Double-β Decay

OMITTED FROM SUMMARY TABLE

LIMITS FROM NEUTRINOLESS DOUBLE-β DECAY

Revised April 2002 by P. Vogel (Caltech).

Neutrinoless double-beta decay, if observed, would signal violation of the total lepton number conservation. The process can be mediated by an exchange of light Majorana neutrino, or by an exchange of other particles. As long as only a limit on its lifetime is available, limits on the effective Majorana neutrino mass, and on the lepton-number violating right-handed current admixture can be obtained, independently on the actual mechanism. These are considered in the following three tables.

At present there is a strong evidence that neutrinos oscillate, i.e. that at least some neutrinos are massive (although one cannot decide whether the mass is Majorana or Dirac). In particular, the atmospheric neutrino anomaly implies $\Delta m^2 \sim 3 \times 10^{-3}$ eV^2 and hence sets the scale of possible neutrino masses at $\sim 5 \times 10^{-2}$ eV. It is likely that the search for neutrinoless double-beta decay will reach sensitivity to this scale in a foreseeable future.

If the exchange of a massive Majorana neutrino is the mechanism responsible for neutrinoless double-beta decay, the decay rate is proportional to the square of the "effective Majorana mass" $\langle m_\nu \rangle^2 = |\sum_i U_{ei}^2 m_{\nu_i}|^2$, where the sum is over all masses $m_{\nu_i} \lesssim 10$ MeV. This sum contains, in general, complex numbers, *i.e.* cancelations may occur due to the CP phases in U_{ei}^2. These phases are peculiar to massive Majorana neutrinos, and affect only total lepton number violating processes. If and when neutrinoless double-beta decay is observed, it will make it therefore possible (assuming still that the Majorana mass is responsible for the decay) to fix a *range* of absolute values of the masses m_{ν_i}. However, if at the same time the direct neutrino mass measurements, *e.g.* in beta decay, yield a positive result, one can learn something about the otherwise inaccessible CP phases. Unlike the direct neutrino mass measurements, however, a limit on $\langle m_\nu \rangle$ does not allow one to constrain the individual mass values m_{ν_i} (even when the mass differences Δm^2 are known).

The derived quantities are dependent on the nuclear model, so the half-life measurements are given first. Where possible, we list the references for the nuclear matrix elements used in the subsequent analysis. Since rates for the more conventional $2\nu\beta\beta$ decay serve to calibrate the theory, results for this process are also given. As an indication of the spread among different ways of evaluating the matrix elements, we show in Fig. 1 some representative examples for the most popular nuclei. The rates, $1/T_{1/2}$, are plotted so that the most favorable cases appear tallest.

To define the limits on lepton-number violating right-handed current admixtures, we display the relevant part of a phenomenological current-current weak interaction Hamiltonian:

$$\begin{aligned} H_W =&(G_F/\sqrt{2}) \\ &\times(J_L \cdot j_L^\dagger + \kappa J_R \cdot j_L^\dagger + \eta J_L \cdot j_R^\dagger + \lambda J_R \cdot j_R^\dagger) + \text{h.c.} \end{aligned} \tag{1}$$

where $j_L^\mu = \bar{e}_L \gamma^\mu \nu_{eL}$, $j_R^\mu = \bar{e}_R \gamma^\mu \nu_{eR}$, and J_L^μ and J_R^μ are left-handed and right-handed hadronic weak currents. Experiments are not sensitive to κ, but quote limits on quantities proportional to η and λ.In analogy to $\langle m_\nu \rangle$ (see Eq. 17 in "Neutrino mass" minireview at the beginning of the 2000 Neutrino Particle Listings), the quantities extracted from experiments are $\langle \eta \rangle = \eta \sum U_{ej} V_{ej}$ and $\langle \lambda \rangle = \lambda \sum U_{ej} V_{ej}$, where $V_{\ell j}$ is a matrix

