Double-β Decay

OMITTED FROM SUMMARY TABLE

LIMITS FROM NEUTRINOLESS DOUBLE-β DECAY

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Neutrinoless double-beta ($0\nu\beta\beta$) decay, if observed, would signal violation of the total lepton number conservation. The process can be mediated by an exchange of a light Majorana neutrino, or by an exchange of other particles. However, the existence of $0\nu\beta\beta$-decay requires Majorana neutrino mass, no matter what the actual mechanism is. As long as only a limit on the lifetime is available, limits on the effective Majorana neutrino mass, and on the lepton-number violating right-handed current can be obtained, independently on the actual mechanism. These limits are listed in the next three tables. In the following we *assume* that the exchange of light Majorana neutrinos ($m_{\nu_i} \leq \mathcal{O}(10\text{ MeV})$) contributes dominantly to the decay rate.

Besides a dependence on the phase space ($G^{0\nu}$) and the nuclear matrix element ($M^{0\nu}$), the observable $0\nu\beta\beta$-decay rate is proportional to the square of the effective Majorana mass ($\langle m_{\beta\beta}\rangle$), $(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot |\langle m_{\beta\beta}\rangle|^2$, with $\langle m_{\beta\beta}\rangle = \sum_i U^2_{ei} m_{\nu_i}$. The sum contains, in general, complex CP phases in U^2_{ei}, i.e., cancelations may occur. For three neutrino flavors there are three physical phases for Majorana neutrinos and one for Dirac neutrinos. The two additional Majorana phases affect only total lepton number violating processes. Given the general 3×3 mixing matrix for Majorana neutrinos, one can construct other analogous lepton number violating quantities, $\sum_i U_{\ell i} U_{\ell' i} m_{\nu_i}$. However, these are currently much less constrained than $\langle m_{\beta\beta}\rangle$.

Nuclear structure calculations are needed to deduce $\langle m_{\beta\beta} \rangle$ from the decay rate. While $G^{0\nu}$ can be calculated reliably, the computation of $M^{0\nu}$ is subject to considerable uncertainty. If the spread among different ways of evaluating the nuclear matrix elements is taken as a measure of error, then there is a factor of $\sim$3 uncertainty in the derived $\langle m_{\beta\beta} \rangle$ values.

The particle physics quantities to be determined are thus nuclear model-dependent, so the half-life measurements are listed first. Where possible, we reference the nuclear matrix elements used in the subsequent analysis. Since rates for the more conventional $2\nu\beta\beta$ decay serve to calibrate the nuclear theory, results for this process are also given.

Neutrino oscillation experiments yield strong evidence that at least some neutrinos are massive. However, these findings shed no light on the mass hierarchy, the absolute neutrino mass values or the properties of neutrinos under CP conjugation (Dirac or Majorana). The atmospheric neutrino anomaly implies $\Delta m^2_{atm} \sim (2-3) \times 10^{-3}$ eV^2 and a large mixing angle $\sin^2\theta_{atm} \approx \sin^2\theta_{23} \approx 0.5$. Oscillations of solar ν_e and reactor $\bar{\nu}_e$ neutrinos lead to the unique 'LMA solution' with $\Delta m^2_{sol} \sim 7 \times 10^{-5}$ eV^2 and $\sin^2\theta_{sol} \approx \sin^2\theta_{12} \approx 0.3$. The investigation of reactor $\bar{\nu}_e$ at 1 km baseline indicates that electron type neutrinos couple only weakly to the third mass eigenstate with $\sin^2\theta_{13} < 0.03$. The so called 'LSND evidence' for oscillations at short baseline requires $\Delta m^2 \sim 0.2 - 2$ eV^2 and small mixing.

