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Study of 2β decays of ^{150}Nd

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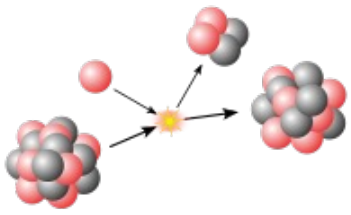
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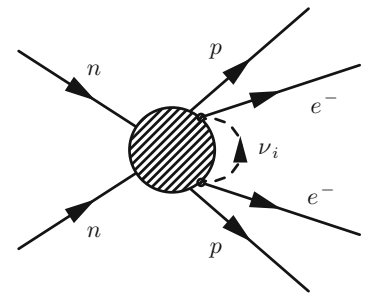
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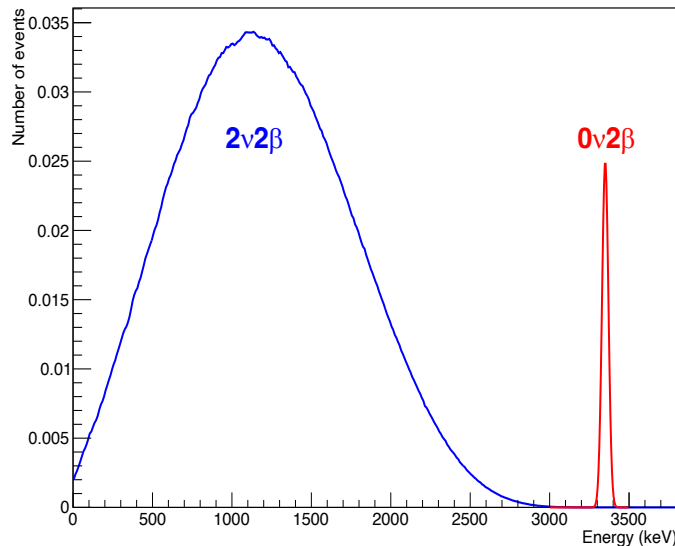
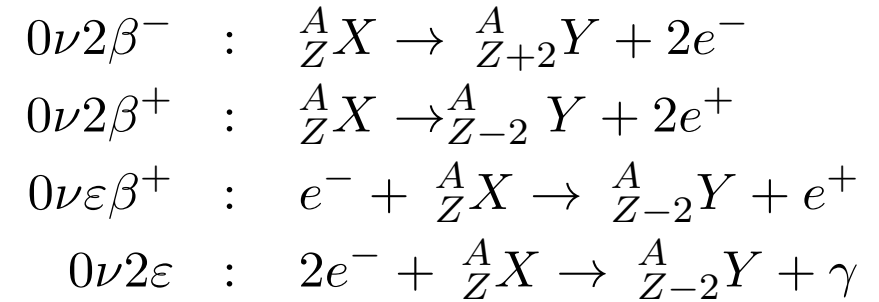
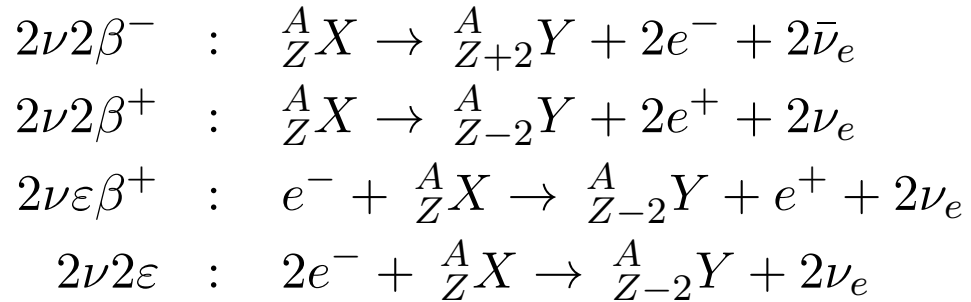


The 2β decay



(Neutrino oscillations)
↓

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

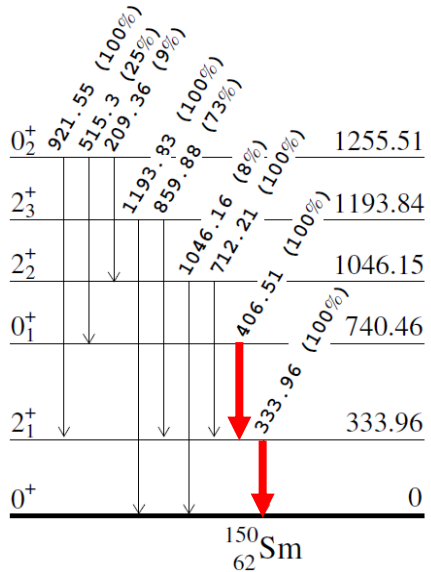
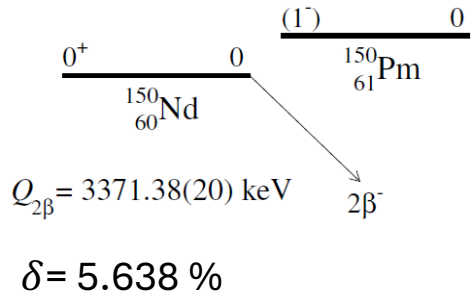


Current sensitivity for $2\nu 2\beta^-$ decay: $T_{1/2} \sim 10^{18}-10^{24}$ yr; for $0\nu 2\beta^-$: $T_{1/2} > 10^{24} - 10^{26}$ yr