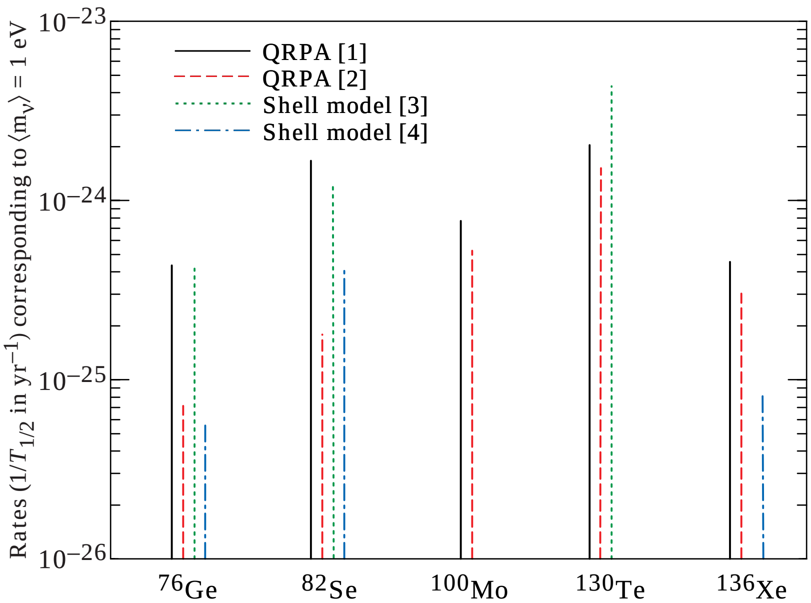

Figure 1: Decay rates (in yr^{-1}) calculated for $\langle m_\nu \rangle = 1$ eV by various representative methods and different authors for the most popular double-beta decay candidate nuclei. The QRPA results from Ref. 2 are recalculated for $g_A = 1.25$ and $\alpha' = -390$ MeV fm^3.

analogous to $U_{\ell j}$ (see Eq. 2 in the "Neutrino mass" from the 2000 edition), but describing the mixing among right-handed neutrinos. The quantities $\langle \eta \rangle$ and $\langle \lambda \rangle$ therefore vanish for massless or unmixed neutrinos. Also, as in the case of $\langle m_\nu \rangle$, cancelations are possible in $\langle \eta \rangle$ and $\langle \lambda \rangle$. 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 warned that a number of earlier experiments did not distinguish between η and λ. Because of evolving reporting conventions and matrix element calculations, we have not tabulated the admixture parameters for experiments published earlier than 1989.

See the section on Majoron searches for additional limits set by these experiments.

Very recently, a reanalysis of a subset of data collected by the Heidelberg-Moscow collaboration was interpreted as evidence for the neutrinoless $\beta\beta$ decay of ^{76}Ge [5]. The statistical significance of the claim is 2.2–3.1 σ depending on the analysis method. Provided that the finding withstands further scrutiny, or better yet, is independently confirmed, the deduced half-life of $1.9^{+16.8}_{-0.7} \times 10^{25}$y implies that $\langle m_\nu \rangle = 0.39^{+0.17}_{-0.28}$ eV for the nuclear matrix elements used in Ref. 5 and $\langle m_\nu \rangle \approx 0.4$–$1.3$ eV for the range of nuclear matrix elements discussed above. This extraordinary claim would imply, in turn, that $\langle m_\nu \rangle \gg \sqrt{\Delta m^2}$, where the quantities Δm^2 are based on the atmospheric and solar neutrino oscillation results.

References

1. A. Staudt, K. Muto, and H.V. Klapdor-Kleingrothaus, Europhys. Lett. **13**, 31 (1990).
2. J. Engel, P. Vogel, and M.R. Zirnbauer, Phys. Rev. **C37**, 731 (1988).
3. W.C. Haxton and G.J. Stephenson Jr., Prog. in Part. Nucl. Phys. **12**, 409 (1984).
4. E. Caurier *et al.*, Phys. Rev. Lett. **77**, 1954 (1996).
5. H.V. Klapdor-Kleingrothaus *et al.*, Mod. Phys. Lett. **16**, 2409 (2001).

