Double-β Decay

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Half-life Measurements and Limits for Double-β Decay

In most cases the transitions (Z,A) $\rightarrow$ (Z+2,A) + $2e^-$ + (0 or 2) $\overline{\nu}_e$ to the 0^+ ground state of the final nucleus are listed. However, we also list transitions that increase the nuclear charge ($2e^+$, e^+/EC and ECEC) and transitions to excited states of the final nuclei (0^+_i, 2^+, and 2^+_i). In the following Listings, only best or comparable limits or lifetimes for each isotope are reported and only those with $\mathrm{T}_{1/2} > 10^{20}$ years that are relevant for particle physics. For 2ν decay, which is well established, only measured half-lives are reported.

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

$t_{1/2}(10^{21}$ yr)	*CL%*	*ISOTOPE*	*TRANSITION*	*METHOD*	*DOCUMENT ID*
>940	90	^{130}Te 0ν	$0^+ \rightarrow 0^+_1$	CUORICINO	[1] ANDREOTTI 12
>16000	90	^{136}Xe 0ν	g.s.$\rightarrow$ g.s.	EXO-200	[2] AUGER 12
> 1.0	90	^{106}Cd 0ν	ECEC, g.s.	^{106}CdWO$_4$ scint.	[3] BELLI 12A
> 2.2	90	^{106}Cd 0ν	EC,β^+,g.s.	^{106}CdWO$_4$ scint.	[4] BELLI 12A
> 1.2	90	^{106}Cd 0ν	$\beta^+\beta^+$,g.s.	^{106}CdWO$_4$ scint.	[5] BELLI 12A
$2.38 \pm 0.02 \pm 0.14$	68	^{136}Xe 2ν	g.s.$\rightarrow$ g.s.	KamLAND-Zen	[6] GANDO 12A
>5700	90	^{136}Xe 0ν	g.s.$\rightarrow$ g.s.	KamLAND-Zen	[7] GANDO 12A
$2.11 \pm 0.04 \pm 0.21$	68	^{136}Xe 2ν		EXO-200	[8] ACKERMAN 11
$0.7 \pm 0.09 \pm 0.11$	68	^{130}Te 2ν		NEMO-3	[9] ARNOLD 11
> 130	90	^{130}Te 0ν		NEMO-3	[10] ARNOLD 11
> 1.3	90	^{112}Sn 0ν	$0^+\rightarrow 0^+_3$	γ Ge det.	[11] BARABASH 11
> 0.69	90	^{112}Sn 0ν	$0^+\rightarrow 0^+_2$	γ Ge det.	[12] BARABASH 11
> 1.3	90	^{112}Sn 0ν	$0^+\rightarrow 0^+_1$	γ Ge det.	[13] BARABASH 11
> 1.06	90	^{112}Sn 0ν		γ Ge det.	[14] BARABASH 11
$(2.8 \pm 0.1 \pm 0.3)$E-2		^{116}Cd 2ν		NEMO-3	[15] BARABASH 11A
$(4.4^{+0.5}_{-0.4} \pm 0.4)$E-2		^{48}Ca 2ν		NEMO-3	[16,17] BARABASH 11A
$(69 \pm 9 \pm 10)$E-2		^{130}Te 2ν		NEMO-3	[17,18] BARABASH 11A
>1100	90	^{100}Mo 0ν		NEMO-3	[17,19] BARABASH 11A
>360	90	^{82}Se 0ν		NEMO-3	[17,20] BARABASH 11A
>100	90	^{130}Te 0ν		NEMO-3	[17,21] BARABASH 11A
>16	90	^{116}Cd 0ν		NEMO-3	[17,22] BARABASH 11A
>13	90	^{48}Ca 0ν		NEMO-3	[17,23] BARABASH 11A
> 0.32	90	^{64}Zn 0ν	ECEC,g.s.	ZnWO$_4$ scint.	[24] BELLI 11D
> 0.85	90	^{64}Zn 0ν	β^+EC,g.s.	ZnWO$_4$ scint.	[24] BELLI 11D
> 0.11	90	^{106}Cd 0ν	$0^+\rightarrow 4^+$	TGV2 det.	[25] RUKHADZE 11
$(2.35 \pm 0.14 \pm 0.16)$E-2		^{96}Zr 2ν		NEMO-3	[26] ARGYRIADES 10
> 9.2	90	^{96}Zr 0ν		NEMO-3	[27] ARGYRIADES 10
> 0.22	90	^{96}Zr 0ν	$0^+\rightarrow 0^+_1$	NEMO-3	[28] ARGYRIADES 10
$0.69^{+0.10}_{-0.08} \pm 0.07$	68	^{100}Mo 2ν	$0^+ \rightarrow 0^+_1$	Ge coinc.	[29] BELLI 10