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

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

2β decay of ¹⁵⁰Nd



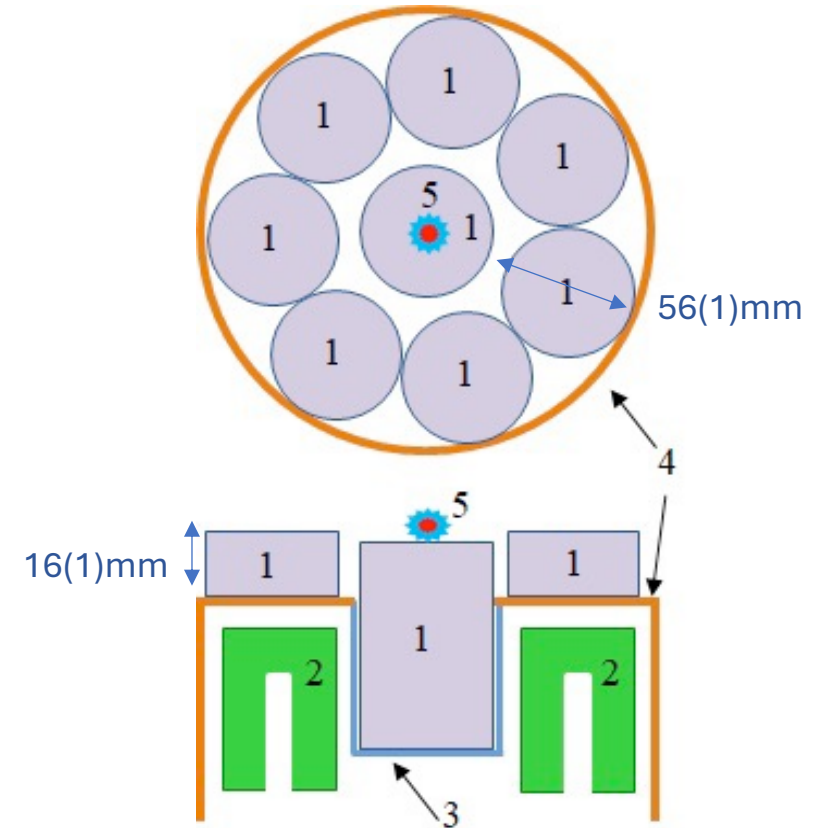
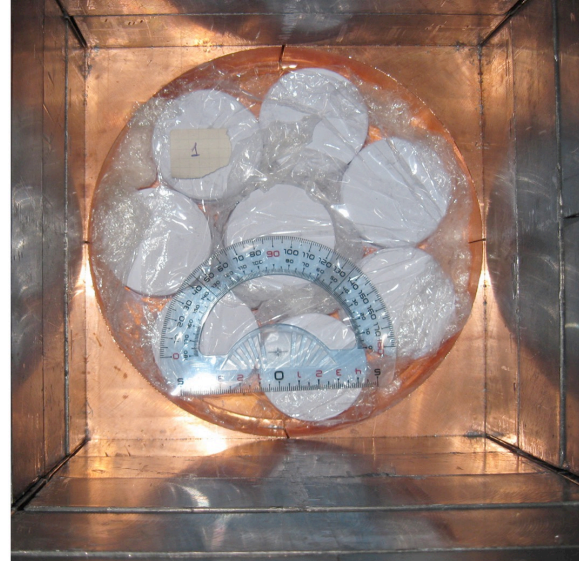
Experiments to search for $2\nu 2\beta \rightarrow 0_1^+$	$T_{1/2, \times 10^{20} \text{ yr}}$	Year [Ref.]
Modane underground laboratory (4800 m w.e.), HPGe 400 cm ³ , 3046 g of Nd ₂ O ₃ ($\delta = 5.638\%$), 1.29 y, 1-d spectrum	$1.4^{+0.5}_{-0.4}$	2004 [1]
Re-estimation of the measurement in [1]	$1.33^{+0.45}_{-0.26}$	2009 [2]
Kimballton Underground Research Facility, USA (1450 m w.e.), 2 HPGe (~304 cm ³ each one), 50 g ¹⁵⁰ Nd ₂ O ₃ ($\delta = 93.6\%$), 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 ₂ O ₃ ($\delta = 91.0\%$), 5.25 yr, tracking-calorimetry	$1.11^{+0.26}_{-0.21}$	2023 [4]
LNGS, 2.38 kg of Nd₂O₃, 4 HPGe ($\approx 225 \text{ cm}^3$ each), 5.85 yr	$1.03^{+0.38}_{-0.29}$	2025 [5]

$2\nu 2\beta \rightarrow g. s. : T_{1/2} = 0.93(7) \times 10^{19} \text{ yr}$ [6]
 $T_{1/2} = 1.16(37) \times 10^{19} \text{ yr}$ [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.

Experimental Setup

- **2.381 kg Nd_2O_3** sample (average density $\sim 2.84 \text{ g/cm}^3$), used in previous experiment [1], additionally purified [2].
- **4 HPGe detectors** ($\approx 225 \text{ cm}^3$ 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.