Half-life Measurements and Limits for Double-β Decay

In all cases of double-beta decay, (Z,A) $\rightarrow$ (Z+2,A) $+ 2e^-$ $+$ (0 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. • • •					
$>$ 1.3	90	^{160}Gd	0ν	^{160}Gd$_2$SiO$_5$:Ce	[1] DANEVICH 01
$>$ 1.3	90	^{160}Gd	0ν $0^+ \rightarrow 2^+$	^{160}Gd$_2$SiO$_5$:Ce	[2] DANEVICH 01
$0.59^{+0.17}_{-0.11} \pm 0.06$		^{100}Mo	0ν+2ν $0^+ \rightarrow 0^+_1$	Ge coinc.	[3] DEBRAECKEL... 01
$>$ 55	90	^{100}Mo	$0\nu,\langle m_\nu \rangle$	ELEGANT V	[4] EJIRI 01
$>$ 42	90	^{100}Mo	$0\nu,\langle \lambda \rangle$	ELEGANT V	[4] EJIRI 01
$>$ 49	90	^{100}Mo	$0\nu,\langle \eta \rangle$	ELEGANT V	[4] EJIRI 01
$>$19000	90	^{76}Ge	0ν	Enriched HPGe	[5] KLAPDOR-K... 01
$1.55 \pm 0.001^{+0.19}_{-0.15}$	90	^{76}Ge	2ν	Enriched HPGe	[6] KLAPDOR-K... 01
$15000^{+168000}_{-\ \ 7000}$	95	^{76}Ge	0ν	Enriched HPGe	[7] KLAPDOR-K... 01B
(9.4 ± 3.2)E-3	90	^{96}Zr	0ν+2ν	Geochem	[8] WIESER 01
$>$144	90	^{130}Te	0ν	Cryog. det.	[9] ALESSAND... 00
$>$ 86	90	^{128}Te	0ν	Cryog. det.	[9] ALESSAND... 00
$>$ 1.5	90	^{48}Ca	0ν	Ge spectrometer	[10] BRUDANIN 00
$0.042^{+0.033}_{-0.013}$		^{48}Ca	2ν	Ge spectrometer	[11] BRUDANIN 00
$0.026 \pm 0.001^{+0.007}_{-0.004}$		^{116}Cd	2ν	^{116}CdWO$_4$ scint.	[12] DANEVICH 00
$>$ 70	90	^{116}Cd	0ν	^{116}CdWO$_4$ scint.	[13] DANEVICH 00
$>$ 7	90	^{116}Cd	0ν $0^+ \rightarrow 0^+_1$	^{116}CdWO$_4$ scint.	[14] DANEVICH 00
$0.021^{+0.008}_{-0.004} \pm 0.002$		^{96}Zr	2ν	NEMO-2	[15] ARNOLD 99
$>$ 1.0	90	^{96}Zr	0ν	NEMO-2	[15] ARNOLD 99
$>$16000(57000)	90	^{76}Ge	0ν	Enriched HPGe	[16] BAUDIS 99B
$>$440	90	^{136}Xe	0ν	Xe TPC	[17] LUESCHER 98
$(7.6^{+2.2}_{-1.4})$E-3		^{100}Mo	2ν	Si(Li)	[18] ALSTON-... 97
$(6.82^{+0.38}_{-0.53} \pm 0.68)$E-3		^{100}Mo	2ν	TPC	[19] DESILVA 97
$(6.75^{+0.37}_{-0.42} \pm 0.68)$E-3		^{150}Nd	2ν	TPC	[20] DESILVA 97
$>$ 1.2	90	^{150}Nd	0ν	TPC	[21] DESILVA 97
$1.77 \pm 0.01^{+0.13}_{-0.11}$		^{76}Ge	2ν	Enriched HPGe	[22] GUENTHER 97
$(3.75 \pm 0.35 \pm 0.21)$E-2		^{116}Cd	2ν $0^+ \rightarrow 0^+$	NEMO 2	[23] ARNOLD 96
$0.043^{+0.024}_{-0.011} \pm 0.014$		^{48}Ca	2ν	TPC	[24] BALYSH 96
$>$ 52	68	^{100}Mo	$0\nu,\langle m_\nu \rangle$ $0^+ \rightarrow 0^+$	ELEGANT V	[25] EJIRI 96
$>$ 39	68	^{100}Mo	$0\nu,\langle \lambda \rangle$ $0^+ \rightarrow 0^+$	ELEGANT V	[25] EJIRI 96
$>$ 51	68	^{100}Mo	$0\nu,\langle \eta \rangle$ $0^+ \rightarrow 0^+$	ELEGANT V	[25] EJIRI 96
0.79 ± 0.10		^{130}Te	0ν+2ν	Geochem	[26] TAKAOKA 96
$0.61^{+0.18}_{-0.11}$		^{100}Mo	0ν+2ν $0^+ \rightarrow 0^+_1$	γ in HPGe	[27] BARABASH 95
$(9.5 \pm 0.4 \pm 0.9)$E18		^{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	$0\nu+2\nu$		Geochem		KAWASHIMA 93
2.7 ± 0.1		^{130}Te	$0\nu+2\nu$		Geochem		BERNATOW... 92
7200 ± 400		^{128}Te	$0\nu+2\nu$		Geochem	28	BERNATOW... 92
> 27	68	^{82}Se	0ν	$0^+ \to 0^+$	TPC		ELLIOTT 92
$0.108^{+0.026}_{-0.006}$		^{82}Se	2ν	$0^+ \to 0^+$	TPC		ELLIOTT 92
2.0 ± 0.6		^{238}U	$0\nu+2\nu$		Radiochem	29	TURKEVICH 91
> 9.5	76	^{48}Ca	0ν		CaF_2 scint.		YOU 91
2.60 ± 0.28		^{130}Te	$0\nu+2\nu$		Geochem	30	KIRSTEN 83