Based on these results (and neglecting the not yet confirmed LSND signal): $|\langle m_{\beta\beta} \rangle|^2 \approx |\cos^2\theta_{sol}\ m_1 + e^{i\alpha_1}\ \sin^2\theta_{sol}\ m_2 + e^{i\alpha_2}\ \sin^2\theta_{13}\ m_3|^2$, with α_1, α_2 denoting CP phases. The apparent smallness of $\sin^2\theta_{13}$ thus effectively shields $\langle m_{\beta\beta} \rangle$ from one of the CP phases. Given the present knowledge of the neutrino oscillation parameters, both of the Δm^2 values and of the mixing angles, one can derive the relation between the effective Majorana mass and the mass of the lightest neutrino, as illustrated in Fig. 1. The contribution of possible sterile neutrinos has been neglected.

If the neutrinoless double-beta decay is observed, it will be possible to fix a *range* of absolute values of the masses m_{ν_i}. However, if direct neutrino mass measurements, e.g. using beta decay (which is sensitive to $m_{\nu_e}^{2(\text{eff})} = \sum_i |U_{ei}|^2 m_{\nu_i}^2$), also yield positive results, we may learn something about the otherwise inaccessible CP phases. To do so we have to assume that the Majorana mass is responsible for the decay and that the calculations of $M^{0\nu}$ will be improved. Unlike the direct neutrino mass measurements, however, a limit on $\langle m_{\beta\beta}\rangle$ does not allow one to constrain the individual mass values m_{ν_i} even when the mass differences Δm^2 are known.

Depending on the pattern of neutrino mass, $0\nu\beta\beta$-decay may be driven by the small Δm^2_{sol}, "normal hierarchy" in Fig. 1 ($\langle m_{\beta\beta}\rangle \sim \sin^2\theta_{sol}\sqrt{\Delta m^2_{sol}} \sim 5$ meV), or by the larger Δm^2_{atm}, "inverse hierarchy" in Fig. 1 ($\langle m_{\beta\beta}\rangle \sim \sqrt{\Delta m^2_{atm}} \sim 50$ meV). In the so called "degenerate" scenario an overall mass offset exists and $\langle m_{\beta\beta}\rangle$ is relatively large.

Neutrino oscillation data imply the existence of a *lower limit* for the Majorana neutrino mass for some of the mass patterns. Several new double-beta searches have been proposed to probe the interesting $\langle m_{\beta\beta}\rangle$ mass range.

If lepton-number violating right-handed current weak interactions exist, the $0\nu\beta\beta$ decay rate also depends on the quantities $\langle\eta\rangle = \eta\sum_i U_{ei}V_{ei}$ and $\langle\lambda\rangle = \lambda\sum_i U_{ei}V_{ei}$, where V_{lj} is a matrix analogous to U_{lj} but describing the mixing with the hypothetical right-handed neutrinos and the coupling constants η and λ characterize the strength of the corresponding

