

# Search for triple and quadruple beta decay of $^{150}\text{Nd}$ using low-background HPGe detector

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**Abstract.** Triple beta decay of  $^{150}\text{Nd}$  to the ground and excited states of  $^{150}\text{Eu}$  and quadruple beta decay of  $^{150}\text{Nd}$  to the excited states of  $^{150}\text{Gd}$  have been studied using a  $400 \text{ cm}^3$  low-background HPGe detector. A half-life limit for the quadruple beta decay to the  $0_1^+$  state of  $^{150}\text{Gd}$  was found to be  $T_{1/2}(0\nu + 4\nu) > 8.7 \times 10^{20} \text{ yr}$  (90% C.L.). For other  $(0\nu + 4\nu)$  transitions to the excited states limits for the first time have been obtained at the level of  $(6.1 - 9.5) \times 10^{20} \text{ yr}$  (90% C.L.). We report here also the results for the first search for triple beta decay to the ground and excited final states of  $^{150}\text{Eu}$ ,  $T_{1/2}(0\nu + 3\nu) > (0.04 - 4.8) \times 10^{20} \text{ yr}$  (90% C.L.).

## 1. 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 standard model (SM) Lagrangian, processes appear that violate  $L$  by two units ( $\Delta L = 2$ ) [1]. Searches for  $\Delta L = 2$  processes such as neutrinoless double beta decay ( $0\nu 2\beta$ ) have, therefore, been the goal of many experiments (see recent reviews [2, 3, 4, 5]). However, it is most often overlooked that LNV and Majorana neutrinos are not necessarily connected. Models with  $\Delta L = 3$  and  $\Delta L = 4$  have some power in explaining naturally small Dirac masses of neutrinos and could mediate leptogenesis (see discussions in [6, 7] and references therein). In [6] the toy model with  $\Delta L = 4$  was constructed which allows neutrinoless quadruple beta decay ( $0\nu 4\beta$ ):

$$(A, Z) \rightarrow (A, Z + 4) + 4e^- \quad (1)$$

This feature is discussed in more detail in [8]. Notice that the neutrino in the framework of this model is Dirac and the neutrinoless double beta decay is forbidden. The process (1) was discussed also in [9] and  $\Delta L \geq 4$  lepton number violating processes were discussed in [10]. Note also that quadruple decay with the emission of 4 neutrinos ( $4\nu 4\beta$ ) is not forbidden by any conservation law:

$$(A, Z) \rightarrow (A, Z + 4) + 4e^- + 4\bar{\nu} \quad (2)$$

This is simply a fourth order process for weak interaction. The authors of [6] pointed out three candidate nuclei for quadruple decay ( $^{150}\text{Nd}$ ,  $^{96}\text{Zr}$  and  $^{136}\text{Xe}$ ) and it was noted that for

$^{150}\text{Nd}$  the energy of  $4\beta$  transition is maximum (2084.2 keV [11]) and even transition to excited levels of the daughter nucleus  $^{150}\text{Gd}$  is possible. In this report, we will also consider the triple beta decay of  $^{150}\text{Nd}$  (neutrinoless decay ( $0\nu 3\beta$ ) and decay with 3 neutrino emission ( $3\nu 3\beta$ )):

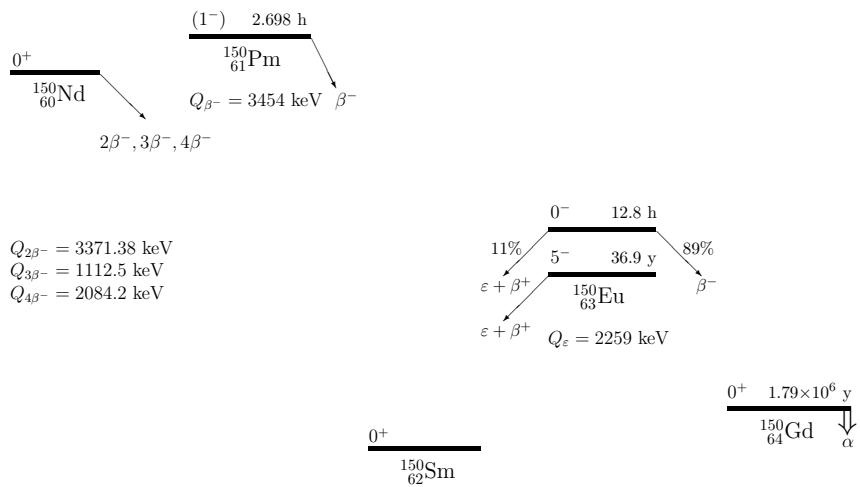
$$(A, Z) \rightarrow (A, Z + 3) + 3e^- \quad (3)$$

$$(A, Z) \rightarrow (A, Z + 3) + 3e^- + 3\bar{\nu} \quad (4)$$

In [6], it was noted that neutrinoless triple beta decay is forbidden, since this process violates Lorentz invariance. This is true, but in this case the search for this process can serve as a test of Lorentz invariance. At the same time, the decay with the emission of three neutrinos is not forbidden by any conservation laws (this is a third-order process for the weak interaction). There are three candidates for this transition only. Besides  $^{150}\text{Nd} - ^{150}\text{Eu}$  transition ( $Q_{3\beta} = 1112.2$  keV), it is also  $^{48}\text{Ca} - ^{48}\text{V}$  ( $Q_{3\beta} = 253.1$  keV) and  $^{96}\text{Zr} - ^{96}\text{Tc}$  ( $Q_{3\beta} = 383.1$  keV).

