

Double- β Decay

OMITTED FROM SUMMARY TABLE

For a discussion of the double- β decay, see sections 14.9.2 and 14.9.3 of the review "14. Neutrino Masses, Mixing, and Oscillations."

See the related review(s):

[Neutrino Masses, Mixing, and Oscillations](#)

Half-life 0ν double- β decay

In most cases the transitions $(Z,A) \rightarrow (Z+2,A) + 2e^-$ to the 0^+ ground state of the final nucleus are listed. We also list transitions that decrease the nuclear charge ($2e^+$, e^+ CC and double EC) and transitions to an excited state of the final nucleus (0_i^+ , 2^+ , and 2_i^+). In the following Listings only the best or comparable limits for the half-lives of each transition are reported and only those with about $T_{1/2} > 10^{23}$ years that are relevant for particle physics.

$t_{1/2}(10^{23} \text{ yr})$	CL%	ISOTOPE	TRANSITION	METHOD	DOCUMENT ID
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●					
>3800	90	^{136}Xe		KamLAND-Zen	1 ABE 25C
> 350	90	^{130}Te		CUORE	2 ADAMS 25B
> 29	90	^{100}Mo		AMoRE-I	3 AGRAWAL 25
> 76	90	^{76}Ge	g.s. $\rightarrow 0_1^+$	MAJORANA	4 ARNQUIST 25
> 35	90	^{76}Ge	g.s. $\rightarrow 2_1^+$	MAJORANA	4 ARNQUIST 25
> 66	90	^{76}Ge	g.s. $\rightarrow 2_2^+$	MAJORANA	4 ARNQUIST 25
> 21	90	^{136}Xe		PandaX-4T	5 ZHANG 25
> 3	90	^{134}Xe		PandaX-4T	6 YAN 24
> 830	90	^{76}Ge		MAJORANA	7 ARNQUIST 23
> 2.1	90	^{100}Mo	g.s. $\rightarrow 2_1^+$	CUPID-Mo	8 AUGIER 23
> 1.2	90	^{100}Mo	g.s. $\rightarrow 0_1^+$	CUPID-Mo	8 AUGIER 23
> 13	90	^{136}Xe		NEXT	9 NOVELLA 23
> 220	90	^{130}Te		CUORE	10 ADAMS 22A
> 36	90	^{128}Te		CUORE	11 ADAMS 22B
> 12	90	^{136}Xe		XENON1T	12 APRILE 22A
> 18	90	^{100}Mo		CUPID-Mo	13 AUGIER 22
> 46	90	^{82}Se		CUPID-0	14 AZZOLINI 22
> 1.8	90	^{82}Se	g.s. $\rightarrow 0_1^+$	CUPID-0	15 AZZOLINI 22
> 3.0	90	^{82}Se	g.s. $\rightarrow 2_1^+$	CUPID-0	16 AZZOLINI 22
> 3.2	90	^{82}Se	g.s. $\rightarrow 2_2^+$	CUPID-0	17 AZZOLINI 22
> 59	90	^{130}Te	g.s. $\rightarrow 0_1^+$	CUORE	18 ADAMS 21A
> 15	90	^{100}Mo		CUPID-Mo	19 ARMENGAUD 21
> 39.9	90	^{76}Ge	g.s. $\rightarrow 0_1^+$	MAJORANA-Dem	20 ARNQUIST 21
> 21.2	90	^{76}Ge	g.s. $\rightarrow 2_1^+$	MAJORANA-Dem	21 ARNQUIST 21
> 9.7	90	^{76}Ge	g.s. $\rightarrow 2_2^+$	MAJORANA-Dem	22 ARNQUIST 21

>1800	90	^{76}Ge		GERDA	²³ AGOSTINI	20B
> 14	90	^{130}Te	g.s. $\rightarrow 0_1^+$	CUORE-0	²⁴ ALDUINO	19
> 350	90	^{136}Xe		EXO-200	²⁵ ANTON	19
> 2.4	90	^{136}Xe		PANDAX-II	²⁶ NI	19
> 150	90	^{130}Te		CUORE	²⁷ ALDUINO	18
> 2.5	90	^{82}Se		NEMO-3	²⁸ ARNOLD	18
> 2.2	90	^{116}Cd		AURORA	²⁹ BARABASH	18
> 1.1	90	^{134}Xe		EXO-200	³⁰ ALBERT	17C
> 1	90	^{116}Cd		NEMO-3	³¹ ARNOLD	17
> 40	90	^{130}Te		CUORICINO	³² ALDUINO	16
> 260	90	^{136}Xe	g.s. $\rightarrow 2_1^+$	KamLAND-Zen	³³ ASAKURA	16
> 260	90	^{136}Xe	g.s. $\rightarrow 2_2^+$	KamLAND-Zen	³⁴ ASAKURA	16
> 240	90	^{136}Xe	g.s. $\rightarrow 0_1^+$	KamLAND-Zen	³⁵ ASAKURA	16
> 11	90	^{100}Mo		NEMO-3	³⁶ ARNOLD	15
> 9.4	90	^{130}Te	g.s. $\rightarrow 0_1^+$	CUORICINO	³⁷ ANDREOTTI	12
> 0.58	90	^{48}Ca		CaF ₂ scint.	³⁸ UMEHARA	08
> 0.89	90	^{100}Mo	g.s. $\rightarrow 0_1^+$	NEMO-3	³⁹ ARNOLD	07
> 1.6	90	^{100}Mo	g.s. $\rightarrow 2^+$	NEMO-3	⁴⁰ ARNOLD	07
> 1.1	90	^{128}Te		Cryog. det.	⁴¹ ARNABOLDI	03
> 1.7	90	^{116}Cd		$^{116}\text{CdWO}_4$ scint.	⁴² DANEVICH	03
> 157	90	^{76}Ge		Enriched HPGe	⁴³ AALSETH	02B

¹ ABE ^{25C} use the complete data set of the KamLAND-Zen experiment, corresponding to a ^{136}Xe exposure of 2097 kg·yr. The experiment made use of 745 kg of isotopically enriched xenon. The presented result utilizes data acquired during both phases of the experiment.