[1] 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.

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

[3] 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.

[4] 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.

[5] 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.

[6] 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.

[7] KLAPDOR-KLEINGROTHAUS 01B use the data collected in the Heidelberg-Moscow experiment (KLAPDOR-KLEINGROTHAUS 01) which they reanalyze and interpret as evidence for the observation of Lepton number violation and violation of Baryon minus Lepton number. The evidence presented is an excess of counts at the energy expected for neutrinoless double beta decay. Depending on the data analysis strategy chosen the significance of this excess varies from 2.2 to 3.1 σ. The analysis has been criticized (AALSETH 02) on several grounds, including the choice of a restrictive energy window (which affects the statistical significance of the reported signal) and the apparent lack of explanation for several similar excesses near the claimed peak. The criticisms have been addressed in KLAPDOR-KLEINGROTHAUS 02.

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

[9] ALESSANDRELLO 00 limit is based on calorimetric measurement with an array of 20 TeO_2 cryogenic detectors. Uses enriched and natural Te crystals. Replaces ALESSANDRELLO 98.

[10] BRUDANIN 00 determine a limit for 0ν halflife of ^{48}Ca. Their value is less accurate than YOU 91.

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

[12] DANEVICH 00 provides calorimetric measurement of 2ν decay of ^{116}Cd using enriched $CdWO_4$ scintillators. Agrees with EJIRI 95 and ARNOLD 96.

[13] DANEVICH 00 places limits on 0ν decay of ^{116}Cd using enriched $CdWO_4$ scintillators. Replaces GEORGADZE 95.

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

[15] 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.

[16] BAUDIS 99B is a continuation of the work of BAUDIS 97. The limit is based on a subset of data using a pulse shape event selection. The exposure time is 24.2 kg-yr. The more stringent limit, in parentheses, results from unphysical data (measured rate significantly below expected background), while the smaller value is the experimental sensitivity as defined by FELDMAN 98. This work supersedes BAUDIS 97 as the most stringent result. AVIGNONE 00 has expressed some concerns about the way the most stringent lifetime limit (given in parentheses) was determined.

[17] LUESCHER 98 report a limit for the 0ν decay of ^{136}Xe TPC. Supersedes VUILLEUMIER 93.

[18] 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.

[19] 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.

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

[21] 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.

[22] 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.

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

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

[25] EJIRI 96 use energy and angular correlations of the $2\,\beta$-rays in efficiency estimate to give limits for the 0ν decay modes associated with $\langle m_\nu \rangle$, $\langle \lambda \rangle$, and $\langle \eta \rangle$, respectively. Enriched ^{100}Mo source is used in tracking calorimeter. These are the best limits for ^{100}Mo. Limit is more stringent than ALSTON-GARNJOST 97.

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

[27] 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).

[28] 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 supression 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.

[29] 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.