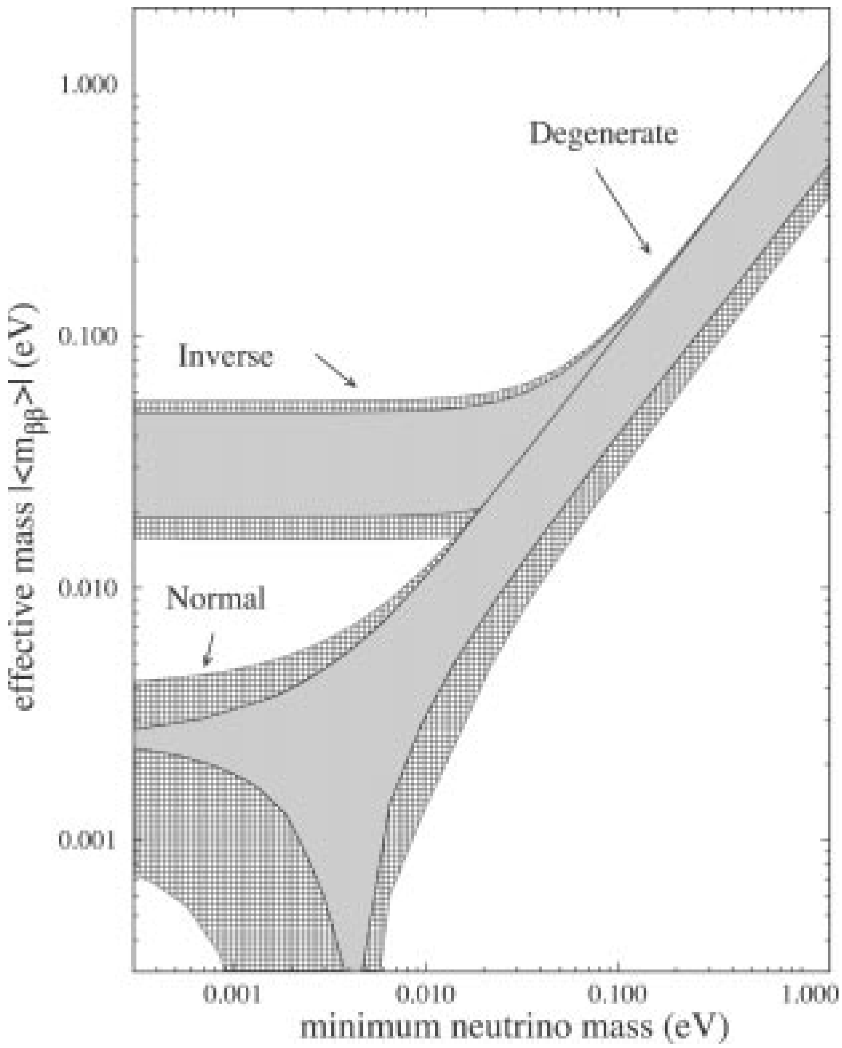

Figure 1: Dependence of the effective Majorana mass $\langle m_{\beta\beta}\rangle$ derived from the rate of neutrinoless double-beta decay $(1/T^{0\nu}_{1/2} \sim \left|\langle m_{\beta\beta}\rangle\right|^2)$ on the absolute mass of the lightest neutrino. The arrows indicate the three possible neutrino mass patterns or "hierarchies." The curves are based on the 'LMA solution,' $\Delta m^2_{sol} = 7 \times 10^{-5}$ eV^2, $\sin^2\theta_{sol} = 0.3$, and $\Delta m^2_{atm} = 2.4 \times 10^{-3}$ eV^2, $\theta_{13} = 0$. The cross-hatched region is covered if one σ errors on these oscillation parameters are included.

right-right and right-left weak interactions. The $\langle\eta\rangle$ and $\langle\lambda\rangle$ vanish for massless or unmixed neutrinos due to the unitarity of the generalized mixing matrix containing both the U and V matrices. The limits on $\langle\eta\rangle$ are of order 10^{-8}, while the limits on $\langle\lambda\rangle$ are of order 10^{-6}. The reader is cautioned that a number of earlier experiments did not distinguish between η and λ. In addition, see the section on Majoron searches for additional limits set by these experiments.

Half-life Measurements and Limits for Double-β Decay

In all cases of double-beta decay, (Z,A) $\rightarrow$ (Z+2,A) $+ 2e^- + (0 \text{ or } 2)\overline{\nu}_e$. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported. For 2ν decay, which is well established, only measured half-lives are reported.

