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.

$t_{1/2}(10^{23}$ yr)	*CL%*	*ISOTOPE*	*TRANSITION*	*METHOD*	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$>$ 3	90	^{134}Xe		PandaX-4T	[1] YAN	24
$>$2300	90	^{136}Xe		KamLAND-Zen	[2] ABE	23
$>$ 830	90	^{76}Ge		MAJORANA	[3] ARNQUIST	23
$>$ 2.1	90	^{100}Mo	g.s. $\rightarrow 2^+_1$	CUPID-Mo	[4] AUGIER	23
$>$ 1.2	90	^{100}Mo	g.s. $\rightarrow 0^+_1$	CUPID-Mo	[4] AUGIER	23
$>$ 13	90	^{136}Xe		NEXT	[5] NOVELLA	23
$>$ 220	90	^{130}Te		CUORE	[6] ADAMS	22A
$>$ 36	90	^{128}Te		CUORE	[7] ADAMS	22B
$>$ 12	90	^{136}Xe		XENON1T	[8] APRILE	22A
$>$ 18	90	^{100}Mo		CUPID-Mo	[9] AUGIER	22
$>$ 46	90	^{82}Se		CUPID-0	[10] AZZOLINI	22
$>$ 1.8	90	^{82}Se	g.s. $\rightarrow 0^+_1$	CUPID-0	[11] AZZOLINI	22
$>$ 3.0	90	^{82}Se	g.s. $\rightarrow 2^+_1$	CUPID-0	[12] AZZOLINI	22
$>$ 3.2	90	^{82}Se	g.s. $\rightarrow 2^+_2$	CUPID-0	[13] AZZOLINI	22
$>$ 59	90	^{130}Te	g.s. $\rightarrow 0^+_1$	CUORE	[14] ADAMS	21A
$>$ 15	90	^{100}Mo		CUPID-Mo	[15] ARMENGAUD	21
$>$ 39.9	90	^{76}Ge	g.s. $\rightarrow 0^+_1$	MAJORANA-Dem	[16] ARNQUIST	21
$>$ 21.2	90	^{76}Ge	g.s. $\rightarrow 2^+_1$	MAJORANA-Dem	[17] ARNQUIST	21
$>$ 9.7	90	^{76}Ge	g.s. $\rightarrow 2^+_2$	MAJORANA-Dem	[18] ARNQUIST	21
$>$ 320	90	^{130}Te		CUORE	[19] ADAMS	20A
$>$1800	90	^{76}Ge		GERDA	[20] AGOSTINI	20B
$>$ 14	90	^{130}Te	g.s. $\rightarrow 0^+_1$	CUORE-0	[21] ALDUINO	19
$>$ 0.95	90	^{100}Mo		AMoRE	[22] ALENKOV	19
$>$ 350	90	^{136}Xe		EXO-200	[23] ANTON	19
$>$ 2.4	90	^{136}Xe		PANDAX-II	[24] NI	19

> 150	90	^{130}Te		CUORE	[25] ALDUINO	18
> 2.5	90	^{82}Se		NEMO-3	[26] ARNOLD	18
> 2.2	90	^{116}Cd		AURORA	[27] BARABASH	18
> 1.1	90	^{134}Xe		EXO-200	[28] ALBERT	17C
> 1	90	^{116}Cd		NEMO-3	[29] ARNOLD	17
> 40	90	^{130}Te		CUORICINO	[30] ALDUINO	16
> 260	90	^{136}Xe	g.s.$\rightarrow 2_1^+$	KamLAND-Zen	[31] ASAKURA	16
> 260	90	^{136}Xe	g.s.$\rightarrow 2_2^+$	KamLAND-Zen	[32] ASAKURA	16
> 240	90	^{136}Xe	g.s.$\rightarrow 0_1^+$	KamLAND-Zen	[33] ASAKURA	16
> 11	90	^{100}Mo		NEMO-3	[34] ARNOLD	15
> 9.4	90	^{130}Te	g.s. $\rightarrow 0_1^+$	CUORICINO	[35] ANDREOTTI	12
> 0.58	90	^{48}Ca		CaF_2 scint.	[36] UMEHARA	08
> 0.89	90	^{100}Mo	g.s. $\rightarrow 0_1^+$	NEMO-3	[37] ARNOLD	07
> 1.6	90	^{100}Mo	g.s. $\rightarrow 2^+$	NEMO-3	[38] ARNOLD	07
> 1.1	90	^{128}Te		Cryog. det.	[39] ARNABOLDI	03
> 1.7	90	^{116}Cd		$^{116}CdWO_4$ scint.	[40] DANEVICH	03
> 157	90	^{76}Ge		Enriched HPGe	[41] AALSETH	02B

[1] 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.