> 18.0	90	^{150}Nd	0ν		NEMO-3	[30] ARGYRIADES	09
$(9.11^{+0.25}_{-0.22} \pm 0.63)$E-3		^{150}Nd	2ν		NEMO-3	[31] ARGYRIADES	09
> 0.43	90	^{64}Zn	0ν	β^+EC	ZnW0$_4$ scint.	[32] BELLI	09A
> 0.11	90	^{64}Zn	0ν	ECEC	ZnW0$_4$ scint.	[33] BELLI	09A
$0.55^{+0.12}_{-0.09}$		^{100}Mo	2ν+0ν	$0^+ \to 0^+_1$	Ge coincidence	[34] KIDD	09
> 3000	90	^{130}Te	0ν		TeO$_2$ bolometer	[35] ARNABOLDI	08
> 0.22	90	^{64}Zn	0ν		ZnWO$_4$ scint.	[36] BELLI	08
> 1.1	90	^{114}Cd	0ν	$\beta\beta$	CdWO$_4$ scint.	[37] BELLI	08B
> 58	90	^{48}Ca	0ν		CaF$_2$ scint.	[38] UMEHARA	08
$0.57^{+0.13}_{-0.09} \pm 0.08$	68	^{100}Mo	2ν	$0^+ \to 0^+_1$	NEMO-3	[39] ARNOLD	07
> 89	90	^{100}Mo	0ν	$0^+ \to 0^+_1$	NEMO-3	[40] ARNOLD	07
> 160	90	^{100}Mo	0ν	$0^+ \to 2^+$	NEMO-3	[41] ARNOLD	07
> 0.0019	90	^{74}Se	0ν+2ν		γ in Ge det.	[42] BARABASH	07
> 0.0055	90	^{74}Se	0ν+2ν	$0^+ \to 2^+_2$	γ in Ge det.	[43] BARABASH	07
22300^{+4400}_{-3100}	68	^{76}Ge	0ν		Enriched HPGe	[44] KLAPDOR-K...	06A
> 1800	90	^{130}Te	0ν		Cryog. det.	[45] ARNABOLDI	05
> 460	90	^{100}Mo	0ν		NEMO-3	[46] ARNOLD	05A
> 100	90	^{82}Se	0ν		NEMO-3	[47] ARNOLD	05A
$(7.11 \pm 0.02 \pm 0.54)$E-3		^{100}Mo	2ν		NEMO-3	[48] ARNOLD	05A
$(9.6 \pm 0.3 \pm 1.0)$E-2		^{82}Se	2ν		NEMO-3	[49] ARNOLD	05A
> 140	90	^{82}Se	0ν		NEMO-3	[50] ARNOLD	04
$(7.68 \pm 0.02 \pm 0.54)$E-3		^{100}Mo	2ν		NEMO-3	[51] ARNOLD	04
$0.14^{+0.04}_{-0.02} \pm 0.03$	68	^{150}Nd	0ν+2ν	$0^+ \to 0^+_1$	γ in Ge det.	[52] BARABASH	04
> 31	90	^{130}Te	0ν	$0^+ \to 2^+$	Cryog. det.	[53] ARNABOLDI	03
$0.61 \pm 0.14^{+0.29}_{-0.35}$	90	^{130}Te	2ν		Cryog. det.	[54] ARNABOLDI	03
> 110	90	^{128}Te	0ν		Cryog. det.	[55] ARNABOLDI	03
$(0.029^{+0.004}_{-0.003})$		^{116}Cd	2ν		^{116}CdWO$_4$ scint.	[56] DANEVICH	03
> 170	90	^{116}Cd	0ν		^{116}CdWO$_4$ scint.	[57] DANEVICH	03
> 29	90	^{116}Cd	0ν	$0^+ \to 2^+$	^{116}CdWO$_4$ scint.	[58] DANEVICH	03
> 14	90	^{116}Cd	0ν	$0^+ \to 0^+_1$	^{116}CdWO$_4$ scint.	[59] DANEVICH	03
> 6	90	^{116}Cd	0ν	$0^+ \to 0^+_2$	^{116}CdWO$_4$ scint.	[60] DANEVICH	03
> 1.1	90	^{186}W	0ν		CdWO$_4$ scint.	[61] DANEVICH	03
> 1.1	90	^{186}W	0ν	$0^+ \to 2^+$	CdWO$_4$ scint.	[62] DANEVICH	03
$1.74 \pm 0.01^{+0.18}_{-0.16}$		^{76}Ge	2ν		Enriched HPGe	[63] DOERR	03
>15700	90	^{76}Ge	0ν		Enriched HPGe	[64] AALSETH	02B
> 58	90	^{134}Xe	0ν		Liquid Xe Scint.	[65] BERNABEI	02D
> 1200	90	^{136}Xe	0ν		Liquid Xe Scint.	[66] BERNABEI	02D
> 4.9	90	^{100}Mo	0ν		Liq. Ar ioniz.	[67] ASHITKOV	01
> 1.3	90	^{160}Gd	0ν		Gd$_2$SiO$_5$:Ce	[68] DANEVICH	01
> 1.3	90	^{160}Gd	0ν	$0^+ \to 2^+$	Gd$_2$SiO$_5$:Ce	[69] DANEVICH	01
$0.59^{+0.17}_{-0.11} \pm 0.06$		^{100}Mo	0ν+2ν	$0^+ \to 0^+_1$	Ge coinc.	[70] DEBRAECKEL...	01
>19000	90	^{76}Ge	0ν		Enriched HPGe	[71] KLAPDOR-K...	01
(9.4 ± 3.2)E-3	90	^{96}Zr	0ν+2ν		Geochem	[72] WIESER	01
$0.042^{+0.033}_{-0.013}$		^{48}Ca	2ν		Ge spectrometer	[73] BRUDANIN	00
$0.021^{+0.008}_{-0.004} \pm 0.002$		^{96}Zr	2ν		NEMO-2	[74] ARNOLD	99