² ADAMS ^{25B} use 567.0 kg·yr of ^{130}Te exposure of the CUORE high-resolution bolometric calorimeter to place a limit on this decay. CUORE operates in the LNGS laboratory.

³ AGRAWAL ²⁵ report a new half-life limit for the $0\nu\beta\beta$ decay of ^{100}Mo , derived from 3.89 kg·yr of isotope exposure of the AMoRE-I experiment, conducted in the Yangyang Underground Laboratory in Korea.

⁴ ARNQUIST ²⁵ use the final data set collected by the MAJORANA DEMONSTRATOR experiment to place a limit on the $0\nu\beta\beta$ half-life of ^{76}Ge to one of the excited states of ^{76}Se . The data set corresponds to a ^{76}Ge isotope exposure of 98.2 kg·yr.

⁵ ZHANG ²⁵ make use of 44.6 kg·y of ^{136}Xe isotope exposure in the PandaX-4T TPC, using natural xenon, to place a limit on the $0\nu\beta\beta$ decay half-life of ^{136}Xe .

⁶ YAN ²⁴ make use of 17.9 kg·y of ^{134}Xe isotope exposure in the PandaX-4T TPC, using natural xenon, to place a limit on the $0\nu\beta\beta$ decay half-life of ^{134}Xe .

⁷ ARNQUIST ²³ use the final data set of the MAJORANA DEMONSTRATOR experiment, operating enriched in ^{76}Ge detectors, to set this limit on the $0\nu\beta\beta$ half-life of ^{76}Ge . The exposure is 64.5 kg·yr. A median sensitivity of 8.1×10^{25} yr is reported.

⁸ AUGIER ²³ utilize the complete data, set collected by the CUPID-Mo bolometric calorimeter with particle ID and located at the LSM, to study various double beta decays of ^{100}Mo to excited states of the daughter nucleus. An exposure of 1.47 kg·yr of ^{100}Mo is available.

⁹ NOVELLA ²³ use data collected by the NEXT-White experiment to limit the $0\nu\beta\beta$ half-life of ^{136}Xe . The experiment contains 3.5 kg of enriched Xe and is based on a high-pressure gas TPC. Two different limits are reported, based on different data analysis approaches, $> 5.5 \times 10^{23}$ yr and $> 13 \times 10^{23}$ yr.

- 10 ADAMS 22A use the CUORE TeO₂ experiment with an exposure of 288.8 kg·yr of ¹³⁰Te to place a limit on its 0ν ββ decay. The median sensitivity is reported as 280 × 10²³ yr. Supersedes ADAMS 20A.
- 11 ADAMS 22B use the CUORE bolometric calorimeter to place a limit on the 0νββ decay half-life of ¹²⁸Te.
- 12 APRILE 22A use 36.16 kg·yr of ¹³⁶Xe exposure of the XENON1T not enriched detector to establish the stated limit.
- 13 AUGIER 22 use the final data set of the CUPID-Mo cryogenic calorimeter, utilizing enriched Li₂¹⁰⁰MoO₄ and an isotope exposure of 1.47 kg·y, to place a limit on the 0νββ decay half-life.
- 14 AZZOLINI 22 use the CUPID-0 scintillating cryogenic bolometer to set a limit on the 0νββ half-life of ⁸²Se. The analyzed isotope exposure is 8.82 kg·yr. A median sensitivity of 7 × 10²⁴ yr is reported. Supersedes AZZOLINI 19.
- 15 AZZOLINI 22 use CUPID-0 data with an isotope exposure of 8.82 kg·yr to set a limit on the 0νββ decay to the first excited 0⁺ state.
- 16 AZZOLINI 22 use CUPID-0 data with an isotope exposure of 8.82 kg·yr to set a limit on the 0νββ decay to the first excited 2⁺ state.
- 17 AZZOLINI 22 use CUPID-0 data with an isotope exposure of 8.82 kg·yr to set a limit on the 0νββ decay to the second excited 2⁺ state.
- 18 ADAMS 21A et al. used 101.76 kg yr of ¹³⁰Te exposure of the CUORE (LNGS) bolometric detector to place a limit on the decay to the first excited state of ¹³⁰Xe, superseding ALDUINO 19 as the most restrictive bound on this particular decay.
- 19 ARMENGAUD 21 use the CUPID-Mo 4.2 kg array of enriched Li₂¹⁰⁰MoO₄ scintillating bolometers, with 1.17 kg·yr exposure, to set this limit.
- 20 ARNQUIST 21 use the MAJORANA demonstrator to set this limit for the 0ν ββ decay to the first excited 0⁺ state, with a 41.9 kg yr isotopic exposure. The median sensitivity is 39.9 × 10²³ yr.
- 21 ARNQUIST 21 use the MAJORANA demonstrator to set this limit for the 0ν ββ decay to the first excited 2⁺ state, with a 41.9 kg yr isotopic exposure. The median sensitivity is 21.2 × 10²³ yr.
- 22 ARNQUIST 21 use the MAJORANA demonstrator to set this limit for the 0ν ββ decay to the second excited 2⁺ state, with a 41.9 kg yr isotopic exposure. The median sensitivity is 18.6 × 10²³ yr.
- 23 AGOSTINI 20B present the final data set of the GERDA experiment, searching for 0ν ββ decay of ⁷⁶Ge with isotopically enriched, high resolution Ge detectors. A final exposure of 127.2 kg·yr is reported. The experiment reports the lowest background and longest half life limit ever achieved by any double beta decay experiment. The reported experiment sensitivity equals the limit. Supersedes AGOSTINI 19.
- 24 ALDUINO 19 use the combined data of the CUORICINO and CUORE-0 experiments to place a lower limit on the half life of the 0ν ββ decay of ¹³⁰Te to the first excited 0⁺ state of ¹³⁰Xe. Supersedes ANDREOTTI 12.
- 25 ANTON 19 uses the complete dataset of the EXO-200 detector to search for the 0ν ββ decay. The exposure is 234.1 kg yr. The median sensitivity is 5.0 × 10²⁵ yr. Supersedes ALBERT 18 and ALBERT 14B.
- 26 NI 19 use the PandaX-II dual phase TPC at CJPL to search for the 0ν ββ decay of ¹³⁶Xe. The half-life limit 2.4 × 10²³ yr is obtained from 22.2 kg yr exposure with a sensitivity of 1.9 × 10²³ yr.
- 27 ALDUINO 18 uses the CUORE detector to search for the 0ν ββ decay of ¹³⁰Te. The exposure is 86.3 kg·year of natural TeO₂ corresponding to 24.0 kg·year for ¹³⁰Te. The median sensitivity is 0.7 × 10²⁵ yr. The limit is obtained combining the new data from CUORE with those of CUORE0 (9.8 kg·year of ¹³⁰Te) and Cuoricino (19.8 kg·year of ¹³⁰Te).

