Search for triple and quadruple beta decay of ^{150}Nd

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OUTLINE

- **Introduction**
- **Experiment**
- **Analysis and results**
- **Conclusion**

I. INTRODUCTION

- **Lepton-number-violating (LNV)** processes could be directly linked to the possible **Majorana nature of neutrinos.**
- If **Majorana mass terms** are added to the SM Lagrangian, processes appear that violate ***L*** by two units **($\Delta L = 2$)**.
- Search for **$\Delta L = 2$** processes such as **0ν2β** decay have, therefore, been the goal of many experiments.

Introduction (2)

- However, it is most often overlooked that **LNV** and **Majorana neutrinos** are not necessary connected.
- Models with $\boldsymbol{\Delta L = 3}$ and $\boldsymbol{\Delta L = 4}$ have some power in explaining naturally small **Dirac masses** of neutrinos and could mediate **Leptogenesis**.
- In [1] the toy model with $\boldsymbol{\Delta L = 4}$ was constructed which allow neutrinoless quadruple beta decay (**0ν4β**):

$$(A,Z) \rightarrow (A,Z+4) + 4e^-$$

- In the framework of this model neutrino is **Dirac** and **0ν2β** is forbidden.

[1] J. Heeck and W. Rodejohann, Eur. Phys. Lett. 103 (2013) 32001.

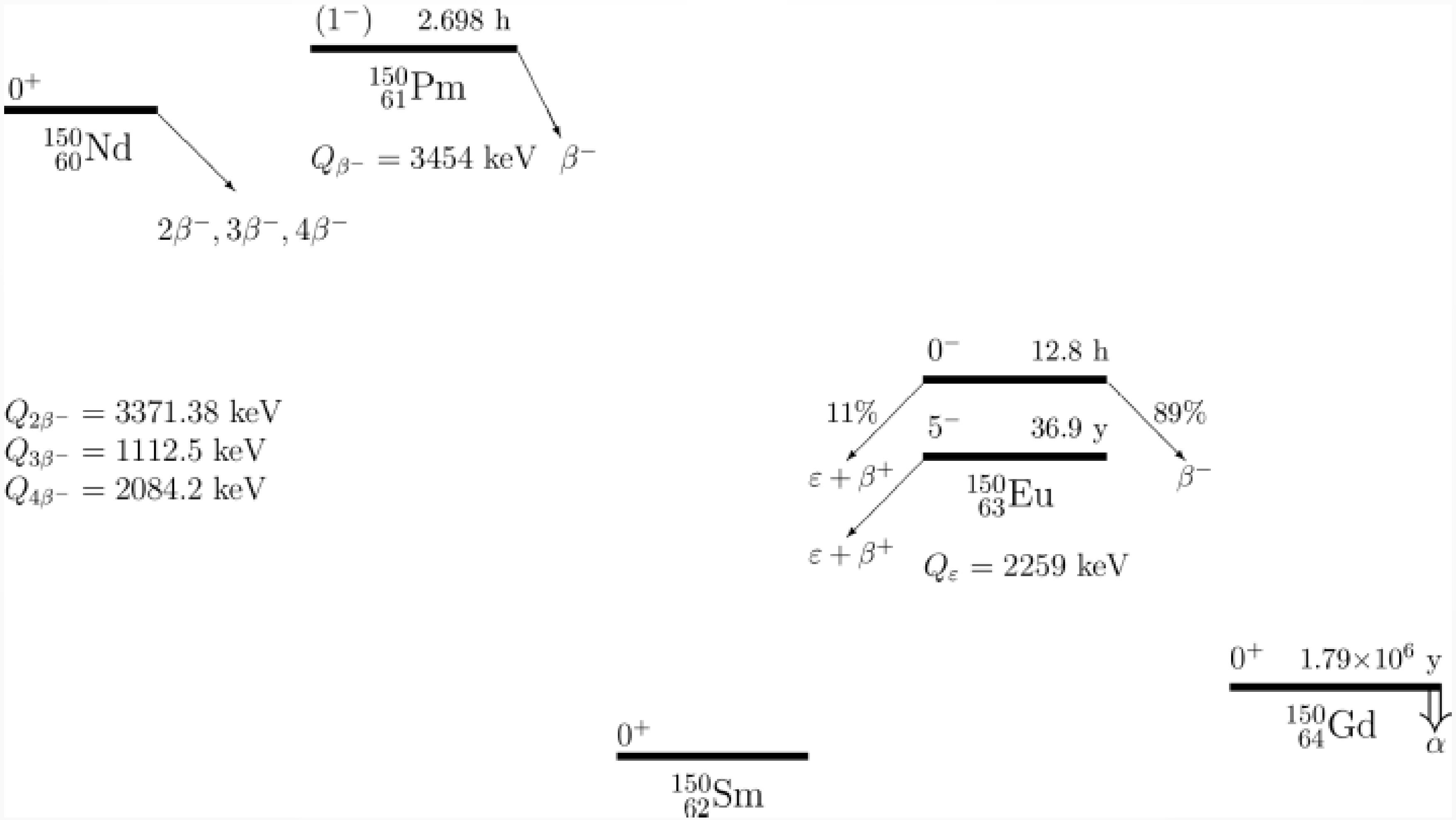
Introduction (3)