$(8.3 \pm 1.0 \pm 0.7)$E-2		^{82}Se	2ν		NEMO-2	[75] ARNOLD	98
$>$ 2.8	90	^{82}Se	0ν	$0^+ \to 2^+$	NEMO-2	[76] ARNOLD	98
$(7.6^{+2.2}_{-1.4})$E-3		^{100}Mo	2ν		Si(Li)	[77] ALSTON-...	97
$(6.82^{+0.38}_{-0.53} \pm 0.68)$E-3		^{100}Mo	2ν		TPC	[78] DESILVA	97
$(6.75^{+0.37}_{-0.42} \pm 0.68)$E-3		^{150}Nd	2ν		TPC	[79] DESILVA	97
$(3.75 \pm 0.35 \pm 0.21)$E-2		^{116}Cd	2ν	$0^+ \to 0^+$	NEMO 2	[80] ARNOLD	96
$0.043^{+0.024}_{-0.011} \pm 0.014$		^{48}Ca	2ν		TPC	[81] BALYSH	96
0.79 ± 0.10		^{130}Te	0ν+2ν		Geochem	[82] TAKAOKA	96
$0.61^{+0.18}_{-0.11}$		^{100}Mo	0ν+2ν	$0^+ \to 0^+_1$	γ in HPGe	[83] BARABASH	95
$0.026^{+0.009}_{-0.005}$		^{116}Cd	2ν	$0^+ \to 0^+$	ELEGANT IV	EJIRI	95
$0.017^{+0.010}_{-0.005} \pm 0.0035$		^{150}Nd	2ν	$0^+ \to 0^+$	TPC	ARTEMEV	93
0.039 ± 0.009		^{96}Zr	0ν+2ν		Geochem	KAWASHIMA	93
2.7 ± 0.1		^{130}Te	0ν+2ν		Geochem	BERNATOW...	92
7200 ± 400		^{128}Te	0ν+2ν		Geochem	[84] BERNATOW...	92
$0.108^{+0.026}_{-0.006}$		^{82}Se	2ν	$0^+ \to 0^+$	TPC	ELLIOTT	92
2.0 ± 0.6		^{238}U	0ν+2ν		Radiochem	[85] TURKEVICH	91
$0.12 \pm 0.01 \pm 0.04$	68	^{82}Se	0ν+2ν		Geochem.	[86] LIN	88
$0.75 \pm 0.03 \pm 0.23$	68	^{130}Te	0ν+2ν		Geochem.	[87] LIN	88
1800 ± 700	68	^{128}Te	0ν+2ν		Geochem.	[88] LIN	88B
2.60 ± 0.28		^{130}Te	0ν+2ν		Geochem	[89] KIRSTEN	83

[1] 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.

[2] AUGER 12 use EXO-200 liquid Xe TPC filled with 79.4 kg (fiducial mass) of ^{136}Xe to constrain the $0\nu\beta\beta$-decay halflife of ^{136}Xe. This result is more sensitive than BERNABEI 02D and GANDO 12A.

[3] BELLI 12A use $^{106}CdWO_4$ 215 g crystal scintillator to search for various $\beta\beta$ decay modes. The limit for the ECEC mode is derived from the fit to the background spectrum in the 1.8–3.2 MeV energy interval in the run of 6590 hours. The same analysis provides several limits ($\sim$ 2–5 $\times 10^{20}$ years) for the ECEC mode leading to the excited 0^+ and 2^+ states. Also a similar size limits for the possible resonance process populating states at 2718 keV, 2741 keV, and 2748 keV were obtained.

[4] BELLI 12A use $^{106}CdWO_4$ 215 g crystal scintillator to search for various $\beta\beta$ decay modes. The limit for the ECβ^+ mode is derived from the fit to the background spectrum in the 2.0–3.0 MeV energy interval in the run of 6590 hours. The same analysis provides several limits ($\sim$ 0.5–1.3 $\times 10^{21}$ years) for the ECβ^+ mode leading to the excited 0^+ and 2^+ states.

[5] BELLI 12A use $^{106}CdWO_4$ 215 g crystal scintillator to search for various $\beta\beta$ decay modes. The limit for the $\beta^+\beta^+$ mode is derived from the fit to the background spectrum in the 0.76–2.8 MeV energy interval in the run of 6590 hours. The same analysis provides the limit (1.2×10^{21} years) for the $\beta^+\beta^+$ mode leading to the first excited 2^+ state.

[6] 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.

[7] 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 $0\nu\beta\beta$ decay rate is derived from the fit where the background rates were allowed to float. This result is more sensitive than BERNABEI 02D.

[8] ACKERMAN 11 use the EXO-200 liquid Xe TPC filled with ∼ 175 kg of enriched ^{136}Xe to determine the 2ν halflife of ^{136}Xe.

[9] ARNOLD 11 use enriched ^{130}Te in the NEMO-3 detector to measure the 2ν $\beta\beta$ decay rate. This result is in agreement with, but more accurate than ARNABOLDI 03.

[10] ARNOLD 11 use the NEMO-3 detector to obtain a limit for the 0ν $\beta\beta$ decay.This result is less significant than ARNABOLDI 05.

[11] BARABASH 11 use 100 g of enriched ^{112}Sn to determine a limit for the ECEC 0ν decay to the 0^+_3 state of ^{112}Cd by searching for the de-excitation γ with a Ge detector. This decay mode is a candidate for resonant rate enhancement.

[12] BARABASH 11 use 100 g of enriched ^{112}Sn to determine a limit for the ECEC 0ν decay to the 0^+_2 state of ^{112}Cd by searching for the de-excitation γ with a Ge detector.