[2] ABE 23 use the combined data set of the KamLAND-Zen 400 and 800 experiments, utilizing 745 kg of isotopically enriched xenon (90.9% ^{136}Xe), dissolved in liquid scintillator and an exposure of 970 kg·yr of ^{136}Xe, to derive this limit on $0\nu\beta\beta$ decay. A half-life sensitivity of 1.5×10^{26} yr is reported.

[3] 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.

[4] 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.

[5] 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.

[6] ADAMS 22A use the CUORE TeO_2 experiment with an exposure of 288.8 kg·yr of ^{130}Te to place a limit on its $0\nu\ \beta\beta$ decay. The median sensitivity is reported as 280×10^{23} yr. Superseeds ADAMS 20A.

[7] ADAMS 22B use the CUORE bolometric calorimeter to place a limit on the $0\nu\beta\beta$ decay half-life of ^{128}Te.

[8] APRILE 22A use 36.16 kg·yr of ^{136}Xe exposure of the XENON1T not enriched detector to establish the stated limit.

[9] AUGIER 22 use the final data set of the CUPID-Mo cryogenic calorimeter, utilizing enriched $Li_2{}^{100}MoO_4$ and an isotope exposure of 1.47 kg·y, to place a limit on the $0\nu\beta\beta$ decay half-life.

[10] AZZOLINI 22 use the CUPID-0 scintillating cryogenic bolometer to set a limit on the $0\nu\beta\beta$ half-life of ^{82}Se. The analyzed isotope exposure is 8.82 kg·yr. A median sensitivity of 7×10^{24} yr is reported. Supersedes AZZOLINI 19.

[11] AZZOLINI 22 use CUPID-0 data with an isotope exposure of 8.82 kg·yr to set a limit on the $0\nu\beta\beta$ decay to the first excited 0^+ state.

[12] AZZOLINI 22 use CUPID-0 data with an isotope exposure of 8.82 kg·yr to set a limit on the $0\nu\beta\beta$ decay to the first excited 2^+ state.

[13] AZZOLINI 22 use CUPID-0 data with an isotope exposure of 8.82 kg·yr to set a limit on the $0\nu\beta\beta$ decay to the second excited 2^+ state.

[14] ADAMS 21A et al. used 101.76 kg yr of ^{130}Te exposure of the CUORE (LNGS) bolometric detector to place a limit on the decay to the first excited state of ^{130}Xe, superseding ALDUINO 19 as the most restrictive bound on this particular decay.

[15] ARMENGAUD 21 use the CUPID-Mo 4.2 kg array of enriched $Li_2{}^{100}MoO_4$ scintillating bolometers, with 1.17 kg·yr exposure, to set this limit.

[16] ARNQUIST 21 use the MAJORANA demonstrator to set this limit for the $0\nu\ \beta\beta$ decay to the first excited 0^+ state, with a 41.9 kg yr isotopic exposure. The median sensitivity is 39.9×10^{23} yr.

[17] ARNQUIST 21 use the MAJORANA demonstrator to set this limit for the $0\nu\ \beta\beta$ decay to the first excited 2^+ state, with a 41.9 kg yr isotopic exposure. The median sensitivity is 21.2×10^{23} yr.

[18] ARNQUIST 21 use the MAJORANA demonstrator to set this limit for the $0\nu\ \beta\beta$ decay to the second excited 2^+ state, with a 41.9 kg yr isotopic exposure. The median sensitivity is 18.6×10^{23} yr.

[19] ADAMS 20A use the CUORE detector to search for the $0\nu\ \beta\beta$ decay of ^{130}Te. The exposure was 372.5 kg·yr of TeO_2 corresponding to 103.6 kg·yr of ^{130}Te. The exclusion sensitivity is 1.7×10^{25}yr. Supersedes ALDUINO 18.

[20] AGOSTINI 20B present the final data set of the GERDA experiment, searching for $0\nu\ \beta\beta$ decay of ^{76}Ge 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.