- Note also that quadruple decay with emission of 4 neutrinos (**4ν4β**) is not forbidden by any conservation low:

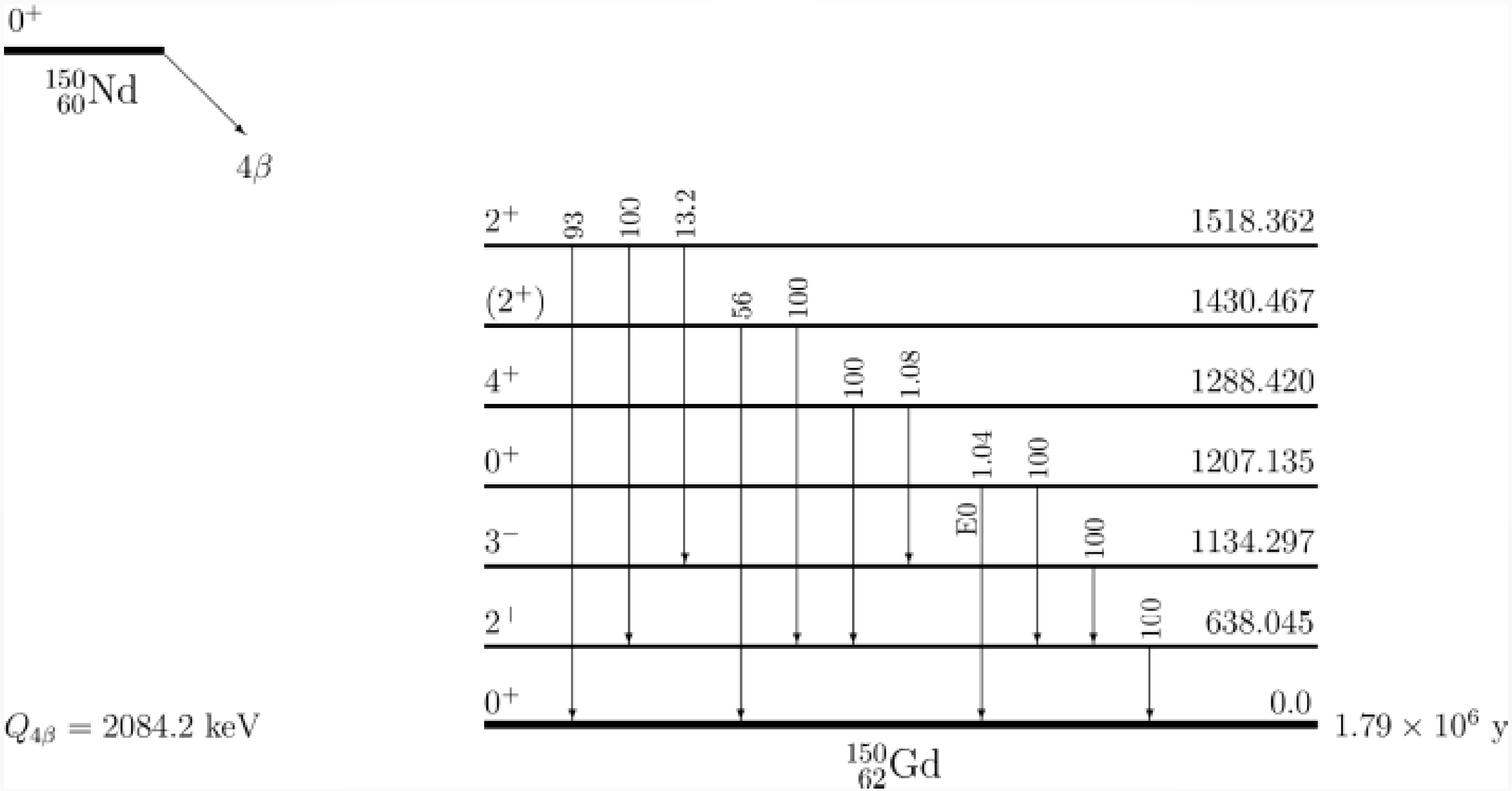
$$(A,Z) \rightarrow (A,Z+4) + 4e^- + 4\nu$$

- The authors of [1] pointed out three candidate nuclei for quadruple decay: **^{150}Nd (2084.2 keV), ^{96}Zr (641.5 keV) and ^{136}Xe (79.2 keV)**
- **^{150}Nd** is the best candidate and even transition to excited levels of daughter nucleus **^{150}Gd** is possible

Introduction (4)



Introduction (5)



Introduction (6)

- We also consider the triple beta decay of ^{150}**Nd**:

  $(A,Z) \rightarrow (A,Z+3) + 3e^-$

  $(A,Z) \rightarrow (A,Z+3) + 3e^- + 3\nu$

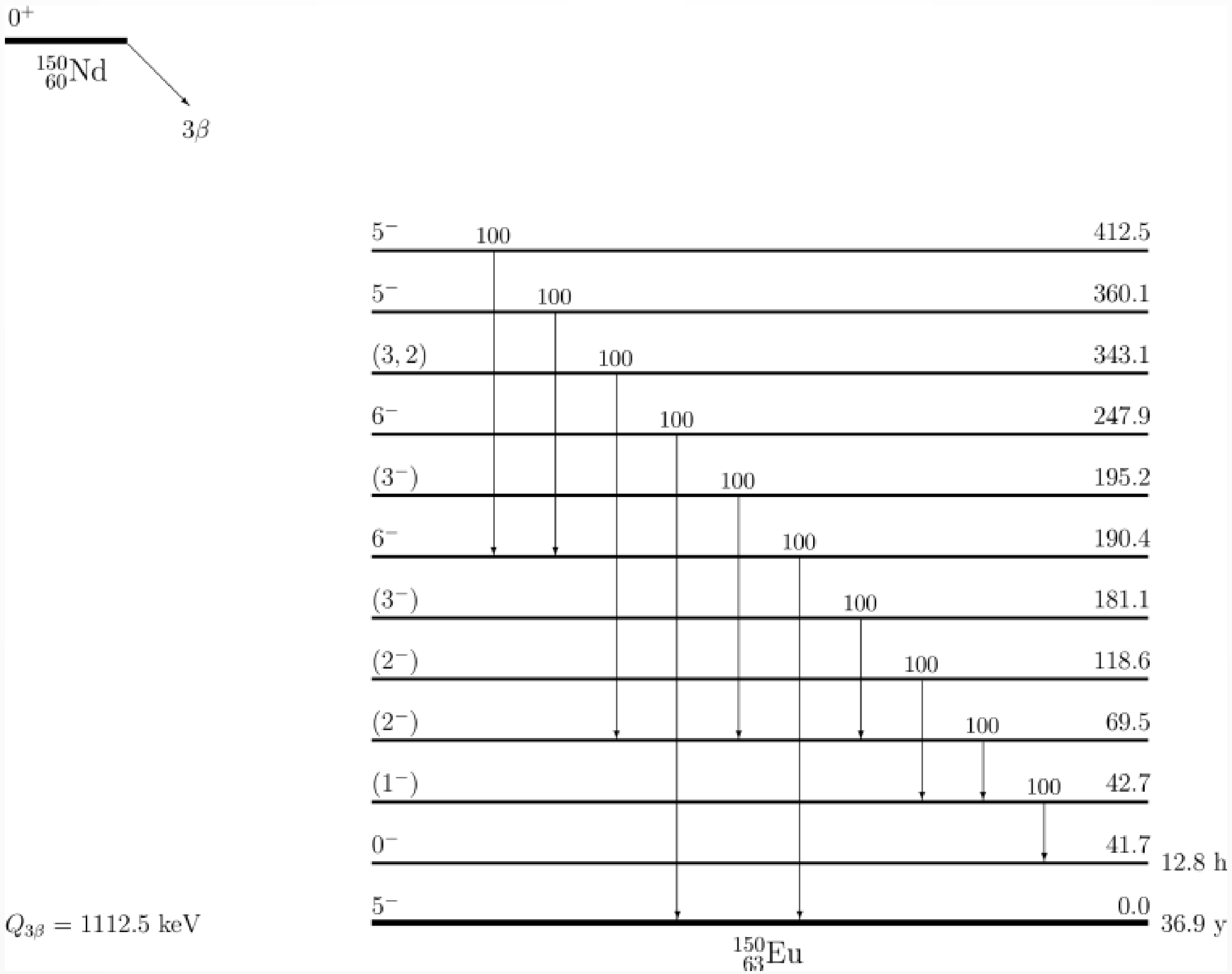
- The **3β** transition energy (^{150}Nd-^{150}Eu) is **1112.2 keV.**

  [There are also ^{48}Ca-^{48}V (253.1 keV) and ^{96}Zr-^{96}Tc (383.1 keV)]