[13] BARABASH 11 use 100 g of enriched ^{112}Sn to determine a limit for the ECEC 0ν decay to the 0^+_1 state of ^{112}Cd by searching for the de-excitation γ with a Ge detector.

[14] BARABASH 11 use 100 g of enriched ^{112}Sn to determine a limit for the ECEC 0ν decay to the ground state of ^{112}Cd by searching for the de-excitation γ with a Ge detector.

[15] Supersedes DANEVICH 03 and ARNOLD 96.

[16] Supersedes BRUDANIN 00 and BALYSH 96.

[17] BARABASH 11A use the NEMO-3 detector to measure $\beta\beta 2\nu$ rates and place limits on $\beta\beta 0\nu$ half lives for various nuclides.

[18] Supersedes ARNABOLDI 03.

[19] Supersedes ARNOLD 05A, ARNOLD 04, ASHITKOV 01, EJIRI 01, and DASSIE 95.

[20] Supersedes ARNOLD 05A, ARNOLD 04, ARNOLD 98, and ELLIOTT 92.

[21] Less restrictive than ARNABOLDI 08.

[22] Less restrictive than DANEVICH 03.

[23] Less restrictive than UMEHARA 08 and OGAWA 04.

[24] BELLI 11D use $ZnWO_4$ scintillator calorimeters to search for various $\beta\beta$ decay modes of ^{64}Zn, ^{70}Zn, ^{180}W, and ^{186}W.

[25] RUKHADZE 11 uses 13.6 g of enriched ^{106}Cd to search for the neutrinoless ECEC decay into an excited state of ^{106}Pd and its characteristic γ-radiation using the TGV2 detector. This decay mode is a candidate for resonant rate enhancement, however, hindered by the large spin difference.

[26] 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.

[27] ARGYRIADES 10 use 9.4 ± 0.2 g of ^{96}Zr in NEMO-3 detector and obtain a limit of the $0\nu\beta\beta$ decay. The result is in agreement and supersedes ARNOLD 99.

[28] ARGYRIADES 10 use 9.4 ± 0.2 g of ^{96}Zr in NEMO-3 detector and obtain a limit of the $0\nu\beta\beta$ decay into the first excited 0^+_1 state in ^{96}Mo.

[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] ARGYRIADES 09 use the NEMO-3 tracking calorimeter containing 36.5 g of ^{150}Nd, a total exposure of 924.7 days, to derive a limit for the $0\nu\beta\beta$ half-life. Supersedes DESILVA 97.

[31] ARGYRIADES 09 use the NEMO-3 tracking calorimeter containing 36.5 g of ^{150}Nd, a total exposure of 924.7 days, to determine the value of the $2\nu\beta\beta$ half-life. This result is in marginal agreement, but has somewhat smaller error bars, than DESILVA 97.

[32] BELLI 09A use $ZnWO_4$ scintillating crystals to search for various modes of $\beta\beta$ decay. This work improves the limits for different modes of ^{64}Zn decay into the ground state of ^{64}Ni, in this case for the 0ν β^+EC mode. Supersedes BELLI 08.

[33] BELLI 09A use $ZnWO_4$ scintillating crystals to search for various modes of $\beta\beta$ decay. This work improves the limits for different modes of ^{64}Zn decay into the ground state of ^{64}Ni, in this case for the 0ν ECEC mode. Supersedes BELLI 08.

[34] KIDD 09 combine past and new data with an improved coincidence detection efficiency determination. The result agrees with ARNOLD 95. Supersedes DEBRAECKELEER 01 and BARABASH 95.

[35] ARNABOLDI 08 use high resolution TeO_2 bolometer calorimeter to search for double beta decay of ^{130}Te. Supersedes ARNABOLDI 05.

[36] BELLI 08 use $ZnWO_4$ scintillation calorimeter to search for neutrinoless β^+ plus electron capture decay of ^{64}Zn. The halflife limit for the 2ν mode is 2.1×10^{20} years.

[37] BELLI 08B use $CdWO_4$ scintillation calorimeter to search for 0ν $\beta\beta$ decay of ^{114}Cd.

[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] 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.

[40] Limit on 0ν-decay to the first excited 0_1^+-state of daughter nucleus using NEMO-3 tracking calorimeter. Supersedes DASSIE 95.

[41] Limit on 0ν-decay to the first excited 2^+-state of daughter nucleus using NEMO-3 tracking calorimeter.

[42] BARABASH 07 use Ge calorimeter to search for γ-radiation following double electron capture or β^+ plus electron capture decays of ^{74}Se to the ground state of ^{74}Ge. This limit is based on the search for the 511 keV annihilation radiation. Various other limits, for the capture from different atomic shells and also to the excited states, are reported in the paper.

[43] BARABASH 07 use Ge calorimeter to search for γ-radiation following double electron capture decay of ^{74}Se into the second excited 2^+-state of ^{74}Ge. That transition has been considered due to a possible resonance enhancement. The 2ν mode would be suppressed for this decay by its extremely small phase space factor.

[44] KLAPDOR-KLEINGROTHAUS 06A present re-analysis of data originally published in KLAPDOR-KLEINGROTHAUS 04A. Modified pulse shape analysis leads the authors to claim improved 6σ statistical evidence for observation of 0ν-decay, compared to 4.2σ in KLAPDOR-KLEINGROTHAUS 04A. Analysis of the systematic uncertainty is not presented. Supersedes KLAPDOR-KLEINGROTHAUS 04A.