$t_{1/2}$(10^{21} yr)	CL%	ISOTOPE	TRANSITION		METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$>$ 210	90	^{130}Te	0ν		Cryog. det.	[1] ARNABOLDI	03
$>$ 31	90	^{130}Te	0ν	$0^+ \rightarrow 2^+$	Cryog. det.	[2] ARNABOLDI	03
$0.61 \pm 0.14^{+0.29}_{-0.35}$	90	^{130}Te	2ν		Cryog. det.	[3] ARNABOLDI	03
$>$ 110	90	^{128}Te	0ν		Cryog. det.	[4] ARNABOLDI	03
$(0.029^{+0.004}_{-0.003})$		^{116}Cd	2ν		^{116}CdWO$_4$ scint.	[5] DANEVICH	03
$>$ 170	90	^{116}Cd	0ν		^{116}CdWO$_4$ scint.	[6] DANEVICH	03
$>$ 29	90	^{116}Cd	0ν	$0^+ \rightarrow 2^+$	^{116}CdWO$_4$ scint.	[7] DANEVICH	03
$>$ 14	90	^{116}Cd	0ν	$0^+ \rightarrow 0^+_1$	^{116}CdWO$_4$ scint.	[8] DANEVICH	03
$>$ 6	90	^{116}Cd	0ν	$0^+ \rightarrow 0^+_2$	^{116}CdWO$_4$ scint.	[9] DANEVICH	03
$>$15700	90	^{76}Ge	0ν		Enriched HPGe	[10] AALSETH	02B
$>$ 58	90	^{134}Xe	0ν		Liquid Xe Scint.	[11] BERNABEI	02D
$>$ 1200	90	^{136}Xe	0ν		Liquid Xe Scint.	[12] BERNABEI	02D
$15000 \ ^{+168000}_{-\ \ 7500}$		^{76}Ge	0ν		Enriched HPGe	[13] KLAPDOR-K...	02D
$(7.2 \pm 0.9 \pm 1.8)$E-3		^{100}Mo	2ν		Liq. Ar ioniz.	[14] ASHITKOV	01
$>$ 4.9	90	^{100}Mo	0ν		Liq. Ar ioniz.	[15] ASHITKOV	01
$>$ 1.3	90	^{160}Gd	0ν		Gd$_2$SiO$_5$:Ce	[16] DANEVICH	01
$>$ 1.3	90	^{160}Gd	0ν	$0^+ \rightarrow 2^+$	Gd$_2$SiO$_5$:Ce	[17] DANEVICH	01
$0.59^{+0.17}_{-0.11} \pm 0.06$		^{100}Mo	0ν+2ν	$0^+ \rightarrow 0^+_1$	Ge coinc.	[18] DEBRAECKEL...	01
$>$ 55	90	^{100}Mo	$0\nu,\langle m_\nu\rangle$		ELEGANT V	[19] EJIRI	01
$>$ 42	90	^{100}Mo	$0\nu,\langle\lambda\rangle$		ELEGANT V	[19] EJIRI	01
$>$ 49	90	^{100}Mo	$0\nu,\langle\eta\rangle$		ELEGANT V	[19] EJIRI	01
$>$19000	90	^{76}Ge	0ν		Enriched HPGe	[20] KLAPDOR-K...	01
$1.55 \pm 0.001^{+0.19}_{-0.15}$	90	^{76}Ge	2ν		Enriched HPGe	[21] KLAPDOR-K...	01
(9.4 ± 3.2)E-3	90	^{96}Zr	0ν+2ν		Geochem	[22] WIESER	01
$0.042^{+0.033}_{-0.013}$		^{48}Ca	2ν		Ge spectrometer	[23] BRUDANIN	00
$0.021^{+0.008}_{-0.004} \pm 0.002$		^{96}Zr	2ν		NEMO-2	[24] ARNOLD	99
$>$ 1.0	90	^{96}Zr	0ν		NEMO-2	[24] ARNOLD	99