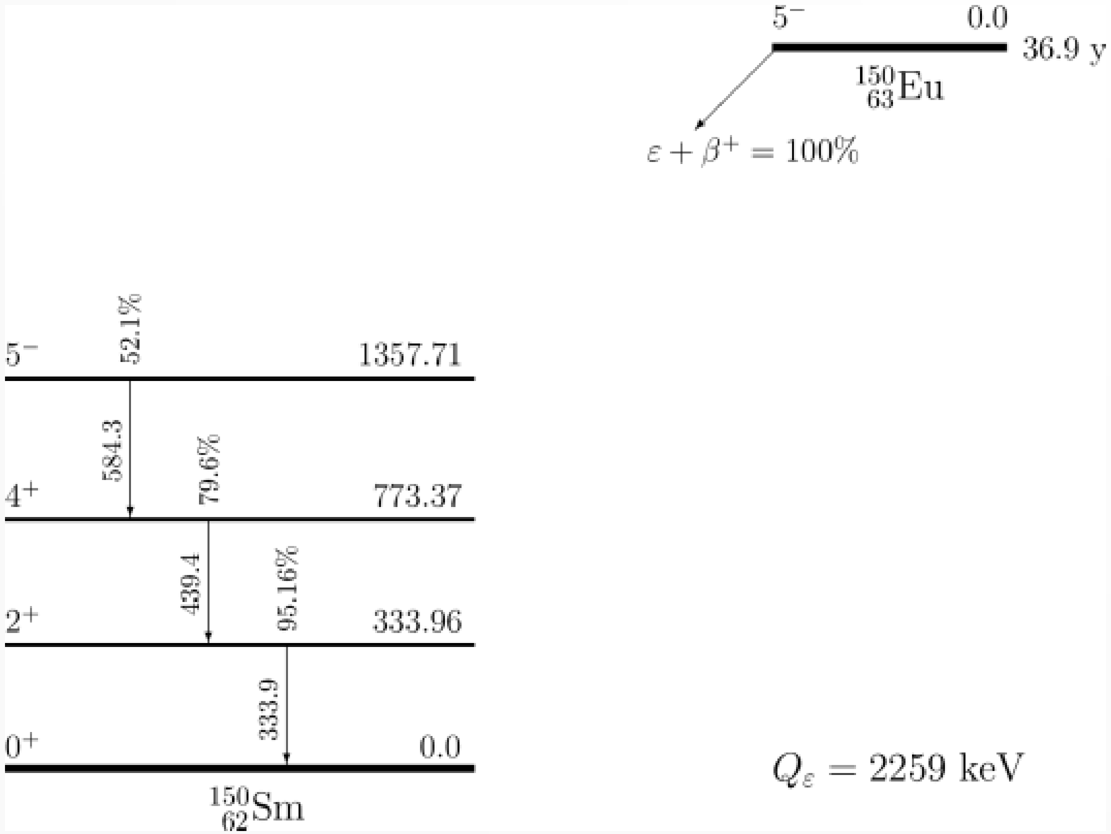
- Neutrinoless **3β** decay is forbidden, because this process violates Lorentz invariance.

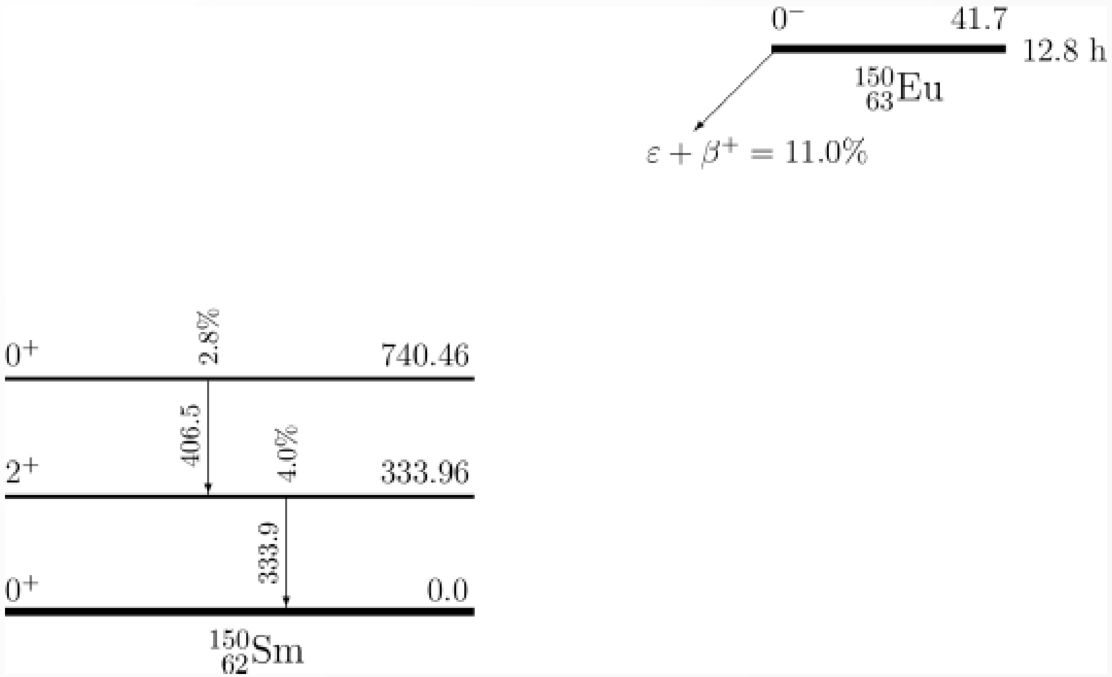
- The decay with emission of **3 neutrinos** is not forbidden by any conservation lows.