[45] Supersedes ARNABOLDI 04. Bolometric TeO_2 detector array CUORICINO is used for high resolution search for $0\nu\beta\beta$ decay. The half-life limit is derived from 3.09 kg yr ^{130}Te exposure.

[46] NEMO-3 tracking calorimeter containing 6.9 kg of enriched ^{100}Mo is used in ARNOLD 05A. A limit for $0\nu\beta\beta$ half-life of ^{100}Mo is reported. Supersedes ARNOLD 04.

[47] NEMO-3 tracking calorimeter is used in ARNOLD 05A to place limit on $0\nu\beta\beta$ half-life of ^{82}Se. Detector contains 0.93 kg of enriched ^{82}Se. Supersedes ARNOLD 04.

[48] ARNOLD 05A use the NEMO-3 tracking calorimeter to determine the $2\nu\beta\beta$ half-life of ^{100}Mo with high statistics and low background (389 days of data taking). Supersedes ARNOLD 04.

[49] 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.

[50] ARNOLD 04 use the NEMO-3 tracking detector to determine the limit for $0\nu\beta\beta$ halflife of ^{82}Se. This represents an improvement, by a factor of ~ 10, when compared with ELLIOTT 92. It supersedes the limit of ARNOLD 98 for this decay using NEMO-2.

[51] ARNOLD 04 use the NEMO-3 tracking detector to determine the $2\nu\beta\beta$ halflife of ^{100}Mo with high statistics and low background. The halflife is determined assuming the Single State Dominance. It is in agreement with, and more accurate than, previous determinations. Supersedes DASSIE 95 determination of this quantity with NEMO-2.

[52] BARABASH 04 perform an inclusive measurement of the $\beta\beta$ decay of ^{150}Nd into the first excited (0_1^+) state of ^{150}Sm. Gamma radiation emitted in decay of the excited state is detected.

[53] Decay into first excited state of daughter nucleus.

[54] Two neutrino decay into ground state. Relatively large error mainly due to uncertainties in background determination. Reported value is shorter than the geochemical measurements of KIRSTEN 83 and BERNATOWICZ 92 but in agreement with LIN 88 and TAKAOKA 96.

[55] Supersedes ALESSANDRELLO 00. Array of $\mathrm{TeO_2}$ crystals in high resolution cryogenic calorimeter. Some enriched in ^{128}Te. Ground state to ground state decay.

[56] Calorimetric measurement of 2ν ground state decay of ^{116}Cd using enriched $\mathrm{CdWO_4}$ scintillators. Agrees with EJIRI 95 and ARNOLD 96. Supersedes DANEVICH 00.

[57] Limit on 0ν decay of ^{116}Cd using enriched $\mathrm{CdWO_4}$ scintillators. Supersedes DANEVICH 00.

[58] Limit on 0ν decay of ^{116}Cd into first excited 2^+ state of daughter nucleus using enriched $\mathrm{CdWO_4}$ scintillators. Supersedes DANEVICH 00.

[59] Limit on 0ν decay of ^{116}Cd into first excited 0^+ state of daughter nucleus using enriched $\mathrm{CdWO_4}$ scintillators. Supersedes DANEVICH 00.

[60] Limit on 0ν decay of ^{116}Cd into second excited 0^+ state of daughter nucleus using enriched $\mathrm{CdWO_4}$ scintillators. Supersedes DANEVICH 00.

[61] Limit on the 0ν ground state decay of ^{186}W using enriched $\mathrm{CdWO_4}$ scintillators.

[62] Limit on the 0ν decay of ^{186}W to the first excited 2^+ state of the daughter nucleus using enriched $\mathrm{CdWO_4}$ scintillators.

[63] Results of the Heidelberg-Moscow experiment (KLAPDOR-KLEINGROTHAUS 01 and GUENTHER 97) are reanalyzed using a new simulation of the complete background spectrum. The $\beta\beta 2\nu$-decay rate is deduced from a 41.57 kg-y exposure. The result is in agreement and supersedes the above referenced halflives with similar statistical and systematic errors.

[64] 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.

[65] BERNABEI 02D report a limit for the 0ν, $0^+ \rightarrow 0^+$ decay of ^{134}Xe, present in the source at 17%, by considering the maximum number of events for this mode compatible with the fitted smooth background.

[66] BERNABEI 02D report a limit for the 0ν, $0^+ \rightarrow 0^+$ decay of ^{136}Xe, by considering the maximum number of events for this mode compatible with the fitted smooth background. The quoted sensitivity is 450×10^{21} yr. The Feldman and Cousins method is used to obtain the quoted limit.

[67] ASHITKOV 01 result for 0ν of ^{100}Mo is less stringent than EJIRI 01.

[68] DANEVICH 01 place limit on 0ν decay of ^{160}Gd using $\mathrm{Gd_2SiO_5}$:Ce crystal scintillators. The limit is more stringent than KOBAYASHI 95.

[69] DANEVICH 01 place limits on 0ν decay of ^{160}Gd into excited 2^+ state of daughter nucleus using $\mathrm{Gd_2SiO_5}$:Ce crystal scintillators.

[70] DEBRAECKELEER 01 performed an inclusive measurement of the $\beta\beta$ decay into the second excited state of the daughter nucleus. A novel coincidence technique counting the de-excitation photons is employed. The result agrees with BARABASH 95.