[30] 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. • • •						
$<$ 2.1–4.8	90	^{100}Mo	0ν	ELEGANT V	[31] EJIRI	01
$<$ 0.35	90	^{76}Ge		Enriched HPGe	[32] KLAPDOR-K...	01
$0.39^{+0.17}_{-0.28}$	95	^{76}Ge		Enriched HPGe	[33] KLAPDOR-K...	01B
$<$ 1.1–2.6	90	^{130}Te	0ν	Cryog. det.	[34] ALESSAND...	00
$<$ 2.4–2.6	90	^{116}Cd	0ν	$^{116}CdWO_4$ scint	[35] DANEVICH	00
$<$23	90	^{96}Zr		NEMO-2	[36] ARNOLD	99
$<$ 0.4(0.2)–1.0(0.6)	90	^{76}Ge		Enriched HPGe	[37] BAUDIS	99B
$<$ 2.4–2.7	90	^{136}Xe	0ν	Xe TPC	[38] LUESCHER	98
$<$9.3	68	^{100}Mo	0ν	Si(Li)	[39] ALSTON-...	97
$<$0.46	90	^{76}Ge	0ν $0^+ \rightarrow 0^+$	Enriched HPGe	[40] BAUDIS	97
$<$2.2	68	^{100}Mo	0ν $0^+ \rightarrow 0^+$	ELEGANT V	[41] EJIRI	96
$<$4.1	90	^{116}Cd	0ν	$^{116}CdWO_4$ scint	[42] DANEVICH	95
$<$ 1.1–1.5		^{128}Te		Geochem	[43] BERNATOW...	92
$<$5	68	^{82}Se		TPC	[44] ELLIOTT	92
$<$8.3	76	^{48}Ca	0ν	CaF_2 scint.	YOU	91

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

[32] 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.

[33] This signal would require that neutrinos are massive Majorana particles. It has been derived from a measured decay rate using the theoretically calculated nuclear matrix element of STAUDT 90. The analysis has been criticized (AALSETH 02) on several grounds and the criticisms have been addressed in KLAPDOR-KLEINGROTHAUS 02. At the time of this writing, the issue remains controversial.

[34] ALESSANDRELLO 00 spread in limit for $\langle m_\nu \rangle$ reflects the range found for theoretical matrix elements.

[35] DANEVICH 00 limit for $\langle m_\nu \rangle$ is based on the nuclear matrix elements of STAUDT 90 (2.6 eV) and ARNOLD 96 (2.4 eV).

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

[37] BAUDIS 99B derive a limit for $\langle m_\nu \rangle$ using the matrix elements of STAUDT 90. For this very restrictive limit, the uncertainty we give for $\langle m_\nu \rangle$ reflects estimated theoretical uncertainties in the matrix element calculations. The less restrictive limit is based on the quoted experimental sensitivity while the lower value in parentheses makes use of measured rates significantly below background.

[38] LUESCHER 98 limit for $\langle m_\nu \rangle$ is based on the matrix elements of ENGEL 88.

[39] ALSTON-GARNJOST 97 obtain the limit for $\langle m_\nu \rangle$ using the matrix elements of ENGEL 88. The limit supersedes ALSTON-GARNJOST 93.

[40] BAUDIS 97 limit for $\langle m_\nu \rangle$ is based on the matrix elements of STAUDT 90.

[41] EJIRI 96 obtain the limit for $\langle m_\nu \rangle$ using the matrix elements of TOMODA 91.

[42] DANEVICH 95 is identical to GEORGADZE 95.

[43] BERNATOWICZ 92 finds these majorona 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.
[44] 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. • • •							
< 3.2–4.7	90	< 2.4–2.7	90	^{100}Mo	ELEGANT V	[45] EJIRI	01
< 1.9–3.9	90	< 1.2–6.4	90	^{130}Te	Cryog. det.	[46] ALESSAND...	00
<3.4	90	<3.9	90	^{116}Cd	$^{116}CdWO_4$ scint.	[47] DANEVICH	00
<1.1	90	<0.64	90	^{76}Ge	Enriched HPGe	[48] GUENTHER	97
<3.7	68	<2.5	68	^{100}Mo	ELEGANT V	[49] EJIRI	96
<4.4	90	<2.3	90	^{136}Xe	TPC	[50] VUILLEUMIER	93
		<5.3		^{128}Te	Geochem	[51] BERNATOW...	92

[45] 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.
[46] ALESSANDRELLO 00 limits for $\langle\lambda\rangle$ and $\langle\eta\rangle$ use several nuclear matrix element calculations. Limits reported for $\langle m_\nu\rangle = \langle\eta\rangle = \langle\lambda\rangle = 0$.
[47] DANEVICH 00 limits for $\langle\lambda\rangle$ and $\langle\eta\rangle$ are based on nuclear matrix element of STAUDT 90. Replaces DANEVICH 95.
[48] GUENTHER 97 limits use the matrix elements of STAUDT 90. Supersedes BALYSH 95 and BALYSH 92.
[49] EJIRI 96 obtain limits for $\langle\lambda\rangle$ and $\langle\eta\rangle$ using the matrix elements of TOMODA 91.
[50] VUILLEUMIER 93 uses the matrix elements of MUTO 89. Based on a half-life limit 2.6×10^{23} y at 90%CL.
[51] 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

AALSETH	02	hep-ex/0202018	C.E. Aalseth *et al.*	
MPL A (to be publ.)				
KLAPDOR-K...	02	hep-ph/0205228	H.V. Klapdor-Kleingrothaus	
MPL A (to be publ.)				
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.*	
AVIGNONE	00	PRL 85 465	F.T. Avignone *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.)
BAUDIS	99B	PRL 83 41	L. Baudis *et al.*	(Heidelberg-Moscow Collab.)