Introduction (7)



Introduction (8)





EXPERIMENT

- Location: **Modane Underground Laboratory** (France, 4800 m v.e. depth).
- Detector: **400 cm^3** low-background **HPGe** detector

  - passive shielding (3-10 cm of OFHC copper + 15 cm of lead).

  - energy resolution: **2.0 keV at 1332 keV line of ^{60}Co.**
- Sample of **Nd_2O_3**:

  - powder in a Marinelli box

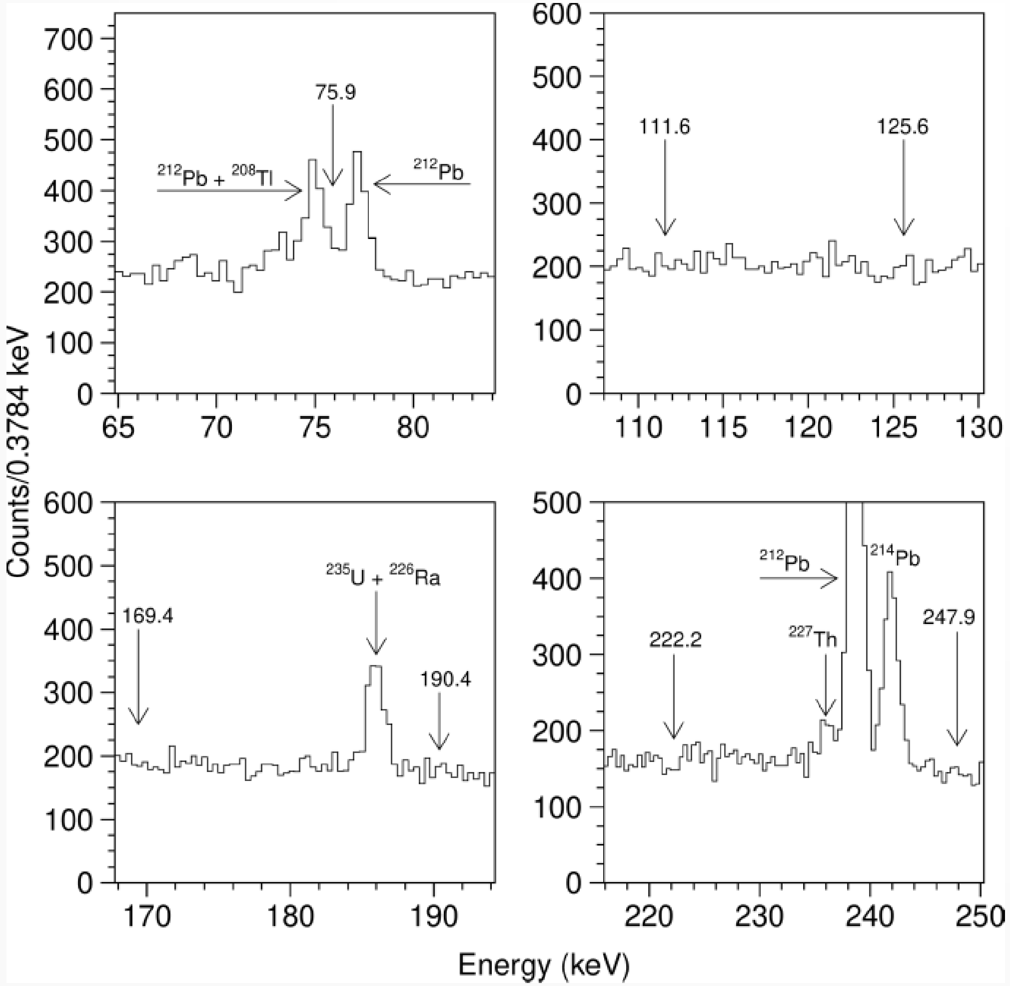
  - mass is **3046 g**