- 28 ARNOLD 18 use the NEMO-3 tracking detector to place a limit on the $0\nu\beta\beta$ decay of ^{82}Se . This is a slightly weaker limit than in BARABASH 11A, using the same detector. Supersedes ARNOLD 05A.
- 29 BARABASH 18 use 1.162 kg of $^{116}\text{CdWO}_4$ scintillating crystals to obtain this limit. Supersedes DANEVICH 03 with analogous source and is more sensitive than ARNOLD 17.
- 30 ALBERT 17C uses the EXO-200 detector that contains $19.098 \pm 0.014\%$ admixture of ^{134}Xe to search for the 0ν and $2\nu\beta\beta$ decay modes. The exposure is 29.6 kg-year. The median sensitivity is 1.9×10^{21} years.
- 31 ARNOLD 17 use the NEMO-3 tracking calorimeter, containing 410 g of enriched ^{116}Cd exposed for 5.26 yr, to determine the half-life limit. Supersedes BARABASH 11A.
- 32 ALDUINO 16 report result obtained with 9.8 kg-y of data collected with the CUORE-0 bolometer, combined with data from the CUORICINO. Supersedes ALFONSO 15.
- 33 ASAKURA 16 use the KamLAND-Zen liquid scintillator calorimeter (^{136}Xe 89.5 kg yr) to place a limit on the $0\nu\beta\beta$ -decay into the first excited state of the daughter nuclide.
- 34 ASAKURA 16 use the KamLAND-Zen liquid scintillator calorimeter (^{136}Xe 89.5 kg yr) to place a limit on the $0\nu\beta\beta$ -decay into the second excited state of the daughter nuclide.
- 35 ASAKURA 16 use the KamLAND-Zen liquid scintillator calorimeter (^{136}Xe 89.5 kg yr) to place a limit on the $0\nu\beta\beta$ -decay into the third excited state of the daughter nuclide.
- 36 ARNOLD 15 use the NEMO-3 tracking calorimeter with 34.3 kg yr exposure to determine the limit of $0\nu\beta\beta$ -half life of ^{100}Mo . Supersedes ARNOLD 2005A and BARABASH 11A.
- 37 ANDREOTTI 12 use high resolution TeO_2 bolometric calorimeter to search for the $0\nu\beta\beta$ decay of ^{130}Te leading to the excited 0_1^+ state at 1793.5 keV.
- 38 UMEHARA 08 use CaF_2 scintillation calorimeter to search for double beta decay of ^{48}Ca . Limit is significantly more stringent than quoted sensitivity: 18×10^{21} years.
- 39 Limit on 0ν -decay to the first excited 0_1^+ -state of daughter nucleus using NEMO-3 tracking calorimeter. Supersedes DASSIE 95.
- 40 Limit on 0ν -decay to the first excited 2^+ -state of daughter nucleus using NEMO-3 tracking calorimeter.
- 41 Supersedes ALESSANDRELLO 00. Array of TeO_2 crystals in high resolution cryogenic calorimeter. Some enriched in ^{128}Te . Ground state to ground state decay.
- 42 Limit on $0\nu\beta\beta$ decay of ^{116}Cd using enriched CdWO_4 scintillators. Supersedes DANEVICH 00.
- 43 AALSETH 02B limit is based on 117 mol-yr of data using enriched Ge detectors. Background reduction by means of pulse shape analysis is applied to part of the data set. Reported limit is slightly less restrictive than that in KLAPDOR-KLEINGROTHAUS 01 However, it excludes part of the allowed half-life range reported in KLAPDOR-KLEINGROTHAUS 01B for the same nuclide. The analysis has been criticized in KLAPDOR-KLEINGROTHAUS 04B. The criticism was addressed and disputed in AALSETH 04.

Half-life measurements of the two-neutrino double- β decay

The measured half-life values for the transitions $(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}_e$ to the 0^+ ground state of the final nucleus are listed. We also list the transitions to an excited state of the final nucleus (0_i^+ , etc.). We report only the measurements with the smallest (or comparable) uncertainty for each transition.

$t_{1/2}(10^{20} \text{ yr})$	ISOTOPE	TRANSITION	METHOD	DOCUMENT ID
9.32 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ $\begin{smallmatrix} 0.05 \\ 0.04 \end{smallmatrix}$ ± 0.07	^{130}Te		CUORE	1 ADAMS 25A
1.03 $\begin{smallmatrix} + \\ - \end{smallmatrix}$ $\begin{smallmatrix} 0.38 \\ 0.29 \end{smallmatrix}$	^{150}Nd	g.s. $\rightarrow 0_1^+$	STELLA	2 BARABASH 25