[71] KLAPDOR-KLEINGROTHAUS 01 is a continuation of the work published in BAUDIS 99. Isotopically enriched Ge detectors are used in calorimetric measurement. The most stringent bound is derived from the data set in which pulse-shape analysis has been used to reduce background. Exposure time is 35.5 kg y. Supersedes BAUDIS 99 as most stringent result.

[72] WIESER 01 reports an inclusive geochemical measurement of ^{96}Zr $\beta\beta$ half life. Their result agrees within 2σ with ARNOLD 99 but only marginally, within 3σ, with KAWASHIMA 93.

[73] BRUDANIN 00 determine the 2ν halflife of ^{48}Ca. Their value is less accurate than BALYSH 96.

[74] ARNOLD 99 measure directly the 2ν decay of Zr for the first time, using the NEMO-2 tracking detector and an isotopically enriched source. The lifetime is more accurate than the geochemical result of KAWASHIMA 93.

[75] ARNOLD 98 measure the 2ν decay of ^{82}Se by comparing the spectra in an enriched and natural selenium source using the NEMO-2 tracking detector. The measured half-life is in agreement, perhaps slightly shorter, than ELLIOTT 92.

[76] ARNOLD 98 determine the limit for 0ν decay to the excited 2^+ state of ^{82}Se using the NEMO-2 tracking detector.

[77] ALSTON-GARNJOST 97 report evidence for 2ν decay of ^{100}Mo. This decay has been also observed by EJIRI 91, DASSIE 95, and DESILVA 97.

[78] DESILVA 97 result for 2ν decay of ^{100}Mo is in agreement with ALSTON-GARNJOST 97 and DASSIE 95. This measurement has the smallest errors.

[79] DESILVA 97 result for 2ν decay of ^{150}Nd is in marginal agreement with ARTEMEV 93. It has smaller errors.

[80] ARNOLD 96 measure the 2ν decay of ^{116}Cd. This result is in agreement with EJIRI 95, but has smaller errors. Supersedes ARNOLD 95.

[81] BALYSH 96 measure the 2ν decay of ^{48}Ca, using a passive source of enriched ^{48}Ca in a TPC.

[82] TAKAOKA 96 measure the geochemical half-life of ^{130}Te. Their value is in disagreement with the quoted values of BERNATOWICZ 92 and KIRSTEN 83; but agrees with several other unquoted determinations, e.g., MANUEL 91.

[83] BARABASH 95 cannot distinguish 0ν and 2ν, but it is inferred indirectly that the 0ν mode accounts for less than 0.026% of their event sample. They also note that their result disagrees with the previous experiment by the NEMO group (BLUM 92).

[84] BERNATOWICZ 92 finds ^{128}Te/^{130}Te activity ratio from slope of ^{128}Xe/^{132}Xe vs ^{130}Xe/^{132}Xe ratios during extraction, and normalizes to lead-dated ages for the ^{130}Te lifetime. The authors state that their results imply that "(a) the double beta decay of ^{128}Te has been firmly established and its half-life has been determined . . . without any ambiguity due to trapped Xe interferences. . . (b) Theoretical calculations . . . underestimate the [long half-lives of ^{128}Te ^{130}Te] by 1 or 2 orders of magnitude, pointing to a real suppression in the 2ν decay rate of these isotopes. (c) Despite [this], most $\beta\beta$-models predict a *ratio* of 2ν decay widths . . . in fair agreement with observation." Further details of the experiment are given in BERNATOWICZ 93. Our listed half-life has been revised downward from the published value by the authors, on the basis of reevaluated cosmic-ray ^{128}Xe production corrections.

[85] TURKEVICH 91 observes activity in old U sample. The authors compare their results with theoretical calculations. They state "Using the phase-space factors of Boehm and Vogel (BOEHM 87) leads to matrix element values for the ^{238}U transition in the same range as deduced for ^{130}Te and ^{76}Ge. On the other hand, the latest theoretical estimates (STAUDT 90) give an upper limit that is 10 times lower. This large discrepancy implies either a defect in the calculations or the presence of a faster path than the standard two-neutrino mode in this case." See BOEHM 87 and STAUDT 90.

[86] Result agrees with direct determination of ELLIOTT 92.

[87] Inclusive half life inferred from mass spectroscopic determination of abundance of $\beta\beta$-decay product ^{130}Te in mineral kitkaite (NiTeSe). Systematic uncertainty reflects variations in U-Xe gas-retention-age derived from different uranite samples. Agrees with geochemical determination of TAKAOKA 96 and direct measurement of ARNABOLDI 03. Inconsistent with results of KIRSTEN 83 and BERNATOWICZ 92.

[88] Ratio of inclusive double beta half lives of ^{128}Te and ^{130}Te determined from minerals melonite ($NiTe_2$) and altaite (PbTe) by means of mass spectroscopic measurement of abundance of $\beta\beta$-decay products. As gas-retention-age could not be determined the authors use half life of ^{130}Te (LIN 88) to infer the half life of ^{128}Te. No estimate of the systematic uncertainty of this method is given. The directly determined half life ratio

agrees with BERNATOWICZ 92. However, the inferred ^{128}Te half life disagrees with KIRSTEN 83 and BERNATOWICZ 92.

[89] KIRSTEN 83 reports "2σ" error. References are given to earlier determinations of the ^{130}Te lifetime.