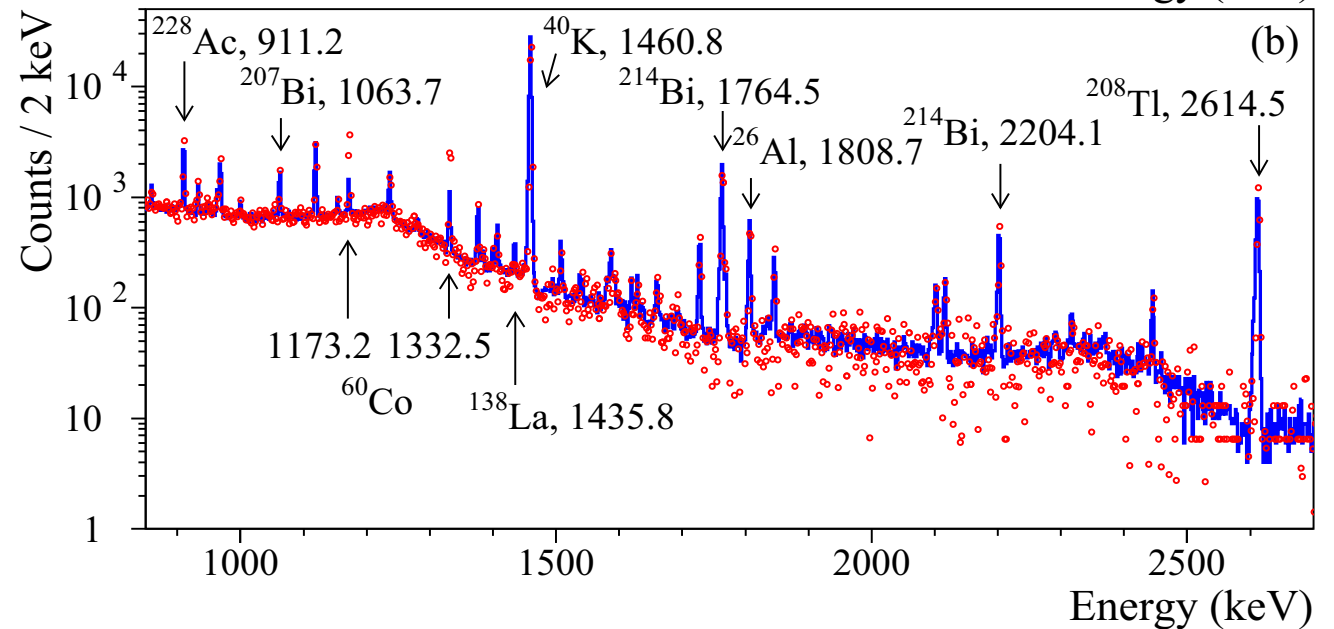
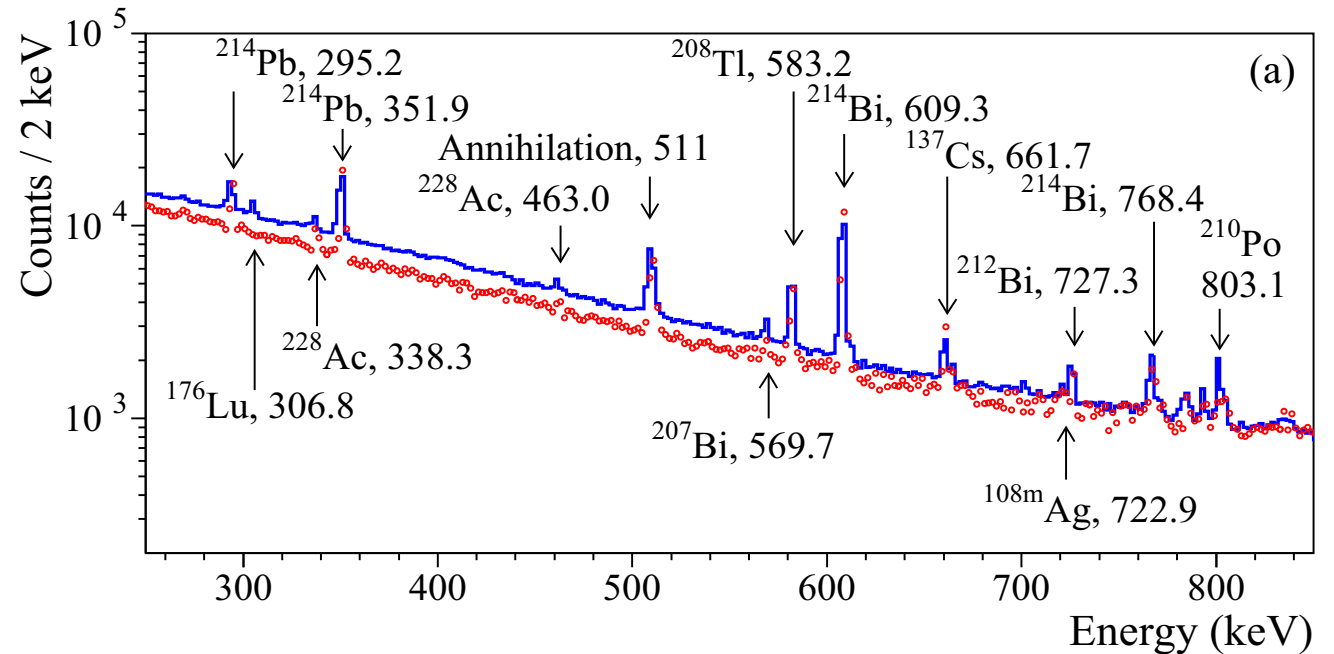
Schematic view of the set-up with Nd-containing source samples (1) installed in the HPGe detector system: (2) coaxial HPGe detectors, (3) aluminium cup of the detector system endcap, (4) copper part of the endcap, (5) position of radioactive γ sources during the calibration campaign.

[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 Nd₂O₃ sample

- ❖ The peaks in the spectra can be assigned to γ quanta of ⁴⁰K and nuclides of the ²³²Th and ²³⁸U chains. In addition, ²⁶Al, ⁶⁰Co, ^{108m}Ag, ¹³⁷Cs, ²⁰⁷Bi γ peaks are observed both in the data with and without sample.
- ❖ Also, γ peaks of lanthanides ¹⁷⁶Lu (306.8 keV) and ¹³⁸La (1435.8 keV) were observed in the spectrum with the Nd₂O₃ sample.