[21] ALDUINO 19 use the combined data of the CUORICINO and CUORE-0 experiments to place a lower limit on the half life of the $0\nu\ \beta\beta$ decay of ^{130}Te to the first excited 0^+ state of ^{130}Xe. Supersedes ANDREOTTI 12.

[22] ALENKOV 19 report the $0\nu\ \beta\beta$ decay half-life limit based on the 52.1 kg·d exposure of ^{100}Mo, of a a cryogenic dual heat and light detector in the Yangyang underground laboratory. The median sensitivity is 1.1×10^{23} years.

[23] ANTON 19 uses he complete dataset of the EXO-200 detector to search for the $0\nu\ \beta\beta$ decay. The exposure is 234.1 kg yr. The median sensitivity is 5.0×10^{25} yr. Supersedes ALBERT 18 and ALBERT 14B.

[24] NI 19 use the PandaX-II dual phase TPC at CJPL to search for the $0\nu\ \beta\beta$ decay of ^{136}Xe. The half-life limit 2.4×10^{23} yr is obtained from 22.2 kg yr exposure with a sensitivity of 1.9×10^{23} yr.

[25] ALDUINO 18 uses the CUORE detector to search for the $0\nu\ \beta\beta$ decay of ^{130}Te. The exposure is 86.3 kg·year of natural TeO_2 corresponding to 24.0 kg·year for ^{130}Te. The median sensitivity is 0.7×10^{25} yr. The limit is obtained combining the new data from CUORE with those of CUORE0 (9.8 kg·year of ^{130}Te) and Cuoricino (19.8 kg·year of ^{130}Te).

[26] 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.

[27] BARABASH 18 use 1.162 kg of $^{116}CdWO_4$ scintillating crystals to obtain this limit. Supersedes DANEVICH 03 with analogous source and is more sensitive than ARNOLD 17.

[28] 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.

[29] 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.
[30] 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.
[31] 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.
[32] 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.
[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 third excited state of the daughter nuclide.
[34] 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.
[35] 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.
[36] 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.
[37] Limit on 0ν-decay to the first excited 0^+_1-state of daughter nucleus using NEMO-3 tracking calorimeter. Supersedes DASSIE 95.
[38] Limit on 0ν-decay to the first excited 2^+-state of daughter nucleus using NEMO-3 tracking calorimeter.
[39] Supersedes ALESSANDRELLO 00. Array of TeO_2 crystals in high resolution cryogenic calorimeter. Some enriched in ^{128}Te. Ground state to ground state decay.
[40] Limit on $0\nu\beta\beta$ decay of ^{116}Cd using enriched $CdWO_4$ scintillators. Supersedes DANEVICH 00.
[41] 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) + $2e^-$ + $2\overline{\nu}_e$ 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 measuremetnts with the smallest (or comparable) uncertainty for each transition.

$t_{1/2}$(10^{20} yr)	ISOTOPE	TRANSITION	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
109 ± 14 ± 5	^{124}Xe	2νDEC	LZ	[1] AALBERS	24C
20.22 ± 0.18 ± 0.38	^{76}Ge		GERDA	[2] AGOSTINI	23
$1.11^{+0.19}_{-0.14}{}^{+0.17}_{-0.15}$	^{150}Nd	$0^+ \rightarrow 0^+_1$	NEMO-3	[3] AGUERRE	23
$7.5 \pm 0.8^{+0.4}_{-0.3}$	^{100}Mo	$0^+ \rightarrow 0^+_1$	CUPID-Mo	[4] AUGIER	23
0.0707 ± 0.0002 ± 0.0011	^{100}Mo		CUPID-Mo	[5] AUGIER	23A
$0.869 \pm 0.005^{+0.009}_{-0.006}$	^{82}Se		CUPID-0	[6] AZZOLINI	23A
$21.6^{+6.2}_{-4.0}{}^{+4.0}_{-2.9}$	^{136}Xe		NEXT	[7] NOVELLA	23
21900 ±700	^{128}Te		CUORE	[8] ADAMS	22B
110 ± 20 ±10	^{124}Xe		XENON1T	[9] APRILE	22A