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

$\langle m_\nu \rangle = |\Sigma\ U^2_{1j} m_{\nu_j}|$, where the sum goes from 1 to n and where n = number of neutrino generations, and ν_j is a Majorana neutrino. Note that U^2_{ej}, not $|U_{ej}|^2$, occurs in the sum. The possibility of cancellations has been stressed. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

VALUE (eV)	*CL%*	*ISOTOPE*	*TRANSITION*	*METHOD*	*DOCUMENT ID*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.14–0.38	90	^{136}Xe	0ν,g.s.→ g.s.	EXO-200	[90] AUGER 12
< 0.3–0.6	90	^{136}Xe	0ν,g.s.→ g.s.	KamLAND-Zen	[91] GANDO 12A
< 0.45–0.93	90	^{100}Mo	0ν	NEMO-3	[92] BARABASH 11A
< 0.89–2.43	90	^{82}Se	0ν	NEMO-3	[93] BARABASH 11A
< 7.2–19.5	90	^{96}Zr	0ν	NEMO-3	[94] ARGYRIADES 10
< 4.0–6.8	90	^{150}Nd	0ν	NEMO-3	[95] ARGYRIADES 09
< 0.19–0.68	90	^{130}Te	0ν	TeO_2 bolometer	[96] ARNABOLDI 08
< 3.5–22	90	^{48}Ca	0ν	CaF_2 scint.	[97] UMEHARA 08
< 9.3–60	90	^{100}Mo	$0^+ \to 0^+_1$	NEMO-3	[98] ARNOLD 07
< 6500	90	^{100}Mo	$0^+ \to 2^+$	NEMO-3	[99] ARNOLD 07
0.32±0.03	68	^{76}Ge	0ν	Enriched HPGe	[100] KLAPDOR-K... 06A
< 0.2–1.1	90	^{130}Te		Cryog. det.	[101] ARNABOLDI 05
< 0.7–2.8	90	^{100}Mo	0ν	NEMO-3	[102] ARNOLD 05A
< 1.7–4.9	90	^{82}Se	0ν	NEMO-3	[103] ARNOLD 05A
< 0.37–1.9	90	^{130}Te		Cryog. det.	[104] ARNABOLDI 04
< 0.8–1.2	90	^{100}Mo	0ν	NEMO-3	[105] ARNOLD 04
< 1.5–3.1	90	^{82}Se	0ν	NEMO-3	[105] ARNOLD 04
0.1–0.9	99.7	^{76}Ge		Enriched HP Ge	[106] KLAPDOR-K... 04A
< 7.2–44.7	90	^{48}Ca		CaF_2 scint.	[107] OGAWA 04
< 1.1–2.6	90	^{130}Te		Cryog. det.	[108] ARNABOLDI 03
< 1.5–1.7	90	^{116}Cd	0ν	$^{116}CdWO_4$ scint.	[109] DANEVICH 03
< 0.33–1.35	90			Enriched HPGe	[110] AALSETH 02B
<2.9	90	^{136}Xe	0ν	Liquid Xe Scint.	[111] BERNABEI 02D
$0.39^{+0.17}_{-0.28}$		^{76}Ge	0ν	Enriched HPGe	[112] KLAPDOR-K... 02D
< 2.1–4.8	90	^{100}Mo	0ν	ELEGANT V	[113] EJIRI 01
< 0.35	90	^{76}Ge		Enriched HPGe	[114] KLAPDOR-K... 01
<23	90	^{96}Zr		NEMO-2	[115] ARNOLD 99
< 1.1–1.5		^{128}Te		Geochem	[116] BERNATOW... 92
<5	68	^{82}Se		TPC	[117] ELLIOTT 92
<8.3	76	^{48}Ca	0ν	CaF_2 scint.	YOU 91

[90] AUGER 12 limit is based on the EXO-200 data. The reported range reflects different nuclear matrix elements.

[91] GANDO 12A limit is based on the KamLAND-Zen data. The reported range reflects different nuclear matrix elements.

[92] BARABASH 11A limit is based on NEMO-3 data for ^{100}Mo. The reported range reflects different nuclear matrix elements. Supersedes ARNOLD 05A and ARNOLD 04.

[93] BARABASH 11A limit is based on NEMO-3 data for ^{82}Se. The reported range reflects different nuclear matrix elements. Supersedes ARNOLD 05A and ARNOLD 04.

[94] 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.

[95] ARGYRIADES 09 limit is based on 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.

[96] Limit was obtained using high resolution TeO_2 bolometer calorimeter to search for double beta decay of ^{130}Te. Reported range of limits reflects spread of matrix element calculations used. Supersedes ARNABOLDI 05.

[97] 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.

[98] ARNOLD 07 use NEMO-3 half life limit for 0ν-decay of ^{100}Mo to the first excited 0^+_1-state of daughter nucleus to obtain neutrino mass limit. The spread reflects the choice of two different nuclear matrix elements. This limit is not competitive when compared to the decay to the ground state.

[99] ARNOLD 07 use NEMO-3 half life limit for 0ν-decay of ^{100}Mo to the first excited 2^+-state of daughter nucleus to obtain neutrino mass limit. This limit is not competitive when compared to the decay to the ground state.

[100] 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 STAUDT 90. Uncertainty of nuclear matrix element is not reflected in stated error. Supersedes KLAPDOR-KLEINGROTHAUS 04A.

[101] Supersedes ARNABOLDI 04. Reported range of limits due to use of different nuclear matrix element calculations.

[102] Mass limits reported in ARNOLD 05A are derived from ^{100}Mo data, obtained by the NEMO-3 collaboration. The range reflects the spread of matrix element calculations considered in this work. Supersedes ARNOLD 04.