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

¹³⁸La: 0.095(7) mBq/kg

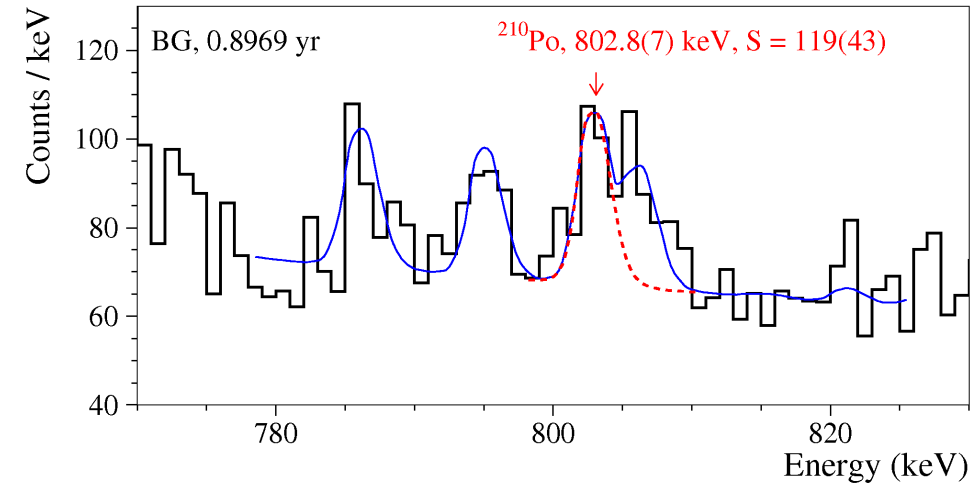
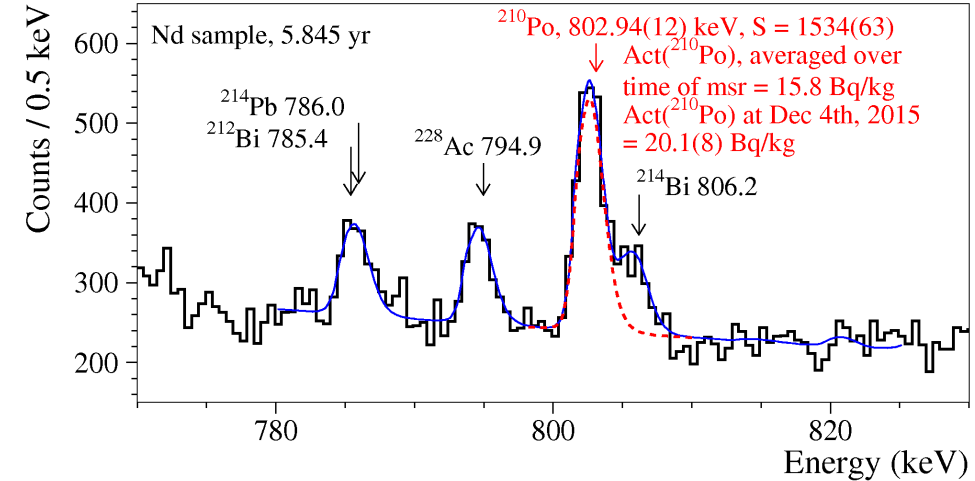
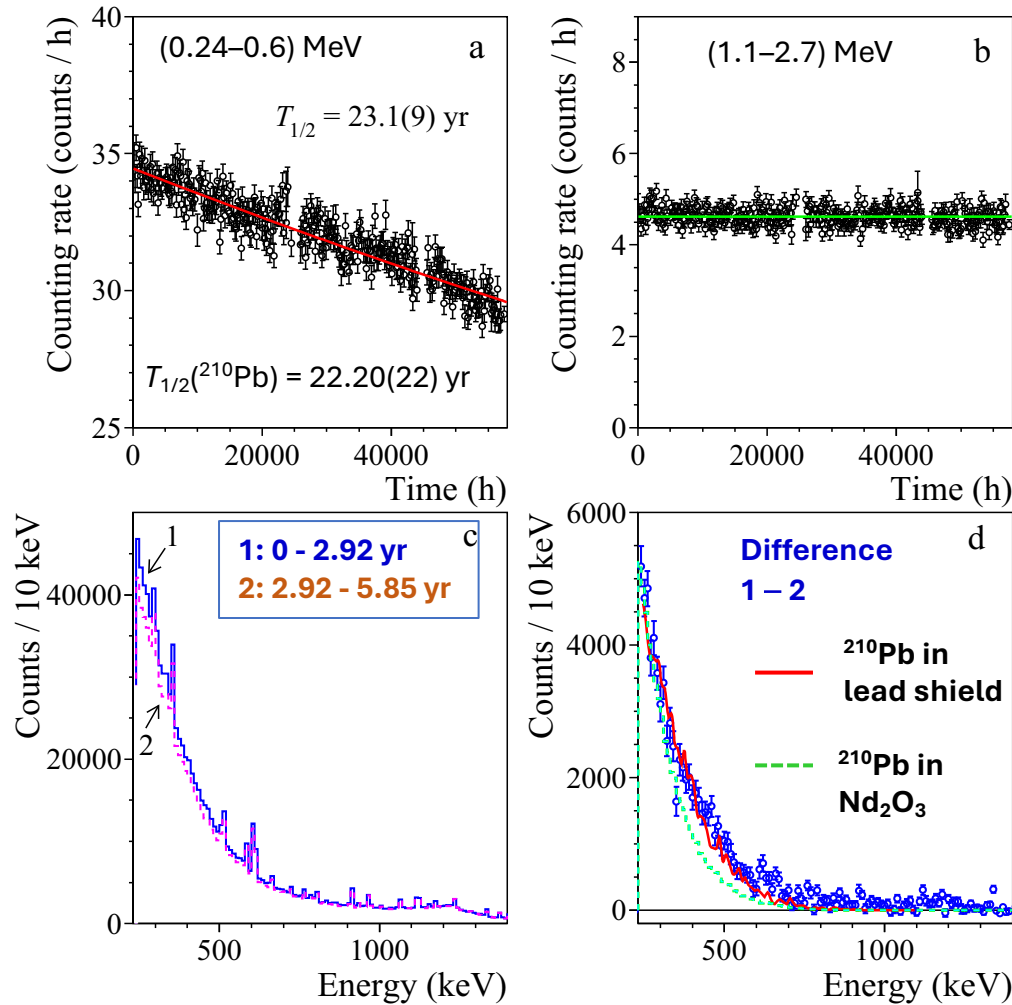
¹⁷⁶Lu: 0.30(2) mBq/kg

Other estimated contaminants: ²²⁸Ra, ²²⁸Th, ²³⁵U, ²²⁷Ac, ⁴⁰K.