• • • We do not use the following data for averages, fits, limits, etc. • • •

440	$\begin{matrix} +160 \\ -90 \end{matrix}$		^{82}Se g.s. $\rightarrow 0_1^+$	OBELIX	3 BARABASH	25A
103	± 15	± 8	^{124}Xe $2\nu\text{DEC}$	PandaX-4T	4 BO	25A
109	± 14	± 5	^{124}Xe $2\nu\text{DEC}$	LZ	5 AALBERS	24C
20.22	± 0.18	± 0.38	^{76}Ge	GERDA	6 AGOSTINI	23
1.11	$\begin{matrix} +0.19 \\ -0.14 \end{matrix}$	$\begin{matrix} +0.17 \\ -0.15 \end{matrix}$	^{150}Nd $0^+ \rightarrow 0_1^+$	NEMO-3	7 AGUERRE	23
7.5	± 0.8	$\begin{matrix} +0.4 \\ -0.3 \end{matrix}$	^{100}Mo $0^+ \rightarrow 0_1^+$	CUPID-Mo	8 AUGIER	23
0.0707	± 0.0002	± 0.0011	^{100}Mo	CUPID-Mo	9 AUGIER	23A
0.869	± 0.005	$\begin{matrix} +0.009 \\ -0.006 \end{matrix}$	^{82}Se	CUPID-0	10 AZZOLINI	23A
21.6	$\begin{matrix} +6.2 \\ -4.0 \end{matrix}$	$\begin{matrix} +4.0 \\ -2.9 \end{matrix}$	^{136}Xe	NEXT	11 NOVELLA	23
21900	± 700		^{128}Te	CUORE	12 ADAMS	22B
110	± 20	± 10	^{124}Xe	XENON1T	13 APRILE	22A
118	± 13	± 14	^{124}Xe	XENONnT	14 APRILE	22B
23.4	$\begin{matrix} +0.8 \\ -4.6 \end{matrix}$	$\begin{matrix} +3.0 \\ -1.7 \end{matrix}$	^{136}Xe	NEXT	15 NOVELLA	22
180	± 50	± 10	^{124}Xe $2\nu\text{DEC}$	XENON1T	16 APRILE	19E
0.0680	± 0.0001	$\begin{matrix} +0.0038 \\ -0.0040 \end{matrix}$	^{100}Mo	NEMO-3	17 ARNOLD	19
0.939	± 0.017	± 0.058	^{82}Se	NEMO-3	18 ARNOLD	18
0.263	$\begin{matrix} +0.011 \\ -0.012 \end{matrix}$		^{116}Cd	AURORA	19 BARABASH	18
> 0.87			^{134}Xe	EXO-200	20 ALBERT	17C
8.2	± 0.2	± 0.6	^{130}Te	CUORE-0	21 ALDUINO	17
0.274	± 0.004	± 0.018	^{116}Cd	NEMO-3	22 ARNOLD	17
0.64	$\begin{matrix} +0.07 \\ -0.06 \end{matrix}$	$\begin{matrix} +0.12 \\ -0.09 \end{matrix}$	^{48}Ca	NEMO-3	23 ARNOLD	16
0.0934	± 0.0022	$\begin{matrix} +0.0062 \\ -0.0060 \end{matrix}$	^{150}Nd	NEMO-3	24 ARNOLD	16A
19.26	± 0.94		^{76}Ge	GERDA	25 AGOSTINI	15A
0.0693	± 0.0004		^{100}Mo	NEMO-3	26 ARNOLD	15
21.65	± 0.16	± 0.59	^{136}Xe	EXO-200	27 ALBERT	14
92	$\begin{matrix} +55 \\ -26 \end{matrix}$	± 13	^{78}Kr	BAKSAN	28 GAVRILYAK	13
23.8	± 0.2	± 1.4	^{136}Xe	KamLAND-Z	29 GANDO	12A
7.0	± 0.9	± 1.1	^{130}Te	NEMO-3	30 ARNOLD	11
0.235	± 0.014	± 0.016	^{96}Zr	NEMO-3	31 ARGYRIADES	10
6.9	$\begin{matrix} +1.0 \\ -0.8 \end{matrix}$	± 0.7	^{100}Mo $0^+ \rightarrow 0_1^+$	Ge coinc.	32 BELLI	10
5.7	$\begin{matrix} +1.3 \\ -0.9 \end{matrix}$	± 0.8	^{100}Mo $0^+ \rightarrow 0_1^+$	NEMO-3	33 ARNOLD	07
0.96	± 0.03	± 0.10	^{82}Se	NEMO-3	34 ARNOLD	05A
0.29	$\begin{matrix} +0.04 \\ -0.03 \end{matrix}$		^{116}Cd	CdWO ₄ sc.	35 DANEVICH	03

¹ ADAMS 25A derive an improved $2\nu\beta\beta$ measurement of the half-life of ^{130}Te from 1038 kg·yr of TeO₂ exposure, with natural Te, of the CUORE experiment.

² BARABASH 25 use the STELLA low background Ge detectors at LNGS to search for $2\nu\beta\beta$ decay of ^{150}Nd to excited states of ^{150}Sm . The observation of $2\nu\beta\beta$ decay to 0_1^+ excited state is reported. The reported half-life value is obtained interpreting an excess observed at 334 keV as an indication of this decay.

