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Massive Neutrinos and Lepton Mixing
THIS IS PART 2 OF 5

To reduce the size of this section's PostScript file, we have divided it into five PostScript files. We present the following index:

PART 1

PART 2

PART 3

PART 4

PART 5

(A) Heavy neutral leptons

Stable Neutral Heavy Lepton MASS LIMITS

Note that LEP results in combination with REUSSER 91 exclude a fourth stable neutrino with $m <$ 2400 GeV.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>45.0	95	ABREU	92B	DLPH	Dirac
>39.5	95	ABREU	92B	DLPH	Majorana
>44.1	95	ALEXANDER	91F	OPAL	Dirac
>37.2	95	ALEXANDER	91F	OPAL	Majorana
none 3–100	90	SATO	91	KAM2	Kamiokande II
>42.8	95	[1] ADEVA	90S	L3	Dirac
>34.8	95	[1] ADEVA	90S	L3	Majorana
>42.7	95	DECAMP	90F	ALEP	Dirac

[1] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $|U_{1j}|^2 + |U_{2j}|^2 + |U_{3j}|^2 > 6.2\times10^{-8}$ at $m_{L^0} = 20$ GeV and $> 5.1\times10^{-10}$ for $m_{L^0} = 40$ GeV.

Neutral Heavy Lepton MASS LIMITS

Limits apply only to heavy lepton type given in comment at right of data Listings. See review above for description of types.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
none 2.5–50	95	[2] ADRIANI	92I	L3	$\lvert U_{\tau \text{ or } \mu}\rvert^2 < 3\times10^{-4}$
none 4–50	95	[2] ADRIANI	92I	L3	$\lvert U_{\tau}\rvert^2 < 3\times10^{-4}$
>46.4	95	[3] ADEVA	90S	L3	Dirac
>45.1	95	[3] ADEVA	90S	L3	Majorana
>46.5	95	[4] AKRAWY	90L	OPAL	Coupling to e or μ
>45.7	95	[4] AKRAWY	90L	OPAL	Coupling to τ
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>44.5	95	[5] ABREU	92B	DLPH	Dirac
>39.0	95	[5] ABREU	92B	DLPH	Majorana
>41	95	[6,7] BURCHAT	90	MRK2	Dirac, $\lvert U_{\ell j}\rvert^2 > 10^{-10}$
>19.6	95	[6,7] BURCHAT	90	MRK2	Dirac, all $\lvert U_{\ell j}\rvert^2$
none 25–45.7	95	[6,8] DECAMP	90F	ALEP	Dirac $\lvert U_{\ell j}\rvert^2 > 10^{-13}$
none 8.2–26.5	95	[9] SHAW	89	AMY	Dirac L^0, $\lvert U_{ej}\rvert^2 > 10^{-6}$
none 8.3–22.4	95	[9] SHAW	89	AMY	Majorana L^0, $\lvert U_{ej}\rvert^2 > 10^{-6}$
none 8.1–24.9	95	[9] SHAW	89	AMY	Majorana L^0, $\lvert U_{\mu j}\rvert^2 > 10^{-6}$
none 1.8–6.7	90	[10] AKERLOF	88	HRS	$\lvert U_{ej}\rvert^2=1$
none 1.8–6.4	90	[10] AKERLOF	88	HRS	$\lvert U_{\mu j}\rvert^2=1$
none 2.5–6.3	80	[10] AKERLOF	88	HRS	$\lvert U_{\tau j}\rvert^2=1$

none 0.25–14	90	[11] MISHRA	87	CNTR	$\lvert U_{\mu j}\rvert^2$=1.
none 0.25–10	90	[11] MISHRA	87	CNTR	$\lvert U_{\mu j}\rvert^2$=0.1
none 0.25–7.7	90	[11] MISHRA	87	CNTR	$\lvert U_{\mu j}\rvert^2$=0.03
none 1.–2.	90	[12] WENDT	87	MRK2	$\lvert U_{e\text{ or }\mu j}\rvert^2$=0.1
none 2.2–4.	90	[12] WENDT	87	MRK2	$\lvert U_{e\text{ or }\mu j}\rvert^2$=0.001
none 2.3–3.	90	[12] WENDT	87	MRK2	$\lvert U_{\tau j}\rvert^2$=0.1
none 3.2–4.8	90	[12] WENDT	87	MRK2	$\lvert U_{\tau j}\rvert^2$=0.001
none 0.3–0.9	90	[13] BADIER	86	CNTR	$\lvert U_{e j}\rvert^2$=0.8
none 0.33–2.0	90	[13] BADIER	86	CNTR	$\lvert U_{e j}\rvert^2$=0.03
none 0.6–0.7	90	[13] BADIER	86	CNTR	$\lvert U_{\mu j}\rvert^2$=0.8
none 0.6–2.0	90	[13] BADIER	86	CNTR	$\lvert U_{\mu j}\rvert^2$=0.01–0.001
$>$ 1.2		MEYER	77	MRK1	Neutral

[2] ADRIANI 92I is a search for isosinglet heavy lepton N_ℓ which might be produced from $Z \rightarrow \nu_\ell N_\ell$, then decay via a number of different channels. Limits are weaker for decay lengths longer than about 1 m.

