample between two large volume ultra-low background HPGe detectors.