- 3 BARABASH 25A use the OBELIX Ge detector counting facility at the Laboratoire Souterrain de Modane to observe the $2\nu\beta\beta$ decay of ^{82}Se to the 0_1^+ excited state of ^{82}Kr .
- 4 BO 25A use data collected by the PandaX-4T experiment to determine the half-life of ^{124}Xe against $2\nu\text{DEC}$. 1.73 ton·yr of xenon exposure were analyzed. Data-derived capture fractions are used in the analysis.
- 5 AALBERS 24C report the observation of ^{124}Xe $2\nu\text{DEC}$. 1.39 kg·yr of isotopic exposure of the LZ dark matter experiment, collected during the first science run, were analyzed. The same capture fractions as used in APRILE 22A were assumed.
- 6 AGOSTINI 23 report an updated value for the $2\nu\beta\beta$ half-life of ^{76}Ge ; the final result of the GERDA Phase II experiment. A subset of the data, corresponding to an exposure of 11.8 kg·yr, is utilized. This is one of the most precise measurements of $2\nu\beta\beta$ decay reported in the literature. An effective nuclear matrix element of 0.101 ± 0.001 is derived from this result.
- 7 AGUERRE 23 report the results of a 5.25 yr search for the $2\nu\beta\beta$ decay to the excited $0^+ \rightarrow 0_1^+$ state of the daughter nucleus, using the NEMO-3 tracking calorimeter. 36.6g of ^{150}Nd isotope were available for the measurement of this decay rate.
- 8 AUGIER 23 utilize the complete data, set collected by the CUPID-Mo bolometric calorimeter with particle ID and located at the LSM, to measure the ^{100}Mo $2\nu\beta\beta$ half-life to excited 0_1^+ state of the daughter nucleus. An exposure of 1.47 kg·yr of ^{100}Mo is available.
- 9 AUGIER 23A use full data set collected by the CUPID-Mo experiment to derive an improved $2\nu\beta\beta$ g.s. to g.s. half-life of ^{100}Mo . An exposure of 1.48 kg·yr of ^{100}Mo is utilized. Supersedes ARMENGAUD 20.
- 10 AZZOLINI 23A report an improved measurement of the $2\nu\beta\beta$ decay with an exposure of 8.82 kg·yr of ^{82}Se , collected with the CUPID-0 detector. Supersedes AZZOLINI 19B.
- 11 NOVELLA 23 used the NEXT-White experiment, with a fiducial mass of 3.5 kg of enriched xenon, to measure the $2\nu\beta\beta$ g.s. to g.s. half-life of ^{136}Xe . The experiment is based on a high-pressure gas TPC. Supersedes NOVELLA 22.
- 12 ADAMS 22B derive the $2\nu\beta\beta$ half-life of ^{128}Te from data of the CUORE bolometric calorimeter and the half-life ratio for $^{130}\text{Te} / ^{128}\text{Te}$ reported in BERNATOWICZ 92.
- 13 APRILE 22A report an improved ^{124}Xe $2\nu\text{DEC}$ half-life measurement for ^{124}Xe , using data collected by the XENON1T detector with an isotopically not enriched Xe target. The analyzed ^{124}Xe exposure is 0.87 kg·yr. The statistical significance of the signal is 7.0 sigma. The stated half-life considers captures from the K shell up to the N5 shell. This result supersedes APRILE 19E, which exclusively considered captures from the K shell.
- 14 APRILE 22B use data collected by the XENONnT dark matter experiment to derive an improved ^{124}Xe $2\nu\text{DEC}$ half-life measurement for ^{124}Xe . This result supersedes APRILE 22A.
- 15 NOVELLA 22 report on a high-pressure gas TPC at Canfranc underground laboratory, filled with 3.5 kg (fiducial) xenon gas, used to measure the $2\nu\beta\beta$ decay of ^{136}Xe . Topological track reconstruction is utilized in the data analysis. The measurement is based on comparing runs with isotopically enriched and depleted xenon. Other measurements with smaller error exist.
- 16 APRILE 19E report first measurement of two-neutrino double electron capture in ^{124}Xe using the XENON1T detector with a 0.73 t·yr exposure. An excess of 126 ± 29 events is observed at 64.3 ± 0.6 keV decay energy, corresponding to $\sqrt{\Delta\chi^2} = 4.4$ with respect to the background-only hypothesis.
- 17 ARNOLD 19 use the NEMO-3 tracking calorimeter with 34.3 kg y exposure to determine the $2\nu\beta\beta$ half-life of ^{100}Mo . Supersedes ARNOLD 15.
- 18 ARNOLD 18 use the NEMO-3 tracking detector to determine the $2\nu\beta\beta$ half-life of ^{82}Se . 0.93 kg of ^{82}Se was observed for 5.25 y. The half-life value was obtained based on the single-state-dominance (SSD) hypothesis, preferred in this case by about 2σ . Supersedes ARNOLD 05A.

- 19 BARABASH 18 use 1.162 kg of $^{116}\text{CdWO}_4$ scintillating crystals to obtain this value. Supersedes DANEVICH 03 with analogous source and agrees with ARNOLD 17 with the NEMO-3 detector.
- 20 ALBERT 17C uses the EXO-200 detector that contains $19.098 \pm 0.014\%$ admixture of ^{134}Xe to search for the $2\nu\beta\beta$ decay mode. The exposure is 29.6 kg-year. The median sensitivity is 1.2×10^{21} years.
- 21 ALDUINO 17 use the CUORE-0 detector containing 10.8 kg of ^{130}Te in 52 crystals of TeO_2 . The exposure was 9.3 kg yr of ^{130}Te . This is a more accurate rate determination than in ARNOLD 11 and BARABASH 11A.
- 22 ARNOLD 17 use the NEMO-3 tracking calorimeter, containing 410 grams of enriched ^{116}Cd exposed for 5.26 years, to determine the half-life value.
- 23 ARNOLD 16 use the NEMO-3 detector and a source of 6.99 g of ^{48}Ca . The half-life is based on 36.7 g year exposure. It is consistent, although somewhat longer, than the previous determinations of the half-life. Supersedes BARABASH 11A.
- 24 ARNOLD 16A use the NEMO-3 tracking calorimeter, containing 36.6 g of ^{150}Nd exposed for 1918.5 days, to determine the half-life. Supersedes ARGYRIADES 09.
- 25 AGOSTINI 15A use 17.9 kg yr exposure of the GERDA calorimeter to derive an improved measurement of the $2\nu\beta\beta$ decay half life of ^{76}Ge .
- 26 ARNOLD 15 use the NEMO-3 tracking calorimeter with 34.3 kg yr exposure to determine the $2\nu\beta\beta$ -half life of ^{100}Mo . Supersedes ARNOLD 05A and ARNOLD 04.
- 27 ALBERT 14 use the EXO-200 tracking detector for a re-measurement of the $2\nu\beta\beta$ -half life of ^{136}Xe . A nuclear matrix element of $0.0218 \pm 0.0003 \text{ MeV}^{-1}$ is derived from this data. Supersedes ACKERMAN 11.
- 28 GAVRILYAK 13 use a proportional counter filled with Kr gas to search for the $2\nu 2\text{K}$ decay of ^{78}Kr . Data with the enriched and depleted Kr were used to determine signal and background. A 2.5σ excess of events obtained with the enriched sample is interpreted as an indication for the presence of this decay.
- 29 GANDO 12A use a modification of the existing KamLAND detector. The $\beta\beta$ decay source/detector is 13 tons of enriched ^{136}Xe -loaded scintillator contained in an inner balloon. The $2\nu\beta\beta$ decay rate is derived from the fit to the spectrum between 0.5 and 4.8 MeV. This result is in agreement with ACKERMAN 11.
- 30 ARNOLD 11 use enriched ^{130}Te in the NEMO-3 detector to measure the $2\nu\beta\beta$ decay rate. This result is in agreement with, but more accurate than ARNOLDI 03.
- 31 ARGYRIADES 10 use $9.4 \pm 0.2 \text{ g}$ of ^{96}Zr in NEMO-3 detector and identify its $2\nu\beta\beta$ decay. The result is in agreement and supersedes ARNOLD 99.
- 32 BELLI 10 use enriched ^{100}Mo with 4 HP Ge detectors to record the 590.8 and 539.5 keV γ rays from the decay of the 0_1^+ state in ^{100}Ru both in singles and coincidences. This result confirms the measurement of KIDD 09 and ARNOLD 07 and supersedes them.
- 33 First exclusive measurement of 2ν -decay to the first excited 0_1^+ -state of daughter nucleus. ARNOLD 07 use the NEMO-3 tracking calorimeter to detect all particles emitted in decay. Result agrees with the inclusive ($0\nu + 2\nu$) measurement of DEBRAECKELEER 01.
- 34 ARNOLD 05A use the NEMO-3 tracking detector to determine the $2\nu\beta\beta$ half-life of ^{82}Se with high statistics and low background (389 days of data taking). Supersedes ARNOLD 04.
- 35 DANEVICH 03 is calorimetric measurement of $2\nu\beta\beta$ ground state decay of ^{116}Cd using enriched CdWO_4 scintillators. Agrees with EJIRI 95 and ARNOLD 96. Supersedes DANEVICH 00.