$(8.3 \pm 1.0 \pm 0.7)$E-2		^{82}Se	2ν		NEMO-2	[25] ARNOLD	98
$>$ 9.5	90	^{82}Se	0ν		NEMO-2	[26] ARNOLD	98
$>$ 2.8	90	^{82}Se	0ν	$0^+ \rightarrow 2^+$	NEMO-2	[27] ARNOLD	98
$(7.6^{+2.2}_{-1.4})$E-3		^{100}Mo	2ν		Si(Li)	[28] ALSTON-...	97
$(6.82^{+0.38}_{-0.53} \pm 0.68)$E-3		^{100}Mo	2ν		TPC	[29] DESILVA	97
$(6.75^{+0.37}_{-0.42} \pm 0.68)$E-3		^{150}Nd	2ν		TPC	[30] DESILVA	97
$>$ 1.2	90	^{150}Nd	0ν		TPC	[31] DESILVA	97
$1.77 \pm 0.01^{+0.13}_{-0.11}$		^{76}Ge	2ν		Enriched HPGe	[32] GUENTHER	97
$(3.75 \pm 0.35 \pm 0.21)$E-2		^{116}Cd	2ν	$0^+ \rightarrow 0^+$	NEMO 2	[33] ARNOLD	96
$0.043^{+0.024}_{-0.011} \pm 0.014$		^{48}Ca	2ν		TPC	[34] BALYSH	96
0.79 ± 0.10		^{130}Te	0ν+2ν		Geochem	[35] TAKAOKA	96
$0.61^{+0.18}_{-0.11}$		^{100}Mo	0ν+2ν	$0^+ \rightarrow 0^+_1$	γ in HPGe	[36] BARABASH	95
$(9.5 \pm 0.4 \pm 0.9)$E-3		^{100}Mo	2ν		NEMO 2	DASSIE	95
$>$ 0.6	90	^{100}Mo	0ν	$0^+ \rightarrow 0^+_1$	NEMO 2	DASSIE	95
$0.026^{+0.009}_{-0.005}$		^{116}Cd	2ν	$0^+ \rightarrow 0^+$	ELEGANT IV	EJIRI	95
$0.017^{+0.010}_{-0.005} \pm 0.0035$		^{150}Nd	2ν	$0^+ \rightarrow 0^+$	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	[37] BERNATOW...	92
$>$ 27	68	^{82}Se	0ν	$0^+ \rightarrow 0^+$	TPC	ELLIOTT	92
$0.108^{+0.026}_{-0.006}$		^{82}Se	2ν	$0^+ \rightarrow 0^+$	TPC	ELLIOTT	92
2.0 ± 0.6		^{238}U	0ν+2ν		Radiochem	[38] TURKEVICH	91
$>$ 9.5	76	^{48}Ca	0ν		CaF_2 scint.	YOU	91
$0.12 \pm 0.01 \pm 0.04$	68	^{82}Se	0ν+2ν		Geochem.	[39] LIN	88
$0.75 \pm 0.03 \pm 0.23$	68	^{130}Te	0ν+2ν		Geochem.	[40] LIN	88
1800 ± 700	68	^{128}Te	0ν+2ν		Geochem.	[41] LIN	88B
2.60 ± 0.28		^{130}Te	0ν+2ν		Geochem	[42] KIRSTEN	83

[1] Supersedes ALESSANDRELLO 00. Array of TeO_2 crystals in high resolution cryogenic calorimeter. Some enriched in ^{130}Te. Ground state to ground state decay.

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

[3] 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.

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

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

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

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

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

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

[10] 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.

[11] 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.

[12] 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.

[13] KLAPDOR-KLEINGROTHAUS 02D is an expanded version of KLAPDOR-KLEINGROTHAUS 01B. The authors re-evaluate the data collected by the Heidelberg-Moscow experiment (KLAPDOR-KLEINGROTHAUS 01) and present a more detailed description of their analysis of an excess of counts at the energy expected for neutrinoless double-beta decay. They interpret this excess, which has a significance of 2.2 to 3.1 σ depending on the data analysis, as evidence for the observation of Lepton Number violation and violation of Baryon minus Lepton Number. The analysis has been criticized by AALSETH 02 and others. The criticisms have been addressed in KLAPDOR-KLEINGROTHAUS 02. See also KLAPDOR-KLEINGROTHAUS 02B.

[14] ASHITKOV 01 result for 2ν of ^{100}Mo is in agreement with other determinations of that halflife.