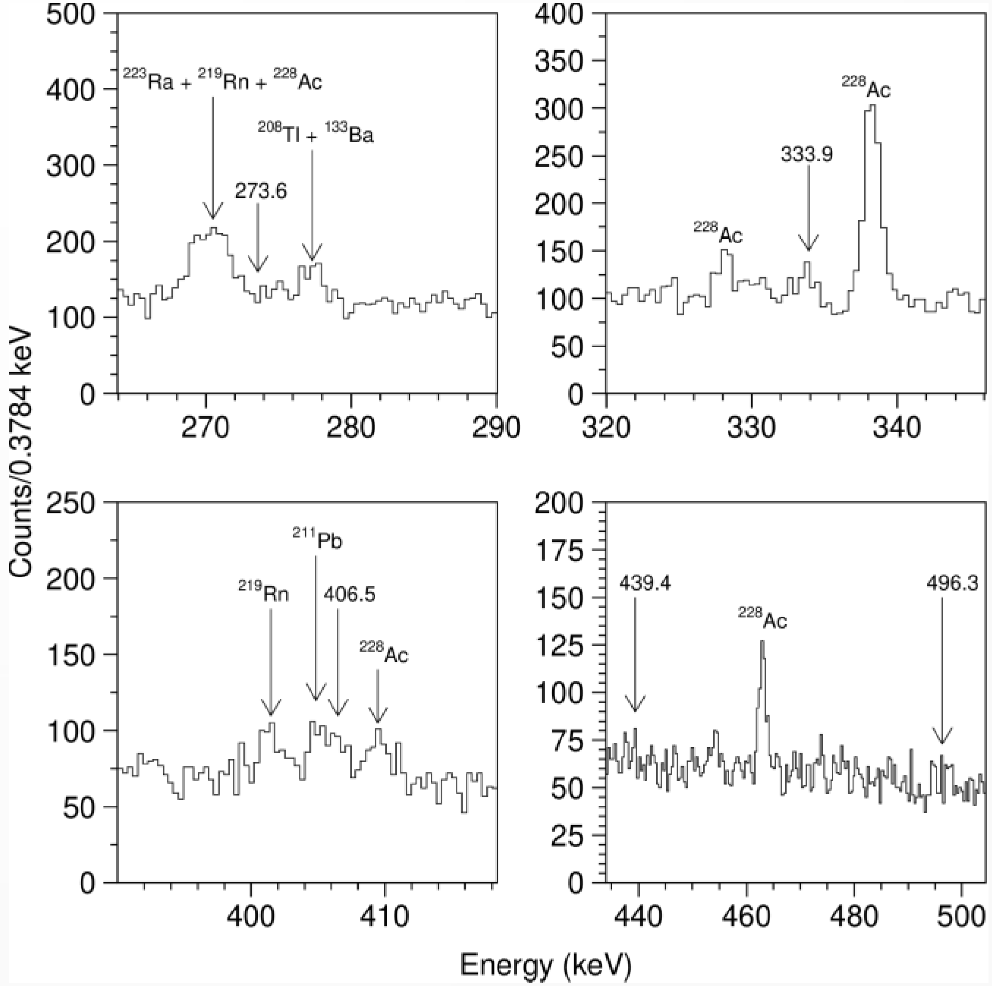
  - natural abundance of **^{150}Nd is 5.6%**

  (**153 g** of **^{150}Nd** or **$6.14 \cdot 10^{23}$** nuclei of **^{150}Nd**)
- Measurement time: **11320.5 hours**

This data was used to search for **2β** decay of **^{150}Nd** to the excited states of **^{150}Sm:** Phys. Rev. C 79 (2009) 045501.

Experimental data (t = 11320.5 h)





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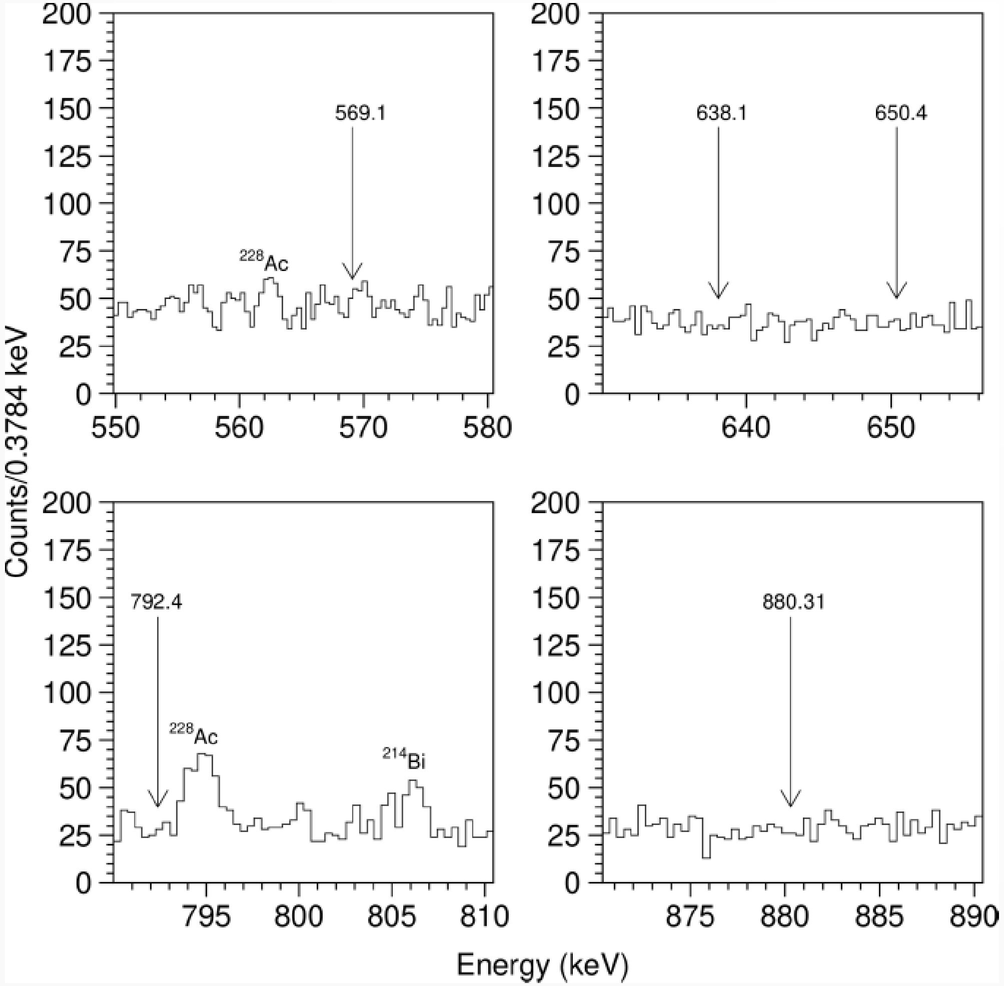