[103] Neutrino mass limits based on ^{82}Se data utilizing the NEMO-3 detector. The range reported in ARNOLD 05A reflects the spread of matrix element calculations considered in this work. Supersedes ARNOLD 04.

[104] Supersedes ARNABOLDI 03. Reported range of limits due to use of different nuclear matrix element calculations.

[105] ARNOLD 04 limit is based on the nuclear matrix elements of SIMKOVIC 99, STOICA 01 and CIVITARESE 03.

[106] Supersedes KLAPDOR-KLEINGROTHAUS 02D. Event excess at $\beta\beta$-decay energy is used to derive Majorana neutrino mass using the nuclear matrix elements of STAUDT 90. The mass range shown is based on the authors evaluation of the uncertainties of the STAUDT 90 matrix element calculation. If this uncertainty is neglected, and only statistical errors are considered, the range in $\langle \mathrm{m} \rangle$ becomes (0.2–0.6) eV at the 3 σ level.

[107] Calorimetric CaF_2 scintillator. Range of limits reflects authors' estimate of the uncertainty of the nuclear matrix elements. Replaces YOU 91 as the most stringest limit based on ^{48}Ca.

[108] Supersedes ALESSANDRELLO 00. Cryogenic calorimeter search. Reported a range reflecting uncertainty in nuclear matrix element calculations.

[109] Limit for $\langle m_\nu \rangle$ is based on the nuclear matrix elements of STAUDT 90 and ARNOLD 96. Supersedes DANEVICH 00.

[110] AALSETH 02B reported range of limits on $\langle m_\nu \rangle$ reflects the spread of theoretical nuclear matrix elements. Excludes part of allowed mass range reported in KLAPDOR-KLEINGROTHAUS 01B.

[111] BERNABEI 02D limit is based on the matrix elements of SIMKOVIC 02. The range of neutrino masses based on a variety of matrix elements is 1.1–2.9 eV.

[112] KLAPDOR-KLEINGROTHAUS 02D is a detailed description of the analysis of the data collected by the Heidelberg-Moscow experiment, previously presented in KLAPDOR-KLEINGROTHAUS 01B. Matrix elements in STAUDT 90 have been used. See the footnote in the preceding table for further details. See also KLAPDOR-KLEINGROTHAUS 02B.

[113] The range of the reported $\langle m_\nu \rangle$ values reflects the spread of the nuclear matrix elements. On axis value assuming $\langle \lambda \rangle = \langle \eta \rangle = 0$.

[114] KLAPDOR-KLEINGROTHAUS 01 uses the calculation by STAUDT 90. Using several other models in the literature could worsen the limit up to 1.2 eV. This is the most stringent experimental bound on m_ν. It supersedes BAUDIS 99B.

[115] ARNOLD 99 limit based on the nuclear matrix elements of STAUDT 90.

[116] BERNATOWICZ 92 finds these majorana neutrino mass limits assuming that the measured geochemical decay width is a limit on the 0ν decay width. The range is the range found using matrix elements from HAXTON 84, TOMODA 87, and SUHONEN 91. Further details of the experiment are given in BERNATOWICZ 93.

[117] ELLIOTT 92 uses the matrix elements of HAXTON 84.

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

For reasons given in the discussion at the beginning of this section, we list only results from 1989 and later. $\langle \lambda \rangle = \lambda \sum U_{ej} V_{ej}$ 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. • • •							
<120	90			^{100}Mo	$0^+ \to 2^+$	[118] ARNOLD	07
$0.692^{+0.058}_{-0.056}$	68	$0.305^{+0.026}_{-0.025}$	68	^{76}Ge	Enriched HPGe	[119] KLAPDOR-K...	06A
< 2.5	90			^{100}Mo	0ν, NEMO-3	[120] ARNOLD	05A
< 3.8	90			^{82}Se	0ν, NEMO-3	[121] ARNOLD	05A
< 1.5–2.0	90			^{100}Mo	0ν, NEMO-3	[122] ARNOLD	04
< 3.2–3.8	90			^{82}Se	0ν, NEMO-3	[123] ARNOLD	04
< 1.6–2.4	90	< 0.9–5.3	90	^{130}Te	Cryog. det.	[124] ARNABOLDI	03
< 2.2	90	<2.5	90	^{116}Cd	^{116}CdWO$_4$ scint.	[125] DANEVICH	03
< 3.2–4.7	90	< 2.4–2.7	90	^{100}Mo	ELEGANT V	[126] EJIRI	01
< 1.1	90	<0.64	90	^{76}Ge	Enriched HPGe	[127] GUENTHER	97
< 4.4	90	<2.3	90	^{136}Xe	TPC	[128] VUILLEUMIER	93
		<5.3		^{128}Te	Geochem	[129] BERNATOW...	92

[118] 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.

[119] 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.

[120] 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.

[121] 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.

[122] 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.

[123] 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.

[124] Supersedes ALESSANDRELLO 00. Cryogenic calorimeter search. Reported a range reflecting uncertainty in nuclear matrix element calculations.

[125] Limits for $\langle\lambda\rangle$ and $\langle\eta\rangle$ are based on nuclear matrix elements of STAUDT 90. Supersedes DANEVICH 00.

[126] 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.

[127] GUENTHER 97 limits use the matrix elements of STAUDT 90. Supersedes BALYSH 95 and BALYSH 92.

[128] VUILLEUMIER 93 uses the matrix elements of MUTO 89. Based on a half-life limit 2.6×10^{23} y at 90%CL.

[129] 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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