ALESSAND...	98	PL B433 156	A. Alessandrello *et al.*	
FELDMAN	98	PR D57 3873	G.J. Feldman, R.D. Cousins	
LUESCHER	98	PL B434 407	R. Luescher *et al.*	
ALSTON-...	97	PR C55 474	M. Alston-Garnjost *et al.*	(LBL, MTHO+)
BAUDIS	97	PL B407 219	L. Baudis *et al.*	(Heidelberg-Moscow Collab.)
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.)
		Translated from ZETFP 61 168.		
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+)
DANEVICH	95	PL B344 72	F.A. Danevich *et al.*	(KIEV)
DASSIE	95	PR D51 2090	D. Dassie *et al.*	(NEMO Collab.)
EJIRI	95	JPSJ 64 339	H. Ejiri *et al.*	(OSAK, KIEV)
GEORGADZE	95	PAN 58 1093	A.Sh. Georgadze *et al.*	
		Translated from YAF 58 1170.		
KOBAYASHI	95	NP A586 457	M. Kobayashi, M. Kobayashi	(KEK, SAGA)
BALYSH	94	PL B322 176	A. Balysh *et al.*	(Heidelberg-Moscow Collab.)
ALSTON-...	93	PRL 71 831	M. Alston-Garnjost *et al.*	(LBL, MTHO+)
ARTEMEV	93	JETPL 58 262	V.A. Artemiev *et al.*	(ITEP, INRM)
		Translated from ZETFP 58 256.		
BERNATOW...	93	PR C47 806	T. Bernatowicz *et al.*	(WUSL, TATA)
KAWASHIMA	93	PR C47 R2452	A. Kawashima, K. Takahashi, A. Masuda	(TOKYC+)
VUILLEUMIER	93	PR D48 1009	J.C. Vuilleumier *et al.*	(NEUC, CIT, VILL)
BALYSH	92	PL B283 32	A. Balysh *et al.*	(MPIH, KIAE, SASSO)
BERNATOW...	92	PRL 69 2341	T. Bernatowicz *et al.*	(WUSL, TATA)
BLUM	92	PL B275 506	D. Blum *et al.*	(NEMO Collab.)
ELLIOTT	92	PR C46 1535	S.R. Elliott *et al.*	(UCI)
AVIGNONE	91	PL B256 559	F.T. Avignone *et al.*	(SCUC, PNL, ITEP+)
EJIRI	91	PL B258 17	H. Ejiri *et al.*	(OSAK)
MANUEL	91	JP G17 S221	O.K. Manuel	(MISSR)
SUHONEN	91	NP A535 509	J. Suhonen, S.B. Khadkikar, A. Faessler	(JYV+)
TOMODA	91	RPP 54 53	T. Tomoda	
TURKEVICH	91	PRL 67 3211	A. Turkevich, T.E. Economou, G.A. Cowan	(CHIC+)
YOU	91	PL B265 53	K. You *et al.*	(BHEP, CAST+)
MILEY	90	PRL 65 3092	H.S. Miley *et al.*	(SCUC, PNL)
STAUDT	90	EPL 13 31	A. Staudt, K. Muto, H.V. Klapdor-Kleingrothaus	
MUTO	89	ZPHY A334 187	K. Muto, E. Bender, H.V. Klapdor	(TINT, MPIH)
ENGEL	88	PR C37 731	J. Engel, P. Vogel, M.R. Zirnbauer	
BOEHM	87	Massive Neutrinos	F. Bohm, P. Vogel	(CIT)
Cambridge Univ. Press, Cambridge				
TOMODA	87	PL B199 475	T. Tomoda, A. Faessler	(TUBIN)
HAXTON	84	PPNP 12 409	W.C. Haxton, G.J. Stevenson	
KIRSTEN	83	PRL 50 474	T. Kirsten, H. Richter, E. Jessberger	(MPIH)