[3] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $|U_{1j}|^2 + |U_{2j}|^2 + |U_{3j}|^2 > 6.2\times10^{-8}$ at $m_{L^0} = 20$ GeV and $> 5.1\times10^{-10}$ for $m_{L^0} = 40$ GeV.

[4] AKRAWY 90L limits valid if coupling strength is greater than a mass-dependent value, e.g., 4.9×10^{-7} at $m_{L^0} = 20$ GeV, 3.5×10^{-8} at 30 GeV, 4×10^{-9} at 40 GeV.

[5] ABREU 92B limit is for mixing matrix element ≈ 1 for coupling to e or μ. Reduced somewhat for coupling to τ, increased somewhat for smaller mixing matrix element. Replaces ABREU 91F.

[6] Limits apply for $\ell = e$, μ, or τ and for $V{-}A$ decays of Dirac neutrinos.

[7] BURCHAT 90 searched for Z decay to unstable L^0 pairs at SLC. It includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[8] For $25 < m_{L^0} < 42.7$ GeV, DECAMP 90F exclude an L^0 for all values of $|U_{\ell j}|^2$.

[9] SHAW 89 also excludes the mass region from 8.0 to 27.2 GeV for Dirac L^0 and from 8.1 to 23.6 GeV for Majorana L^0 with equal full-strength couplings to e and μ. SHAW 89 also gives correlated bounds on lepton mixing.

[10] AKERLOF 88 is PEP e^+e^- experiment at $E_{cm} = 29$ GeV. The L^0 is assumed to decay via $V{-}A$ to e or μ or τ plus a virtual W.

[11] MISHRA 87 is Fermilab neutrino experiment looking for either dimuon or double vertex events (hence long-lived).

[12] WENDT 87 is MARK-II search at PEP for heavy ν with decay length 1–20 cm (hence long-lived).

[13] BADIER 86 is a search for a long-lived penetrating sequential lepton produced in π^- – nucleon collisions with lifetimes in the range from $5 \times 10^{-7} - 5 \times 10^{-11}$ s and decaying into at least two charged particles. U_{ej} and U_{mj} are mixing angles to ν_e and ν_μ. See also the BADIER 86 entry in the section "Searches for Massive Neutrinos and Lepton Mixing".

Astrophysical Limits on Neutrino MASS for $m_\nu > 1$ GeV

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 60–115		[14] FARGION	95	ASTR	Dirac

none 26–4700		[15] BECK	94	COSM	Dirac
none 6 – hundreds		[16,17] MORI	92B	KAM2	Dirac neutrino
none 24 – hundreds		[16,17] MORI	92B	KAM2	Majorana neutrino
none 10–2400	90	[18] REUSSER	91	CNTR	HPGe search
none 3–100	90	SATO	91	KAM2	Kamiokande II
		[19] ENQVIST	89	COSM	
none 12–1400		[15] CALDWELL	88	COSM	Dirac ν
none 4–16	90	[15,16] OLIVE	88	COSM	Dirac ν
none 4–35	90	OLIVE	88	COSM	Majorana ν
>4.2 to 4.7		SREDNICKI	88	COSM	Dirac ν
>5.3 to 7.4		SREDNICKI	88	COSM	Majorana ν
none 20–1000	95	[15] AHLEN	87	COSM	Dirac ν
>4.1		GRIEST	87	COSM	Dirac ν

[14] FARGION 95 bound is sensitive to assumed ν concentration in the Galaxy. See also KONOPLICH 94.

[15] These results assume that neutrinos make up dark matter in the galactic halo.

[16] Limits based on annihilations in the sun and are due to an absence of high energy neutrinos detected in underground experiments.

[17] MORI 92B results assume that neutrinos make up dark matter in the galactic halo. Limits based on annihilations in earth are also given.

[18] REUSSER 91 uses existing $\beta\beta$ detector (see FISHER 89) to search for CDM Dirac neutrinos.

[19] ENQVIST 89 argue that there is no cosmological upper bound on heavy neutrinos.

(B) Sum of neutrino masses

The limits on low mass ($m_\nu \lesssim$ 1 MeV) neutrinos apply to $m_{\rm tot}$ given by

$$m_{\rm tot} = \sum_\nu (g_\nu/2) m_\nu \ ,$$

where g_ν is the number of spin degrees of freedom for ν plus $\overline{\nu}$: $g_\nu = 4$ for neutrinos with Dirac masses; $g_\nu = 2$ for Majorana neutrinos. The limits on high mass ($m_\nu >$ 1 MeV) neutrinos apply separately to each neutrino type.