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

Chain	Nuclide	Activity (mBq/kg)	
		Before purification	After purification
	⁴⁰ K	<u>16 ± 8</u>	<u>3.4 ± 0.7</u>
	¹³⁸ La		0.095 ± 0.007
	¹⁵⁰ Eu		≤ 0.037
	¹⁷⁶ Lu	<u>1.1 ± 0.4</u>	<u>0.30 ± 0.02</u>
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	<u>15 ± 0.8</u>	<u>≤ 0.18</u>
	²¹⁰ Pb		≤ 178

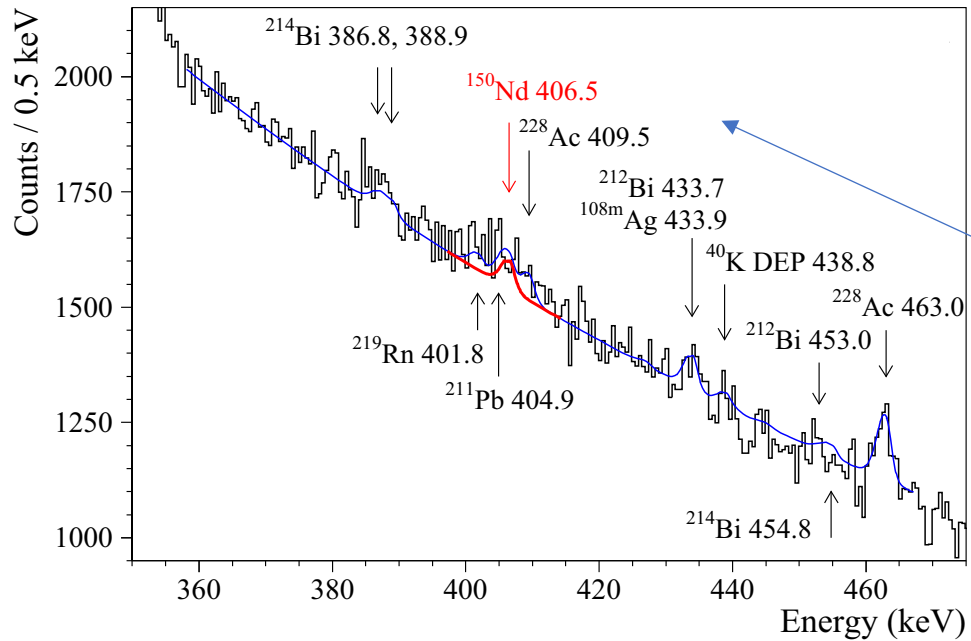
Detector is sensitive to ^{210}Pb in the lead shield (despite the low-active lead, and 10-cm layer of copper)



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.

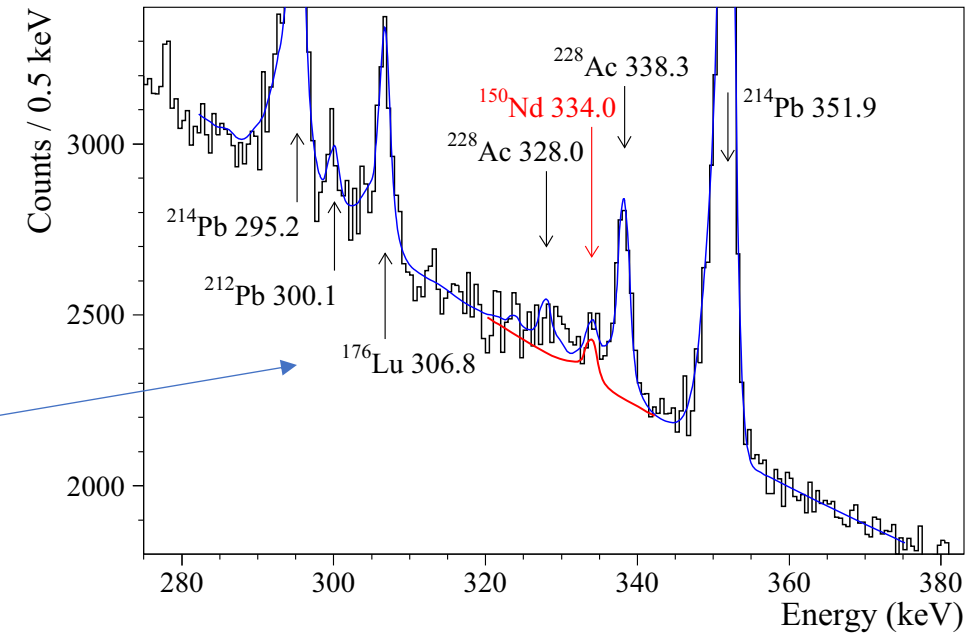
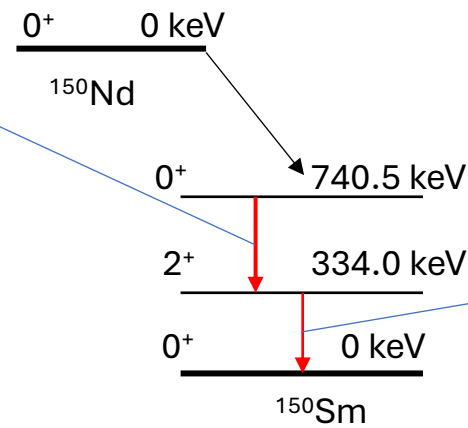
γ peak at 803 keV from α decays of ^{210}Po to the first excited level of ^{206}Pb with the absolute intensity $0.00103(6)\%$ was detected too.