$\langle m_{ee} \rangle$, The Effective Weighted Sum of Majorana Neutrino Masses Contributing to Neutrinoless Double- β Decay

$\langle m_{ee} \rangle = |\sum U_{ei}^2 m_{\nu_i}|$, $i = 1, 2, 3$. It is assumed that ν_i are Majorana particles and that the transition is dominated by the known (light) neutrinos. Note that U_{ei}^2 and not $|U_{ei}|^2$ occur in the sum, and that consequently cancellations are possible. The experiments obtain the limits on $\langle m_{\nu} \rangle$ from the measured ones on $T_{1/2}$ using a range of nuclear matrix elements (NME), which is reflected in the spread of $\langle m_{\nu} \rangle$. Different experiments may choose different NME. All assume $g_A = 1.27$. In the following Listings, only the best or comparable limits for each isotope are reported. When not mentioned explicitly the transition is between ground states, but transitions between excited states are also reported.

VALUE (eV)	ISOTOPE	METHOD	DOCUMENT ID
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
< 0.028–0.122	^{136}Xe	KamLAND-Zen	¹ ABE 25C
< 0.07–0.25	^{130}Te	CUORE	² ADAMS 25B
< 0.21–0.61	^{100}Mo	AMoRE-I	³ AGRAWAL 25
< 0.4–1.6	^{136}Xe	PandaX-4T	⁴ ZHANG 25
< 0.113–0.269	^{76}Ge	MAJORANA	⁵ ARNQUIST 23
< 0.48–3.19	^{136}Xe	NEXT	⁶ NOVELLA 23
< 0.09–0.305	^{130}Te	CUORE	⁷ ADAMS 22A
< 0.8–2.5	^{136}Xe	XENON1T	⁸ APRILE 22A
< 0.28–0.49	^{100}Mo	CUPID-Mo	⁹ AUGIER 22
< 0.263–0.545	^{82}Se	CUPID-0	¹⁰ AZZOLINI 22
< 0.31–0.54	^{100}Mo	CUPID-Mo	¹¹ ARMENGAUD 21
< 0.079–0.180	^{76}Ge	GERDA	¹² AGOSTINI 20B
< 1.2–2.1	^{100}Mo	AMoRE	¹³ ALENKOV 19
< 0.093–0.286	^{136}Xe	EXO-200	¹⁴ ANTON 19
< 1.3–3.5	^{136}Xe	PANDAX-II	¹⁵ NI 19
< 0.11–0.52	^{130}Te	CUORE	¹⁶ ALDUINO 18
< 1.2–3.0	^{82}Se	NEMO-3	¹⁷ ARNOLD 18
< 1.0–1.7	^{116}Cd	AURORA	¹⁸ BARABASH 18
< 1.4–2.5	^{116}Cd	NEMO-3	¹⁹ ARNOLD 17
< 0.27–0.76	^{130}Te	CUORICINO	²⁰ ALDUINO 16
< 1.6–5.3	^{150}Nd	NEMO-3	²¹ ARNOLD 16A
< 0.33–0.62	^{100}Mo	NEMO-3	²² ARNOLD 15
< 7.2–19.5	^{96}Zr	NEMO-3	²³ ARGYRIADES 10
< 3.5–22	^{48}Ca	CaF ₂ scint.	²⁴ UMEHARA 08
< 1.5–1.7	^{116}Cd	$^{116}\text{CdWO}_4$ scint.	²⁵ DANEVICH 03

¹ ABE 25C use the complete data set of the KamLAND-Zen experiment, corresponding to a ^{136}Xe exposure of 2097 kg·yr. The experiment made use of 745 kg of isotopically enriched xenon. The stated range of effective Majorana neutrino masses corresponds to the authors' assessment of nuclear matrix element variability.

² ADAMS 25B use 567.0 kg·yr of ^{130}Te exposure of the CUORE high-resolution bolometric calorimeter to place a limit on the effective Majorana neutrino mass. The range corresponds to the authors' assessment of nuclear matrix element variability.