118	±13	±14	^{124}Xe	XENONnT	10 APRILE	22B
23.4	$^{+0.8}_{-4.6}$	$^{+3.0}_{-1.7}$	^{136}Xe	NEXT	11 NOVELLA	22
8.76	$^{+0.09}_{-0.07}$	$^{+0.14}_{-0.17}$	^{130}Te	CUORE	12 ADAMS	21
180	±50	±10	^{124}Xe 2νDEC	XENON1T	13 APRILE	19E
0.0680	±0.0001	$^{+0.0038}_{-0.0040}$	^{100}Mo	NEMO-3	14 ARNOLD	19
0.939	±0.017	±0.058	^{82}Se	NEMO-3	15 ARNOLD	18
0.263	$^{+0.011}_{-0.012}$		^{116}Cd	AURORA	16 BARABASH	18
>0.87			^{134}Xe	EXO-200	17 ALBERT	17C
8.2	±0.2	±0.6	^{130}Te	CUORE-0	18 ALDUINO	17
0.274	±0.004	±0.018	^{116}Cd	NEMO-3	19 ARNOLD	17
0.64	$^{+0.07}_{-0.06}$	$^{+0.12}_{-0.09}$	^{48}Ca	NEMO-3	20 ARNOLD	16
0.0934	±0.0022	$^{+0.0062}_{-0.0060}$	^{150}Nd	NEMO-3	21 ARNOLD	16A
19.26	±0.94		^{76}Ge	GERDA	22 AGOSTINI	15A
0.0693	±0.0004		^{100}Mo	NEMO-3	23 ARNOLD	15
21.65	±0.16	±0.59	^{136}Xe	EXO-200	24 ALBERT	14
92	$^{+55}_{-26}$	±13	^{78}Kr	BAKSAN	25 GAVRILYAK	13
23.8	±0.2	±1.4	^{136}Xe	KamLAND-Z	26 GANDO	12A
7.0	±0.9	±1.1	^{130}Te	NEMO-3	27 ARNOLD	11
0.235	±0.014	±0.016	^{96}Zr	NEMO-3	28 ARGYRIADES	10
6.9	$^{+1.0}_{-0.8}$	±0.7	^{100}Mo $0^+ \to 0^+_1$	Ge coinc.	29 BELLI	10
5.7	$^{+1.3}_{-0.9}$	±0.8	^{100}Mo $0^+ \to 0^+_1$	NEMO-3	30 ARNOLD	07
0.96	±0.03	±0.10	^{82}Se	NEMO-3	31 ARNOLD	05A
0.29	$^{+0.04}_{-0.03}$		^{116}Cd	$CdWO_4$ sc.	32 DANEVICH	03

[1] AALBERS 24C report the observation of ^{124}Xe 2νDEC. 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.

[2] AGOSTINI 23 report an updated value for the 2ν $\beta\beta$ half-life of ^{76}Ge; the final result of the GERDA Phase II experiment. A subset of the data, corresponding to an exposure of exposure is 11.8 kg·yr, is utilized. This is one of the most precise measurements of 2ν $\beta\beta$ decay reported in the literature. An effective nuclear matrix element of 0.101 ± 0.001 is derived from this result.

[3] AGUERRE 23 report the results of a 5.25 yr search for the 2ν $\beta\beta$ decay to the exited $0^+ \to 0^+_1$ 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.

[4] 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.

[5] AUGIER 23A use full data set collected by the CUPID-Mo experiment to derive an improved 2ν $\beta\beta$ 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.

[6] AZZOLINI 23A report an improved measurement of the 2ν $\beta\beta$ decay with an exposure of 8.82 kg·yr of ^{82}Se, collected with the CUPID-0 detector. Superseded AZZOLINI 19B.

[7] 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.

[8] ADAMS 22B derive the $2\nu\beta\beta$ half-life of ^{128}Te from data of the CUORE bolometric calorimeter and the half-live ratio for ^{130}Te / ^{128}Te reported in BERNATOWICZ 92.

[9] APRILE 22A report an improved ^{124}Xe 2νDEC 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.

[10] APRILE 22B use data collected by the XENONnT dark matter experiment to derive an improved ^{124}Xe 2νDEC half-life measurement for ^{124}Xe. This result supersedes APRILE 22A.

[11] 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.

[12] ADAMS 21 use 102.7 kg yr of ^{130}Te exposure, collected by the CUORE bolometric detector at LNGS, to perform a measurement of the $2\nu\ \beta\beta$ decay of ^{130}Te. The dataset is more than 10-times that collected by the CUORE-0 experiment. The result has been revised in ADAMS 23A. Supersedes ALDUINO 17.

[13] 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.

[14] 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.

[15] 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 2 σ. Supersedes ARNOLD 05A.