Energy spectrum in the ROI - 1D spectra



406.5-keV peak area = 341(111) counts

$\chi^2/\text{n.d.f.} = 221/205 = 1.08$



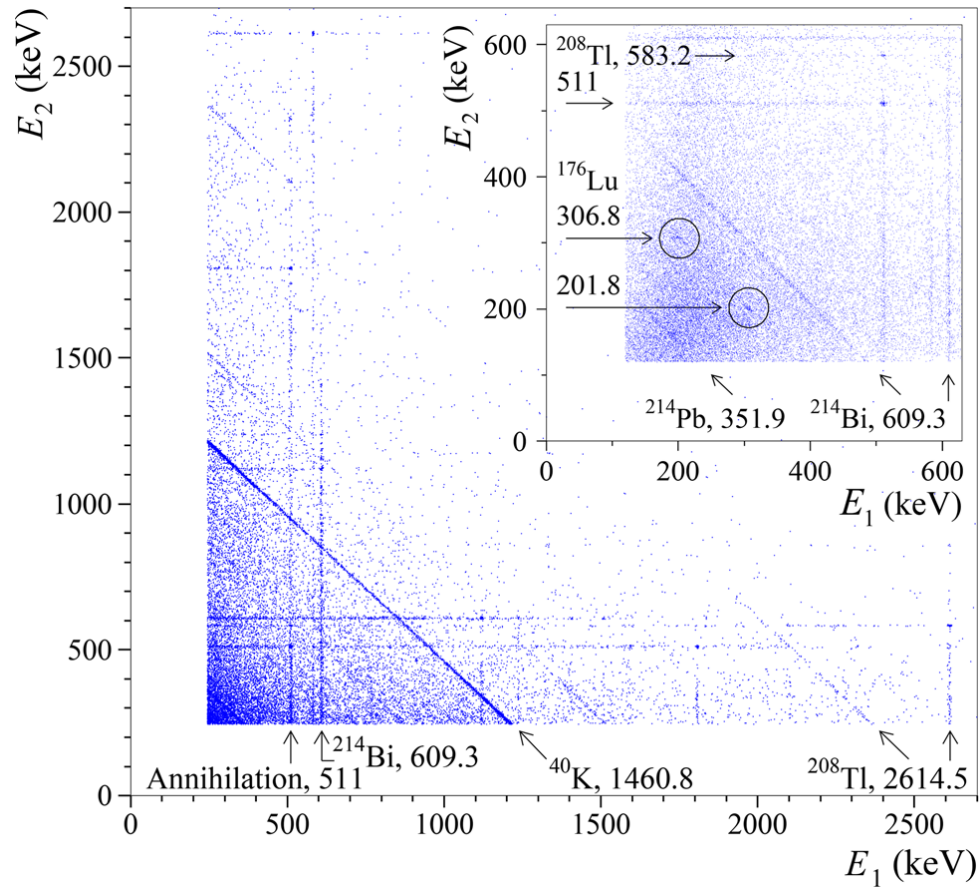
334.0-keV peak area = 616(141) counts

$\chi^2/\text{n.d.f.} = 227/175 = 1.29$

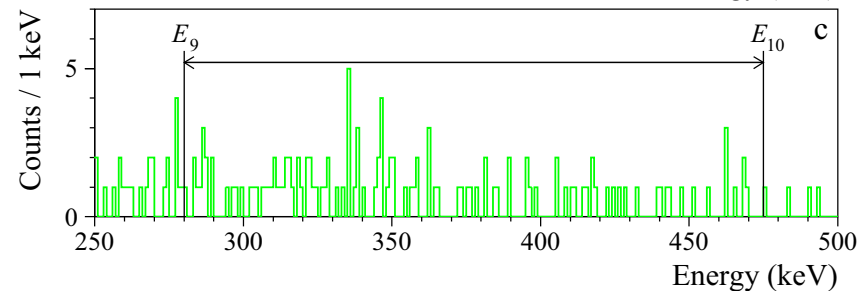
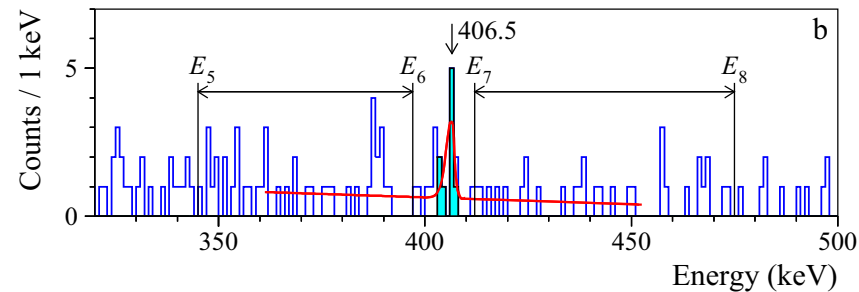
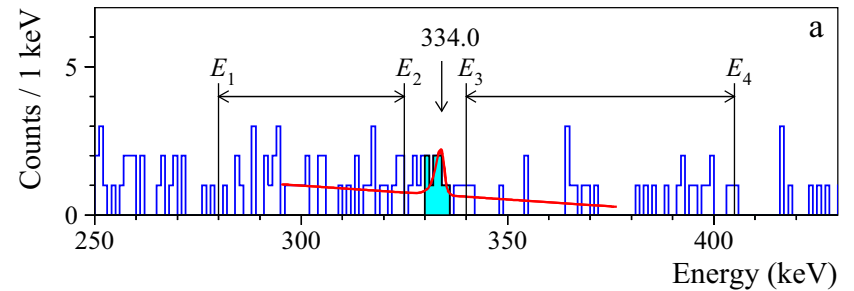
$$T_{1/2}^{406}({}^{150}\text{Nd} \rightarrow {}^{150}\text{Sm}(0_1^+)) = [1.06_{-0.26}^{+0.51}(\text{stat})_{-0.20}^{+0.10}(\text{syst})] \times 10^{20} \text{ yr}$$

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

Coincidence spectrum in 2 HPGe Detectors



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.