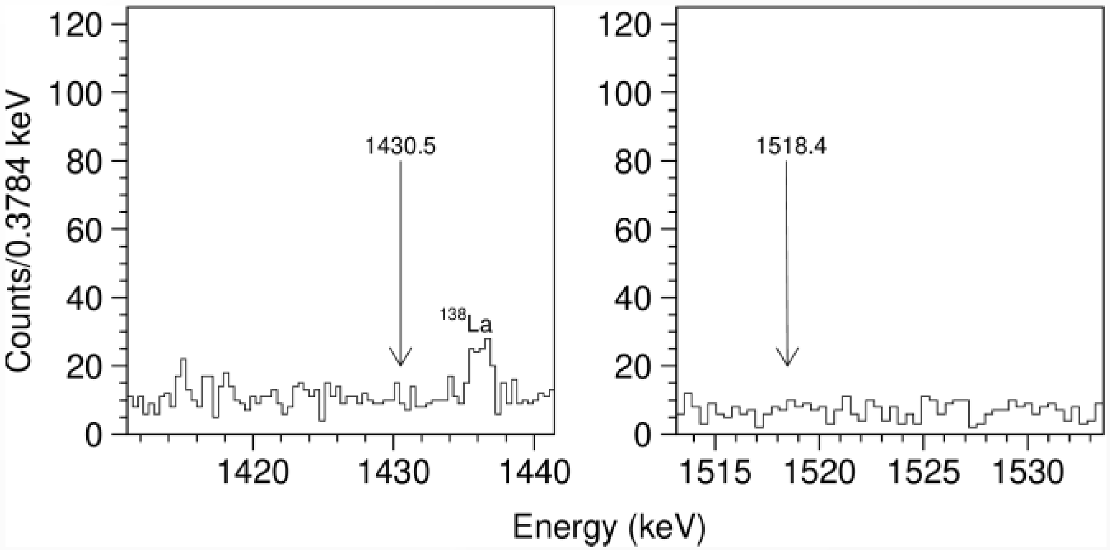

Limits for 4β(0ν+4ν) decay of ^{150}Nd to the excited states of ^{150}Gd. Limits at 90% C.L.

Excited state, keV	Energy of γ-rays, kev (efficiency)	$T_{1/2}$(0ν+4ν), (x 10^{20} yr) This work	Ref. [2]
2^+ (638.05)	638.05 (2.23%)	7.52	-
3^-_1 (1134.30)	496.25 (2.27%) + 638.05 (2.09%)	7.79	-
0^+_1 (1207.14)	564.09 (2.11%) + 638.05 (2.06%)	**8.70**	**1.76**
4^+_1 (1288.42)	638.05 (2.05%) + 650.37 (2.02%)	8.98	-
2^+_2 (1430.47)	638.05 (1.33%) + 792.42 (1.20%) + 1430.47 (0.62%)	9.49	-
2^+_3 (1518.36)	638.05 (1.13%) + 880.31 (0.86%) + 1518.36 (0.73%)	6.10	-

[2] M.F. Kidd and W. Tornow, Phys. Rev. C 98 (2018) 055501.

Limits for 3β(0ν+3ν) decay of ^{150}Nd to the ground and excited states of ^{150}Eu. Limits at 90% C.L.

Excited state, keV	Energy of γ-rays, kev (efficiency)	$T_{1/2}$(0ν+3ν), (x 10^{20} yr) This work	Previous work
5^-_1, 36.9 yr	439.43 (1.71%)	2.00	-
0^-_1 (41.7 keV), 12.8 h	333.96 (0.10%)	0.04	-
2^-_1 (118.6 keV)	75.6 (0.12%)	0.30	-
3^-_1 (181.1 keV)	111.60 (0.485)	0.63	-
6^-_1 (190.37 keV)	190.40 (1.52%)	1.81	-
3^-_2 (195.2 keV)	125.60 (0.66%)	0.78	-
6^-_2 (247.89 keV)	247.89 (2.24%)	3.27	-
(3,2) (343.1 keV)	273.60 (2.11%)	3.16	-
5^-_2 (360.14 keV)	169.40 (1.28%) + 190.40 (1.44%)	2.24	-
5^-_3 (412.53%)	190.40 (1.39%) + 222.20 (1.86%)	4.83	-