[16] BARABASH 18 use 1.162 kg of $^{116}CdWO_4$ scintillating crystals to obtain this value. Supersedes DANEVICH 03 with analogous source and agrees with ARNOLD 17 with the NEMO-3 detector.

[17] 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.

[18] 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.

[19] 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.

[20] 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.

[21] 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.

[22] 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.

[23] 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.

[24] 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 ± 0.0003 MeV^{-1} is derived from this data. Supersedes ACKERMAN 11.

[25] GAVRILYAK 13 use a proportional counter filled with Kr gas to search for the 2ν2K 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.

[26] 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.

[27] 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 ARNABOLDI 03.

[28] ARGYRIADES 10 use 9.4 ± 0.2 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.

[29] 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.

[30] 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.

[31] 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.

[32] DANEVICH 03 is calorimetric measurement of $2\nu\beta\beta$ ground state decay of ^{116}Cd using enrichedCdWO$_4$ 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

$\langle m_{ee} \rangle = |\Sigma U_{ei}^2 m_{\nu_i}|$, 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. • • •				
< 0.036–0.156	^{136}Xe	KamLAND-Zen	[1] ABE	23
< 0.113–0.269	^{76}Ge	MAJORANA	[2] ARNQUIST	23
< 0.48–3.19	^{136}Xe	NEXT	[3] NOVELLA	23
< 0.09–0.305	^{130}Te	CUORE	[4] ADAMS	22A
< 0.8–2.5	^{136}Xe	XENON1T	[5] APRILE	22A
< 0.28–0.49	^{100}Mo	CUPID-Mo	[6] AUGIER	22
< 0.263–0.545	^{82}Se	CUPID-0	[7] AZZOLINI	22
< 0.31–0.54	^{100}Mo	CUPID-Mo	[8] ARMENGAUD	21
< 0.075–0.35	^{130}Te	CUORE	[9] ADAMS	20A

$<$ 0.079–0.180	^{76}Ge	GERDA	[10] AGOSTINI	20B
$<$ 1.2–2.1	^{100}Mo	AMoRE	[11] ALENKOV	19
$<$ 0.093–0.286	^{136}Xe	EXO-200	[12] ANTON	19
$<$ 1.3–3.5	^{136}Xe	PANDAX-II	[13] NI	19
$<$ 0.11–0.52	^{130}Te	CUORE	[14] ALDUINO	18
$<$ 1.2–3.0	^{82}Se	NEMO-3	[15] ARNOLD	18
$<$ 1.0–1.7	^{116}Cd	AURORA	[16] BARABASH	18
$<$ 1.4–2.5	^{116}Cd	NEMO-3	[17] ARNOLD	17
$<$ 0.27–0.76	^{130}Te	CUORICINO	[18] ALDUINO	16
$<$ 1.6–5.3	^{150}Nd	NEMO-3	[19] ARNOLD	16A
$<$ 0.33–0.62	^{100}Mo	NEMO-3	[20] ARNOLD	15
$<$ 7.2–19.5	^{96}Zr	NEMO-3	[21] ARGYRIADES	10
$<$ 3.5–22	^{48}Ca	CaF_2 scint.	[22] UMEHARA	08
$<$ 1.5–1.7	^{116}Cd	$^{116}CdWO_4$ scint.	[23] DANEVICH	03

[1] ABE 23 utilize 745 kg of ^{136}Xe isotope exposure from the combined data set of the KamLAND-Zen 400 and 800 to derive a limit on $\langle m_{\beta\beta}\rangle$. The range reflects the author's assessment of the variability of the theoretically calculated nuclear matrix elements.

[2] 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.

[3] 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.

[4] 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.

[5] 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.

[6] 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.

[7] 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.

[8] 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.

[9] ADAMS 20A use the data of CUORE (372.5 kg·yr exposure of TeO_2) to obtain this limit.

[10] 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.

[11] 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.

[12] 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.

[13] 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.

[14] ALDUINO 18 use the combined data of CUORE, CUORE0, and Cuoricino to obtain this limit.

[15] 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.

[16] BARABASH 18 use 1.162 kg of $^{116}CdWO_4$ scintillating crystals to obtain these limits. The spread reflects the estimated uncertainty in the nuclear matrix element. Supersedes DANEVICH 03.

[17] 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.

[18] 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. Supersededs ALFONSO 15.

[19] 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.

[20] 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.

[21] 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.

[22] 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.

[23] 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}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}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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