Background:
 $b = 2.53 \pm 0.21$ counts
 Total events observed:
 $n_0 = 9$ counts
 Signal central value:
 $n_0 - b = 6.47$ counts

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

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

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

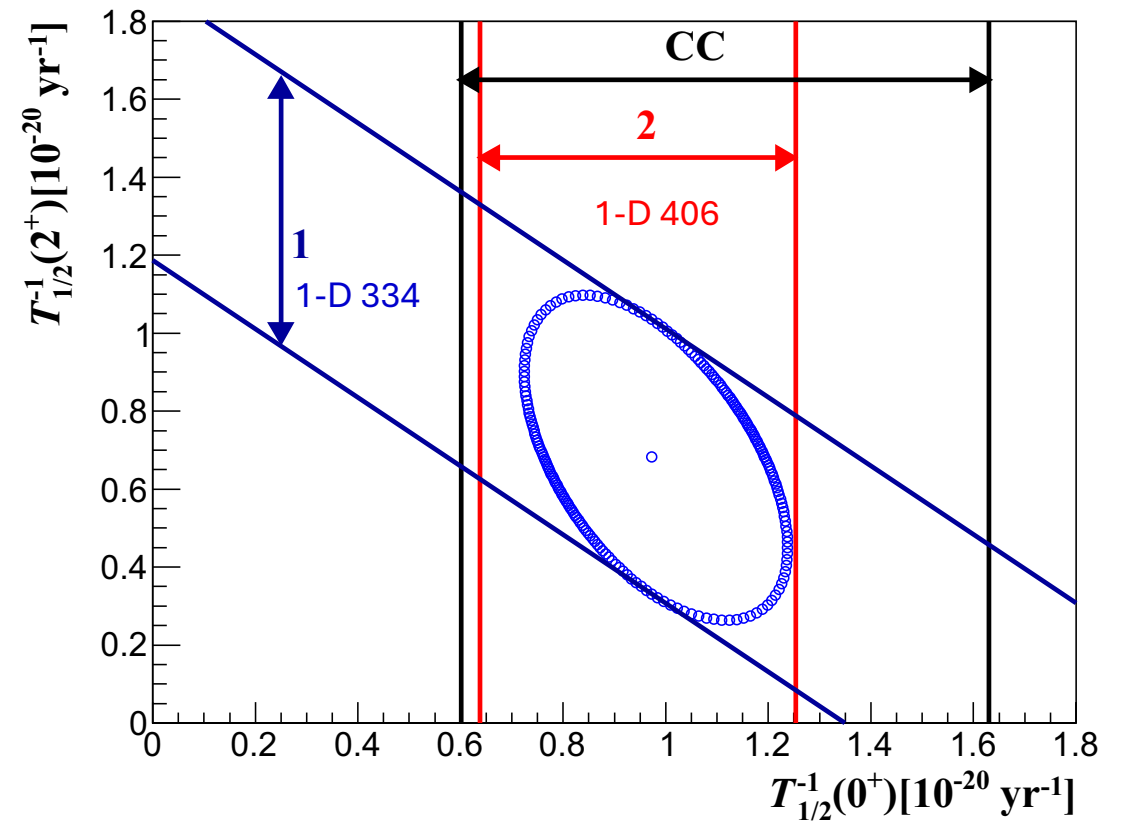
Maximum likelihood procedure for 1-D and CC, including the possible contribution of the decay to the 2_1^+ level

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

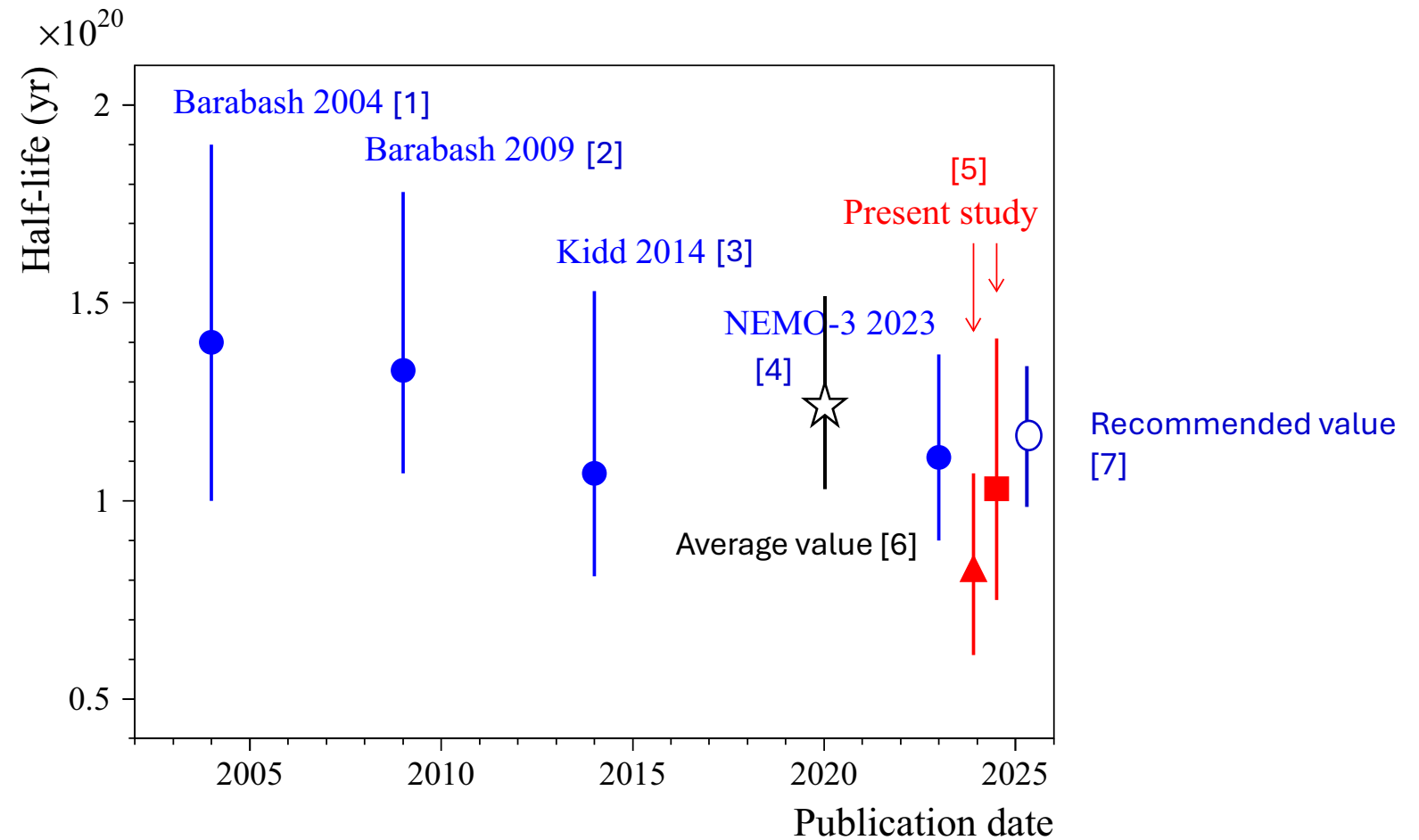
$$T_{1/2}^{2\nu 2\beta \rightarrow 2_1^+} = [1.53_{-0.6}^{+2.3}(\text{stat}) \pm 0.4(\text{syst})] \times 10^{20} \text{ yr},$$