Limit on Total ν MASS, $m_{\rm tot}$

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to $m_{\rm tot}$. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

VALUE (eV)	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<180	SZALAY	74	COSM
<132	COWSIK	72	COSM
<280	MARX	72	COSM
<400	GERSHTEIN	66	COSM

Limits on MASSES of Light Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (eV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<100–200	[20] OLIVE	82	COSM	Dirac ν
<200–2000	[20] OLIVE	82	COSM	Majorana ν

[20] Depending on interaction strength G_R where $G_R < G_F$.

Limits on MASSES of Heavy Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 10	[21] OLIVE	82	COSM	G_R/G_F <0.1
>100	[21] OLIVE	82	COSM	G_R/G_F <0.01

[21] These results apply to heavy Majorana neutrinos and are summarized by the equation: m_ν >1.2 GeV (G_F/G_R). The bound saturates, and if G_R is too small no mass range is allowed.

(C) Searches for neutrinoless double-β decay

LIMITS FROM NEUTRINOLESS $\beta\beta$ DECAY

(Revised 1995 by Petr Vogel, Caltech)

Limits on an effective Majorana neutrino mass and a lepton-number violating current admixture can be obtained from lifetime limits on $0\nu\beta\beta$ nuclear decay. The derived quantities are model-dependent, so the half-life measurements are given first. Where possible we list the references for the 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. For further calculations, see, *e.g.*, Ref. 1.

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:

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

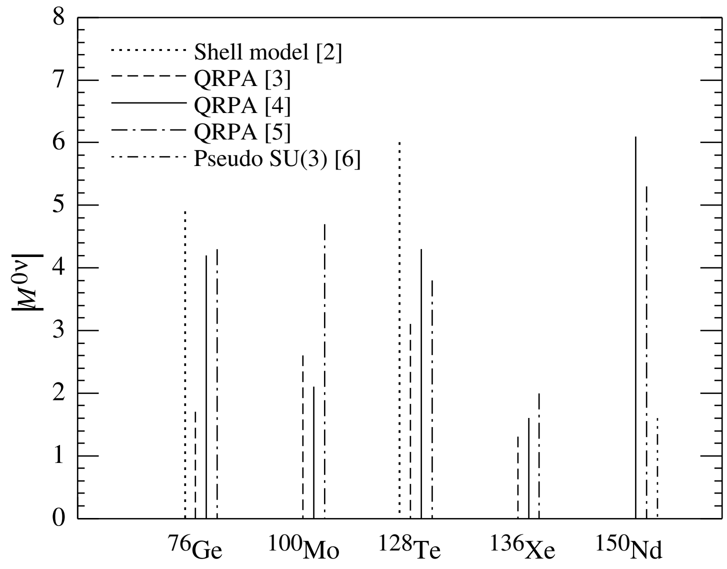

Figure 1: Nuclear matrix elements for $0\nu\beta\beta$ decay calculated by a subset of different methods and different authors for the most popular double-beta decay candidate nuclei. Recalculated from the published half-lives using consistent phase-space factors and $g_A = 1.25$. The QRPA [3] value is for $\alpha' = -390$ MeV fm^3.

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. 11 in the "Note on Neutrinos" at the beginning of the Neutrino Particle Listings), the quantities extracted from experiments are $\langle \eta \rangle = \eta \sum U_{1j} V_{1j}$ and $\langle \lambda \rangle = \lambda \sum U_{1j} V_{1j}$, where V_{ij} is a matrix analogous to U_{ij} (see Eq. 2 in the "Note on Neutrinos"), 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 $\langle m_\nu\rangle$, cancellations 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.

Footnotes and References

* We have previously used a less accepted but more explicit notation in which $\eta_{RL} \equiv \kappa$, $\eta_{LR} \equiv \eta$, and $\eta_{RR} \equiv \lambda$.

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4. A. Staudt, K. Muto, and H.V. Klapdor-Kleingrothaus, Europhys. Lett. **13**, 31 (1990).
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6. J.G. Hirsch, O. Castaños, and P.O. Hess, Nucl. Phys. **A582**, 124 (1995).

Half-life Measurements and Limits for Double β Decay

In all cases of double beta decay, (Z,A) $\rightarrow$ (Z+2,A) + $2\beta^-$ + (0 or 2)$\overline{\nu}_e$.