- 3 ARAWAL 25 derive a range of upper limits on the effective Majorana neutrino mass, using 3.89 kg·yr of isotope exposure of the AMoRE-I experiment. The experiment is conducted in the Yangyang Underground Laboratory in Korea. The reported range is due to the authors' evaluation of the spread of relevant nuclear matrix elements.
- 4 ZHANG 25 make use of 44.6 kg·y of ^{136}Xe isotope exposure in the PandaX-4T TPC, using natural xenon, to place a limit on the $0\nu\beta\beta$ decay half-life of ^{136}Xe . The derived range of effective Majorana neutrino masses reflects the author's evaluation of the spread of relevant nuclear matrix elements.
- 5 ARNQUIST 23 use the final data set of the MAJORANA DEMONSTRATOR experiment, with 64.5 kg·yr of isotop exposure, to derive an upper limit for $\langle m_{\beta\beta} \rangle$. The range reflects the author's assessment of the variability of the theoretically calculated nuclear matrix elements.
- 6 NOVELLA 23 use data collected with the NEXT-White experiment to derive a range of upper limits for $\langle m_{\beta\beta} \rangle$. The range reflects the author's assessment of the variability of the theoretically calculated nuclear matrix elements and both half-life limits stated in NOVELLA 23.
- 7 ADAMS 22A use 1038.4 kg·yr of TeO_2 exposure collected by the CUORE experiment to determine this range of limits. The range reflects the uncertainty of nuclear matrix element calculations needed for the conversion of half-life to neutrino mass.
- 8 APRILE 22A use data taken with the XENON1T detector to limit the Majorana neutrino mass. 36.16 kg·yr of ^{136}Xe exposure were utilized. The reported range of limits is due to uncertainties in the nuclear matrix elements.
- 9 AUGIER 22 use the final data set of the CUPID-Mo cryogenic calorimeter with an isotop exposure of 1.47 kg·y to derive a range of neutrino mass limits. The range reflects the authors' estimate of the spread of nuclear matrix element calculations.
- 10 AZZOLINI 22 use 8.82 kg·yr of isotopic exposure of the CPID-0 scintillating cryogenic bolometer to set this range of neutrino mass limits. The range reflects the authors' estimate of the spread of nuclear matrix element calculations.
- 11 ARMENGAUD 21 use the CUPID-Mo demonstrator, with 1.17 kg·yr exposure of ^{100}Mo , to set this limit. The range reflects the estimated uncertainty of the calculated nuclear matrix elements.
- 12 AGOSTINI 20B use the final data set of the GERDA experiment, representing an exposure of 127.2 kg·yr to derive an upper limit for $\langle m_{\beta\beta} \rangle$. Isotopically enriched Ge detectors were used. The range reflects the variability of the theoretically calculated nuclear matrix elements. Supersedes AGOSTINI 19.
- 13 ALENKOV 19 report the range of the effective masses $\langle m_{\beta\beta} \rangle$ corresponding to the $0\nu\beta\beta$ decay half-life limit. It is based on the 52.1 kg·d exposure of ^{100}Mo , in the Yangyang underground laboratory. The median sensitivity is 1.1×10^{23} years. The range of $\langle m_{\beta\beta} \rangle$ reflects the uncertainty of nuclear matrix elements.
- 14 ANTON 19 uses the complete dataset of the EXO-200 experiment to obtain these limits. The spread reflect the uncertainty in the nuclear matrix elements. Supersedes ALBERT 18 and ALBERT 14B.
- 15 NI 19 use the PandaX-II dual phase TPC at CJPL to search for the $0\nu\beta\beta$ decay of ^{136}Xe with 22.2 kg yr exposure. The range in the $m_{\beta\beta}$ limit of 1.3–3.5 eV reflects the range of the calculated nuclear matrix elements. The sensitivity is 1.9×10^{23} yr.
- 16 ALDUINO 18 use the combined data of CUORE, CUORE0, and Cuoricino to obtain this limit.
- 17 ARNOLD 18 use the NEMO-3 tracking detector to constrain the $0\nu\beta\beta$ decay of ^{82}Se . The limit on $\langle m_{\beta\beta} \rangle$ is obtained assuming light neutrino exchange; the range reflects different calculations of the nuclear matrix elements. This is a somewhat weaker limit than in BARABASH 11A using the same detector.
- 18 BARABASH 18 use 1.162 kg of $^{116}\text{CdWO}_4$ scintillating crystals to obtain these limits. The spread reflects the estimated uncertainty in the nuclear matrix element. Supersedes DANEVICH 03.

- 19 ARNOLD 17 utilize NEMO-3 data, taken with enriched ^{116}Cd to limit the effective Majorana neutrino mass. The reported range results from the use of different nuclear matrix elements. Supersedes BARABASH 11A.
- 20 ALDUINO 16 place a limit on the effective Majorana neutrino mass using the combined data of the CUORE-0 and CUORICINO experiments. The range reflects the authors' evaluation of the variability of the nuclear matrix elements. Supersedes ALFONSO 15.
- 21 ARNOLD 16A limit is derived from data taken with the NEMO-3 detector and ^{150}Nd . A range of nuclear matrix elements that include the effect of nuclear deformation have been used. Supersedes ARGYRIADES 09.
- 22 ARNOLD 15 use the NEMO-3 tracking calorimeter with 34.3 kg yr exposure to determine the neutrino mass limit based on the $0\nu\beta\beta$ -half life of ^{100}Mo . The spread range reflects different nuclear matrix elements. Supersedes ARNOLD 14 and BARABASH 11A.
- 23 ARGYRIADES 10 use ^{96}Zr and the NEMO-3 tracking detector to obtain the reported mass limit. The range reflects the fluctuation of the nuclear matrix elements considered.
- 24 Limit was obtained using CaF_2 scintillation calorimeter to search for double beta decay of ^{48}Ca . Reported range of limits reflects spread of QRPA and SM matrix element calculations used. Supersedes OGAWA 04.
- 25 Limit for $\langle m_{\nu} \rangle$ is based on the nuclear matrix elements of STAUDT 90 and ARNOLD 96. Supersedes DANEVICH 00.