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

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

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

[18] 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.

[19] EJIRI 01 uses tracking calorimeter and isotopically enriched passive source. Efficiencies were calculated assuming $\langle m_\nu \rangle$, $\langle \lambda \rangle$, or $\langle \eta \rangle$ driven decay. This is a continuation of EJIRI 96 which it supersedes.

[20] 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.

[21] KLAPDOR-KLEINGROTHAUS 01 is a measurement of the $\beta\beta 2\nu$-decay rate with higher statistics than GUENTHER 97. The reported value has a worse systematic error than their previous result.

[22] 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.

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

[24] 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.

[25] 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.

[26] ARNOLD 98 determine the limit for 0ν decay to the ground state of ^{82}Se using the NEMO-2 tracking detector. The half-life limit is in agreement, but less stringent, than ELLIOTT 92.

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

[28] 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.

[29] 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.

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

[31] DESILVA 97 do not explain whether their efficiency for 0ν decay of ^{150}Nd was calculated under the assumption of a $\langle m_\nu \rangle$, $\langle \lambda \rangle$, or $\langle \eta \rangle$ driven decay.

[32] GUENTHER 97 half-life for the 2ν decay of ^{76}Ge is not in good agreement with the previous measurements of BALYSH 94, AVIGNONE 91, and MILEY 90.

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

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

[35] 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.

[36] 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).

[37] 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.

[38] 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.

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

[40] 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.

[41] 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.

[42] 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. • • •						
$<$ 1.1–2.6	90	^{130}Te		Cryog. det.	[43] ARNABOLDI	03
$<$ 1.5–1.7	90	^{116}Cd	0ν	$^{116}CdWO_4$ scint.	[44] DANEVICH	03
$<$ 0.33–1.35	90			Enriched HPGe	[45] AALSETH	02B
$<$2.9	90	^{136}Xe	0ν	Liquid Xe Scint.	[46] BERNABEI	02D
$0.39^{+0.17}_{-0.28}$		^{76}Ge	0ν	Enriched HPGe	[47] KLAPDOR-K...	02D
$<$ 2.1–4.8	90	^{100}Mo	0ν	ELEGANT V	[48] EJIRI	01
$<$ 0.35	90	^{76}Ge		Enriched HPGe	[49] KLAPDOR-K...	01
$<$23	90	^{96}Zr		NEMO-2	[50] ARNOLD	99
$<$ 1.1–1.5		^{128}Te		Geochem	[51] BERNATOW...	92
$<$5	68	^{82}Se		TPC	[52] ELLIOTT	92
$<$8.3	76	^{48}Ca	0ν	CaF_2 scint.	YOU	91

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

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

[45] 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.

[46] 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.

[47] 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.

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

[49] 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.

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

[51] 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.

[52] 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. • • •							
< 1.6–2.4	90	< 0.9–5.3	90	^{130}Te	Cryog. det.	[53] ARNABOLDI	03
<2.2	90	<2.5	90	^{116}Cd	$^{116}CdWO_4$ scint.	[54] DANEVICH	03
< 3.2–4.7	90	< 2.4–2.7	90	^{100}Mo	ELEGANT V	[55] EJIRI	01
<1.1	90	<0.64	90	^{76}Ge	Enriched HPGe	[56] GUENTHER	97
<4.4	90	<2.3	90	^{136}Xe	TPC	[57] VUILLEUMIER	93
		<5.3		^{128}Te	Geochem	[58] BERNATOW...	92

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

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

[55] 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.

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

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

[58] 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.