The search for  $4\beta$  decay was first carried out in the NEMO-3 experiment [12]. The  $0\nu 4\beta$  decay of  $^{150}\text{Nd}$  was investigated. For the transition to the ground state of the  $^{150}\text{Gd}$  the limit  $T_{1/2}(0\nu) > (1.1 - 3.2) \times 10^{21}$  yr (90% C.L.) was obtained, depending on the model used for the kinematic distributions of the emitted electrons. Recently, first limit on the  $0\nu 4\beta$  decay of  $^{150}\text{Nd}$  to the  $0_1^+$  state (1207.13 keV) of  $^{150}\text{Gd}$  was obtained,  $T_{1/2}(0\nu) > 1.76 \times 10^{20}$  yr (90% C.L.) [13].

In this report, results of an experimental investigation of the  $3\beta(0\nu + 3\nu)$  and  $4\beta(0\nu + 4\nu)$  decays of  $^{150}\text{Nd}$  to the ground and excited states of  $^{150}\text{Eu}$  and excited states of  $^{150}\text{Gd}$  are presented. Mass-chain decay scheme is shown in Fig. 1 and demonstrates the fact that  $^{150}\text{Nd}$  energetically can decay to  $^{150}\text{Sm}$  (double beta decay),  $^{150}\text{Eu}$  (triple beta decay) and  $^{150}\text{Gd}$  (quadruple beta decay). The measurements have been carried out using a HPGe detector to look for  $\gamma$ -ray lines corresponding to the decay scheme (taken from [14]). We used experimental data obtained in [15, 16], that previously used to investigate  $2\beta(0\nu + 2\nu)$  decay of  $^{150}\text{Nd}$  to the excited states of  $^{150}\text{Sm}$ .



**Figure 1.** Mass-chain decay scheme (taken from [14]).

## 2. Experiment

The experimental work was performed in the Modane Underground Laboratory (depth of 4800 m w.e.). A 400 cm<sup>3</sup> low-background HPGe detector was used to measure a 3046 g sample of

**Table 1.** Experimental limits for  $4\beta(0\nu + 4\nu)$  decay of  $^{150}\text{Nd}$  to the excited states of  $^{150}\text{Gd}$ . All limits are given at the 90% C.L.

Excited state, keV	Energy of $\gamma$ -rays, keV (efficiency)	$T_{1/2}^{0\nu+4\nu}, (\times 10^{20} \text{ yr})$	This work	Ref. [13]
$2_1^+$ (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)	569.09 (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	-	

$\text{Nd}_2\text{O}_3$  powder in a special Marinelli delrin box which was placed on the detector endcap. Taking into account the natural abundance of  $^{150}\text{Nd}$  (5.64%) there are 153 g of  $^{150}\text{Nd}$  (or  $6.14 \times 10^{23}$  nuclei of  $^{150}\text{Nd}$ ) in the sample. Data was collected for 11320.5 hours.

A full description of the installation is given in [16].

The current data of accepted values for different isotopes published in Nuclear Data Sheets [14] were used for analysis of the energy spectrum. The photon detection efficiency for each investigated process has been calculated with the CERN Monte Carlo code GEANT 3.21.

### 3. Analysis and results

The limit has been calculated using the likelihood function described in [17, 18] which takes into account all the peaks identified above as background.

#### 3.1. Search for $4\beta(0\nu + 4\nu)$ processes in $^{150}\text{Nd}$

Quadruple beta decays of  $^{150}\text{Nd}$  to  $2_1^+$  (638.045 keV),  $3_1^-$  (1134.297 keV),  $0_1^+$  (1207.135 keV),  $4_1^+$  (1288.420 keV),  $2_2^+$  (1430.467 keV) and  $2_3^+$  (1518.362 keV) excited states of  $^{150}\text{Gd}$  have been investigated. The results are presented in Table 1.

#### 3.2. Search for $3\beta(0\nu + 3\nu)$ processes in $^{150}\text{Nd}$

Triple beta decays of  $^{150}\text{Nd}$  to the ground state of  $^{150}\text{Eu}$  ( $5^-$ ), metastable state of  $^{150}\text{Eu}$  ( $0_1^-$ ; 41.7 keV),  $2_2^-$  (118.6 keV),  $3_1^-$  (181.1 keV),  $6_1^-$  (190.4 keV),  $3_2^-$  (195.2 keV),  $6_2^-$  (247.9 keV), ( $3,2$ ) (343.1 keV),  $5_1^-$  (360.1 keV) and  $5_2^-$  (412.5 keV) excited states of  $^{150}\text{Eu}$  have been investigated. Obtained results are presented in Table 2.