Theoretical predictions

- There are no “real” (accurate) theoretical investigations for **4β-** and **3β-** processes

  (But it is clear that such transitions should be strongly suppressed compared to the **2β** decay processes)
- There are a few “qualitative” estimations for **4β(0ν)** decay of ^{150}**Nd** to the ground state of ^{150}**Gd** [3]:

  Most “optimistic” estimation is: $T_{1/2} \approx 10^{41}$ **yr**

  (Experiment NEMO-3 - $T_{1/2} > (1.1\text{-}3.2) \cdot 10^{21}$ yr)

  (In [1] and [4] it is mentioned about possible enhancement; more careful theoretical investigations are needed)
- **Can one ever prove that neutrinos are Dirac particles?** → Yes, if **4β(0ν)** decay will be detected!

  (see discussion in M. Hirsch, R. Srivastava and J.W.F. Valle, PLB 781 (2018) 302)
- No any estimation for **3β(3ν)** and **4β(4ν)** decays

[1] J. Heeck and W. Rodejohann, Eur. Phys. Lett. 103 (2013) 32001.

[3] R.M. Fonseca and M. Hirsch, Phys, Rev. D 98 (2018) 015035.

[4] A. Dasgupta, S.K. Kang and O. Popov, hep-ph/1903.12558.

FUTURE EXPERIMENTAL POSSIBILITIES - 1

- **Direct experiments:**
- If one will use **~ 2-3 kg** of **^{150}Nd** the sensitivity could be increased up to:

  ~ (3-5)·10^{22} yr

  (**4β** and **3β** decay to the excited states)

- Using **NEMO-3**-like detector (**SuperNEMO-D**):

  ~ 10^{23} yr

  (**4β(0ν)** transition to the ground state)

FUTURE EXPERIMENTAL POSSIBILITIES - 2

- **Radiochemical experiments**

I. 4β decay:

^{150}**Nd** → ^{150}**Gd** (α-decay, E_α = 2.7 MeV, $T_{1/2}$ = $2\cdot10^6$ yr)

[In such experiment **2β2ν** decay of ^{238}**U** has been detected;

$T_{1/2}$ = (2 ± 0.6)·10^{21} yr]

II. 3β decay:

^{150}**Nd** → ^{150}**Eu (5^-)** (EC, β^+, $T_{1/2}$ = 36.9 yr)

→ ^{150}**Eu(0^-)** (EC, β^+, $T_{1/2}$ = 12.8 h)

[The same scheme as for **Cl-Ar** or **Ga-Ge** solar neutrino experiments.

In this case sensitivity could be **~ 10^{25}-10^{27} yr.**]

FUTURE EXPERIMENTAL POSSIBILITIES - 3

- **Geochemical experiment**

  4β decay:

  $^{150}Nd \rightarrow {}^{150}Gd$ (α-decay, E_α = 2.7 MeV, $T_{1/2} = 2 \cdot 10^6$ yr)

  [By analogy with geochemical experiments with ^{130}Te, ^{124}Te, ^{82}Se, ^{130}Ba, ^{96}Zr and ^{100}Mo]

CONCLUSION

- **Quadruple beta decay of ^{150}Nd to the excited states of ^{150}Gd has been investigated:**

  For transition to 0^+_1 excited state limit is:

  $T_{1/2}(0\nu+4\nu) > 8.7\cdot10^{20}$ yr (90% C.L.)

  (~ 5 times better then previous limit)

  For other excited states (2^+_1, 3^-_1, 4^+_1, 2^+_2, 2^+_3) limits are:

  $T_{1/2}(0\nu+4\nu) > (6.1\text{-}9.5)\cdot10^{20}$ yr (90% C.L.)

- **Triple beta decay of ^{150}Nd to the ground end excited states of ^{150}Eu has been investigated for the first time:**

  Only limits have been obtained:

  $T_{1/2}(0\nu+3\nu) > (0.04\text{-}4.8)\cdot10^{20}$ yr (90% C.L.)

BACKUP SLIDES

6β and 8β DECAYS

- **6β decay:**

  $^{134}Te - {}^{134}Ce$ (Q = 2.4 MeV); $T_{1/2}(^{134}Te) = 41.8$ min

- **8β decay:**

  $^{131}Sn - {}^{131}Ce$ (Q = 2.4 MeV); $T_{1/2}(^{131}Sn) = 56$ s

  $^{132}Sn - {}^{132}Ce$ (Q = 5.9 MeV); $T_{1/2}(^{132}Sn) = 39.7$ s

Thus, no realistic candidate for **6β** and **8β** decays

[Renato M. Fonseca and Martin Hirsch, "ΔL ≥ 4 lepton number violating processes", Phys. Rev. D 98 (2018) 015035.]