Double-β Decay REFERENCES

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DANEVICH	03	PR C68 035501	F.A. Danevich *et al.*	
AALSETH	02	MPL A17 1475	C.E. Aalseth *et al.*	
AALSETH	02B	PR D65 092007	C.E. Aalseth *et al.*	(IGEX Collab.)
BERNABEI	02D	PL B546 23	R. Bernabei *et al.*	(DAMA Collab.)
KLAPDOR-K...	02	hep-ph/0205228	H.V. Klapdor-Kleingrothaus	
KLAPDOR-K...	02B	JINRRC 110 57	H.V. Klapdor-Kleingrothaus, A. Dietz, I.V. Krivosheina	
KLAPDOR-K...	02D	FP 32 1181	H.V. Klapdor-Kleingrothaus, A. Dietz, I.V. Krivosheina	
SIMKOVIC	02	hep-ph/0204278	F. Simkovic, P. Domin, A. Faessler	
ASHITKOV	01	JETPL 74 529	V.D. Ashitkov *et al.*	
		Translated from ZETFP 74 601.		
DANEVICH	01	NP A694 375	F.A. Danevich *et al.*	
DEBRAECKEL...	01	PRL 86 3510	L. De Braeckeleer *et al.*	
EJIRI	01	PR C63 065501	H. Ejiri *et al.*	
KLAPDOR-K...	01	EPJ A12 147	H.V. Klapdor-Kleingrothaus *et al.*	
KLAPDOR-K...	01B	MPL A16 2409	H.V. Klapdor-Kleingrothaus *et al.*	
WIESER	01	PR C64 024308	M.E. Wieser, J.R. De Laeter	
ALESSAND...	00	PL B486 13	A. Alessandrello *et al.*	
BRUDANIN	00	PL B495 63	V.B. Brudanin *et al.*	
DANEVICH	00	PR C62 045501	F.A. Danevich *et al.*	
ARNOLD	99	NP A658 299	R. Arnold *et al.*	(NEMO Collab.)
BAUDIS	99	PR D59 022001	L. Baudis *et al.*	(Heidelberg-Moscow Collab.)
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ARNOLD	98	NP A636 209	R. Arnold *et al.*	(NEMO-2 Collab.)
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DESILVA	97	PR C56 2451	A. de Silva *et al.*	(UCI)
GUENTHER	97	PR D55 54	M. Gunther *et al.*	(Heidelberg-Moscow Collab.)
ARNOLD	96	ZPHY C72 239	R. Arnold *et al.*	(BCEN, CAEN, JINR+)
BALYSH	96	PRL 77 5186	A. Balysh *et al.*	(KIAE, UCI, CIT)

EJIRI	96	NP A611 85	H. Ejiri *et al.*	(OSAK)
TAKAOKA	96	PR C53 1557	N. Takaoka, Y. Motomura, K. Nagao	(KYUSH, OKAY)
ARNOLD	95	JETPL 61 170	R.G. Arnold *et al.*	(NEMO Collab.)
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BALYSH	95	PL B356 450	A. Balysh *et al.*	(Heidelberg-Moscow Collab.)
BARABASH	95	PL B345 408	A.S. Barabash *et al.*	(ITEP, SCUC, PNL+)
DASSIE	95	PR D51 2090	D. Dassie *et al.*	(NEMO Collab.)
EJIRI	95	JPSJ 64 339	H. Ejiri *et al.*	(OSAK, KIEV)
KOBAYASHI	95	NP A586 457	M. Kobayashi, M. Kobayashi	(KEK, SAGA)
BALYSH	94	PL B322 176	A. Balysh *et al.*	(Heidelberg-Moscow Collab.)
ARTEMEV	93	JETPL 58 262	V.A. Artemiev *et al.*	(ITEP, INRM)
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BALYSH	92	PL B283 32	A. Balysh *et al.*	(MPIH, KIAE, SASSO)
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ELLIOTT	92	PR C46 1535	S.R. Elliott *et al.*	(UCI)
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MANUEL	91	JPG 17 S221	O.K. Manuel	(MISSR)
SUHONEN	91	NP A535 509	J. Suhonen, S.B. Khadkikar, A. Faessler	(JYV+)
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MILEY	90	PRL 65 3092	H.S. Miley *et al.*	(SCUC, PNL)
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