### 4. Discussion and conclusion

The results are shown in Tables 1 and 2. Note that the limit on  $4\beta(0\nu + 4\nu)$  decay of  $^{150}\text{Nd}$  to the  $0_1^+$  excited state of  $^{150}\text{Gd}$  obtained in this work is five times stronger than the limit obtained in [13]. For other ( $0\nu+4\nu$ ) transitions to the  $2_1^+$ ,  $3_1^-$ ,  $4_1^+$ ,  $2_2^+$  and  $2_3^+$  excited states limits for the first time have been obtained. Results for  $3\beta(0\nu + 3\nu)$  decay are obtained for the first time. Unfortunately, there are no "real" (accurate) theoretical calculations for these processes. Therefore, we cannot compare our results with theoretical predictions. It is clear only that such transitions should be strongly suppressed compared to the  $2\beta$  decay processes. However, as indicated in [6, 8], under certain conditions it is possible to have significant enhancement for the  $4\beta(0\nu)$  decay process. In [10] it was demonstrated (using "qualitative" estimates) that, under the most favorable assumptions, the half-life of  $^{150}\text{Nd}$  for  $0\nu4\beta$  decay is  $\sim 10^{41}$  yr [10]

**Table 2.** Experimental limits for  $3\beta(0\nu + 3\nu)$  decay of  $^{150}\text{Nd}$  to the ground and excited states of  $^{150}\text{Eu}$ . All limits are given at the 90% C.L.

Excited state, keV	Energy of $\gamma$ -rays, keV (efficiency)	$T_{1/2}^{0\nu+3\nu}, (\times 10^{20} \text{ yr})$	This work	Previous work
$5_{g.s.}^-, 36.9 \text{ yr}$	439.40 (1.71%)	0.50	-	-
$0_1^-$ (41.7 keV), 12.8 h	333.96 (0.10%)	0.04	-	-
$2_1^-$ (118.6 keV)	75.9 (0.12%)	0.30	-	-
$3_1^-$ (181.1 keV)	111.6 (0.48%)	0.63	-	-
$6_1^-$ (190.37 keV)	190.4 (1.52%)	1.81	-	-
$3_2^-$ (195.2 keV)	125.6 (0.66%)	0.78	-	-
$6_2^-$ (247.89 keV)	247.9 (2.24%)	3.27	-	-
(3,2) (343.1 keV)	273.6 (2.11%)	3.16	-	-
$5_1^-$ (360.14 keV)	169.4 (1.28%) + 190.4 (1.44%)	2.24	-	-
$5_2^-$ (412.53 keV)	190.4 (1.39%) + 222.2 (1.86%)	4.83	-	-

(this can be compared with the best present experimental limit,  $T_{1/2} > (1.1 - 3.2) \times 10^{21} \text{ yr}$  [12]). Thus, it is clear that sensitivity of present experiments are very far from theoretical expectations. And, apparently, the prospects for the search for  $0\nu 3\beta$  decays look even more pessimistic. It seems that the search for processes with the emission of neutrinos is more likely to succeed. Unfortunately for these processes there are not even qualitative theoretical estimates. Therefore, both theoretical studies and experimental verification of the possibility of observing such processes are necessary.

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#### References

- [1] Schechter J and Valle J W F 1982 *Phys. Rev. D* **25** 2951
- [2] Vergados J D Ejiri H and Simkovic F 2016 *Int. J. Mod. Phys. E* **25** 163007
- [3] Barabash A S 2018 *Int. J. Mod. Phys. A* **33** 1843001
- [4] Barabash A S 2019 *Frontiers in Phys.* **6** 00160
- [5] Dolinski M J Poon A W P and Rodejohann W *Preprint* nucl-ex/1902.04097
- [6] Heeck J and Rodejohann W 2013 *Eur. Phys. Lett.* **103** 32001
- [7] Heeck J 2013 *Phys. Rev. D* **88** 076004
- [8] Dasgupta A Kang S K and Popov O *Preprint* hep-ph/1903.12558
- [9] Hirsch M Srivastava R and Valle J W F 2018 *Phys. Let. B* **781** 302
- [10] Fonseca R M and Hirsch M 2018 *Phys. Rev. D* **98** 015035
- [11] Wang M et al 2017 *Chin. Phys. C* **41** 030003
- [12] Arnold R et al 2017 *Phys. Rev. Lett.* **119** 041801
- [13] Kidd M F and Tornow W 2018 *Phys. Rev. C* **98** 055501
- [14] Basu S K and Sonzogni A A 2013 *Nuclear Data Sheets* **114** 435
- [15] Barabash A S et al 2004 *JETP Lett.* **79** 10
- [16] Barabash A S Hubert Ph Nachab A and Umatov V I 2009 *Phys. Rev. C* **79** 045501
- [17] Barabash A S et al 1996 *J. Phys.* **G22** 487
- [18] Barabash A S et al 1996 *Nucl. Phys.* **A604** 115