Limits on Lepton-Number Violating (V+A) Current Admixture

Considering that a number of experiments earlier than 1989 did not distinguish between λ and η , we list only results from that year on. $\langle \lambda \rangle = \lambda \sum U_{ej} V_{ej}$ and $\langle \eta \rangle = \eta \sum U_{ej} V_{ej}$, where the sum is over the number of neutrino generations. This sum vanishes for massless or unmixed neutrinos. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

$\langle \lambda \rangle$ (10^{-6})	CL%	$\langle \eta \rangle$ (10^{-8})	CL%	ISOTOPE	METHOD	DOCUMENT ID
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●						
< 2.2–2.6	90	< 1.7–2.1	90	^{82}Se	NEMO-3	¹ ARNOLD 18
< 1.8–22	90	< 1.6–21	90	^{116}Cd	AURORA	² BARABASH 18
< 0.9–1.3	90	< 0.5–0.8	90	^{100}Mo	NEMO-3	³ ARNOLD 14
<120	90			^{100}Mo	$0^+ \rightarrow 2^+$	⁴ ARNOLD 07
$0.692^{+0.058}_{-0.056}$	68	$0.305^{+0.026}_{-0.025}$	68	^{76}Ge	Enriched HPGe	⁵ KLAPDOR-K...06A
< 2.5	90			^{100}Mo	0ν , NEMO-3	⁶ ARNOLD 05A
< 3.8	90			^{82}Se	0ν , NEMO-3	⁷ ARNOLD 05A
< 1.5–2.0	90			^{100}Mo	0ν , NEMO-3	⁸ ARNOLD 04
< 3.2–3.8	90			^{82}Se	0ν , NEMO-3	⁹ ARNOLD 04
< 1.6–2.4	90	< 0.9–5.3	90	^{130}Te	Cryog. det.	¹⁰ ARNABOLDI 03
< 2.2	90	<2.5	90	^{116}Cd	$^{116}\text{CdWO}_4$ scint.	¹¹ DANEVICH 03
< 3.2–4.7	90	< 2.4–2.7	90	^{100}Mo	ELEGANT V	¹² EJIRI 01
< 1.1	90	<0.64	90	^{76}Ge	Enriched HPGe	¹³ GUENTHER 97
< 4.4	90	<2.3	90	^{136}Xe	TPC	¹⁴ VUILLEUMIER 93
		<5.3		^{128}Te	Geochem	¹⁵ BERNATOW... 92

¹ ARNOLD 18 use the NEMO03 tracking detector, with 0.93 kg of ^{82}Se mass and 5.25 y exposure to obtain the limits for the hypothetical right-handed currents. Supersedes ARNOLD 05A.

² BARABASH 18 use 1.162 kg of $^{116}\text{CdWO}_4$ scintillating crystals to obtain this limits for the hypothetical right-handed currents in the $0\nu\beta\beta$ decay of ^{116}Cd .

- ³ ARNOLD 14 is based on 34.7 kg yr of exposure of the NEMO-3 tracking calorimeter. The reported range limit on $\langle\lambda\rangle$ and $\langle\eta\rangle$ reflects the nuclear matrix element uncertainty in ^{100}Mo .
- ⁴ ARNOLD 07 use NEMO-3 half life limit for 0ν -decay of ^{100}Mo to the first excited 2^+ -state of daughter nucleus to limit the right-right handed admixture of weak currents $\langle\lambda\rangle$. This limit is not competitive when compared to the decay to the ground state.
- ⁵ Re-analysis of data originally published in KLAPDOR-KLEINGROTHAUS 04A. Modified pulse shape analysis leads the authors to claim 6σ statistical evidence for observation of 0ν -decay. Authors use matrix element of MUTO 89 to determine $\langle\lambda\rangle$ and $\langle\eta\rangle$. Uncertainty of nuclear matrix element is not reflected in stated errors.
- ⁶ ARNOLD 05A derive limit for $\langle\lambda\rangle$ based on ^{100}Mo data collected with NEMO-3 detector. No limit for $\langle\eta\rangle$ is given. Supersedes ARNOLD 04.
- ⁷ ARNOLD 05A derive limit for $\langle\lambda\rangle$ based on ^{82}Se data collected with NEMO-3 detector. No limit for $\langle\eta\rangle$ is given. Supersedes ARNOLD 04.
- ⁸ ARNOLD 04 use the matrix elements of SUHONEN 94 to obtain a limit for $\langle\lambda\rangle$, no limit for $\langle\eta\rangle$ is given. This limit is more stringent than the limit in EJIRI 01 for the same nucleus.
- ⁹ ARNOLD 04 use the matrix elements of TOMODA 91 and SUHONEN 91 to obtain a limit for $\langle\lambda\rangle$, no limit for $\langle\eta\rangle$ is given.
- ¹⁰ Supersedes ALESSANDRELLO 00. Cryogenic calorimeter search. Reported a range reflecting uncertainty in nuclear matrix element calculations.
- ¹¹ Limits for $\langle\lambda\rangle$ and $\langle\eta\rangle$ are based on nuclear matrix elements of STAUDT 90. Supersedes DANEVICH 00.
- ¹² The range of the reported $\langle\lambda\rangle$ and $\langle\eta\rangle$ values reflects the spread of the nuclear matrix elements. On axis value assuming $\langle m_\nu \rangle = 0$ and $\langle\lambda\rangle = \langle\eta\rangle = 0$, respectively.
- ¹³ GUENTHER 97 limits use the matrix elements of STAUDT 90. Supersedes BALYSH 95 and BALYSH 92.
- ¹⁴ VUILLEUMIER 93 uses the matrix elements of MUTO 89. Based on a half-life limit 2.6×10^{23} y at 90%CL.
- ¹⁵ BERNATOWICZ 92 takes the measured geochemical decay width as a limit on the 0ν width, and uses the SUHONEN 91 coefficients to obtain the least restrictive limit on η . Further details of the experiment are given in BERNATOWICZ 93.

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EJIRI	95	JPSJ 64 339	H. Ejiri <i>et al.</i>	(OSAK, KIEV)
SUHONEN	94	PR C49 3055	J. Suhonen, O. Civitarese	
BERNATOW...	93	PR C47 806	T. Bernatowicz <i>et al.</i>	(WUSL, TATA)
VUILLEUMIER	93	PR D48 1009	J.C. Vuilleumier <i>et al.</i>	(NEUC, CIT, VILL)

BALYSH	92	PL B283 32	A. Balysh <i>et al.</i>	(MPIK, KIAE, SASSO)
BERNATOW...	92	PRL 69 2341	T. Bernatowicz <i>et al.</i>	(WUSL, TATA)
SUHONEN	91	NP A535 509	J. Suhonen, S.B. Khadkikar, A. Faessler	(JYV+)
TOMODA	91	RPP 54 53	T. Tomoda	
STAUDT	90	EPL 13 31	A. Staudt, K. Muto, H.V. Klapdor-Kleingrothaus	
MUTO	89	ZPHY A334 187	K. Muto, E. Bender, H.V. Klapdor	(TINT, MPIK)