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

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



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



[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.

Theoretical calculations of ^{150}Nd $2\nu 2\beta$ -decay probability

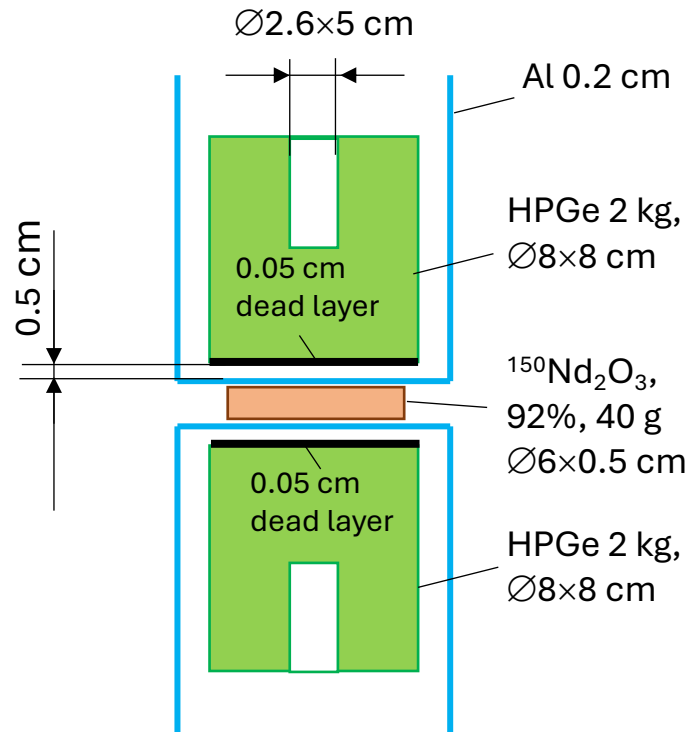
Probabilities of ^{150}Nd $2\nu 2\beta$ -transitions to the 0_1^+ and 2_1^+ excited levels were calculated in the framework of proton-neutron QRPA with isospin restoration combined with like-nucleon QRPA for a description of excited states in the final nuclei.

Transition $^{150}\text{Nd} \rightarrow$ ^{150}Sm	g_A^{eff}	Theoretical $T_{1/2}$ (yr)	Experimental $T_{1/2}$ (yr)
$0^+ \rightarrow 0^+$	1.276	9.34×10^{18}	$9.3(7) \times 10^{18}$ [1]
	0.957	9.31×10^{18}	
$0^+ \rightarrow 0_1^+$	1.276	0.43×10^{20}	$1.03_{-0.29}^{+0.38} \times 10^{20}$
	0.957	1.19×10^{20}	
$0^+ \rightarrow 2_1^+$	1.276	1.32×10^{20} *)	$1.5_{-0.7}^{+2.3} \times 10^{20}$
	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., Eur. Phys. J. C 83 (2023) 1117.

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 $T_{1/2}(\rightarrow 0_1^+) = 1 \times 10^{20}$ yr can be measured over 3 year with $\sim 20\%$ precision both in 1-D and CC modes. The decay to the 2_1^+ 334 keV level with $T_{1/2} = 4 \times 10^{20}$ 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 Braekeleer 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 $2\nu 2\beta$ decay of ^{150}Nd to the first 740.5 keV 0^+ level of ^{150}Sm was detected in both one-dimensional and coincidence spectra:

$$T_{1/2}^{2\nu 2\beta \rightarrow 0_1^+} = [0.83_{-0.13}^{+0.18}(\text{stat})_{-0.19}^{+0.16}(\text{syst})] \times 10^{20} \text{ yr}$$

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

$$T_{1/2}^{2\nu 2\beta \rightarrow 2_1^+} = [1.53_{-0.6}^{+2.3}(\text{stat}) \pm 0.4(\text{syst})] \times 10^{20} \text{ yr},$$

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

- ❖ 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.