$t_{1/2}(10^{21}$ yr)	CL%	ISOTOPE		TRANSITION	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$0.036^{+0.006}_{-0.005} \pm 0.003$		^{116}Cd	2ν	$0^+ \rightarrow 0^+$	NEMO	[22] ARNOLD	95
>5600	90	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	Enriched HPGe	BALYSH	95
$0.61^{+0.18}_{-0.11}$		^{100}Mo	2ν	$0^+ \rightarrow 0^+$	γ in HPGe	[23] BARABASH	95
> 0.00013	99	^{160}Gd	2ν	$0^+ \rightarrow 0^+$	Gd_2SiO_5:Ce scint[24]	BURACHAS	95
> 0.00012	99	^{160}Gd	2ν	$0^+ \rightarrow 2^+$	Gd_2SiO_5:Ce scint[24]	BURACHAS	95

$>$ 0.014	90	^{160}Gd	0ν	$0^+ \rightarrow 0^+$	Gd_2SiO_5:Ce scint	[24] BURACHAS	95
$>$ 0.013	90	^{160}Gd	0ν	$0^+ \rightarrow 2^+$	Gd_2SiO_5:Ce scint	[24] BURACHAS	95
$(9.5 \pm 0.4 \pm 0.9)$E18		^{100}Mo	2ν		NEMO 2	DASSIE	95
$>$ 6.4	90	^{100}Mo	0ν	$0^+ \rightarrow 0^+$	NEMO 2	DASSIE	95
$>$ 0.8	90	^{100}Mo	0ν	$0^+ \rightarrow 2^+_1$	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
$>$ 2.9	90	^{116}Cd	0ν	$0^+ \rightarrow 0^+$	ELEGANT IV	EJIRI	95
$>$ 29	90	^{116}Cd	0ν	$0^+ \rightarrow 0^+$	$^{116}CdWO_4$ scint	[25] GEORGADZE	95
$>$ 0.3	68	^{160}Gd	0ν		Gd_2SiO_5: Ce scint	KOBAYASHI	95
$>$ 18	90	^{130}Te	0ν	$0^+ \rightarrow 0^+$	Bolometer	[26] ALESSAND...	94
$>$ 0.041	90	^{96}Zr	0ν+2ν	$0^+ \rightarrow 2^+_1$	γ in HPGe	ARPESELLA	94
$>$ 0.033	90	^{96}Zr	0ν+2ν	$0^+ \rightarrow 0^+_1$	γ in HPGe	ARPESELLA	94
$>$ 0.024	90	^{96}Zr	0ν+2ν	$0^+ \rightarrow 2^+_2$	γ in HPGe	ARPESELLA	94
$>$ 0.031	90	^{96}Zr	0ν+2ν	$0^+ \rightarrow 2^+_3$	γ in HPGe	ARPESELLA	94
$1.42 \pm 0.03 \pm 0.13$		^{76}Ge	2ν		Enriched HPGe	BALYSH	94
$>$ 2.37	90	^{116}Cd	0ν+2ν	$0^+ \rightarrow 2^+$	γ in HPGe	[27] PIEPKE	94
$>$ 2.05	90	^{116}Cd	0ν+2ν	$0^+ \rightarrow 0^+_1$	γ in HPGe	[27] PIEPKE	94
$>$ 2.05	90	^{116}Cd	0ν+2ν	$0^+ \rightarrow 0^+_2$	γ in HPGe	[27] PIEPKE	94
$>$ 44	68	^{100}Mo	0ν	$0^+ \rightarrow 0^+$	Si(Li)	ALSTON-...	93
$0.017^{+0.010}_{-0.005} \pm 0.0035$		^{150}Nd	2ν	$0^+ \rightarrow 0^+$	TPC	ARTEMEV	93
0.039 ± 0.009		^{96}Mo	0ν+2ν		Geochem	KAWASHIMA	93
$>$ 340	90	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	TPC	[28] VUILLEUMIER	93
$>$ 260	90	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	TPC	[29] VUILLEUMIER	93
$>$ 0.21	90	^{136}Xe	2ν	$0^+ \rightarrow 0^+$	TPC	VUILLEUMIER	93
$>$ 0.093	90	^{136}Xe	2ν	$0^+ \rightarrow 0^+$	Drift chamber	ARTEMJEV	92
$>$1400	90	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	Enriched HPGe	BALYSH	92
$>$ 430	90	^{76}Ge	0ν	$0^+ \rightarrow 2^+$	Enriched HPGe	BALYSH	92
2.7 ± 0.1		^{130}Te			Geochem	BERNATOW...	92
7200 ± 400		^{128}Te			Geochem	[30] BERNATOW...	92
$>$ 0.5	90	^{100}Mo	0ν+2ν	$0^+ \rightarrow 2^+_1$	γ in HPGe	[31] BLUM	92
$>$ 0.9	90	^{100}Mo	0ν+2ν	$0^+ \rightarrow 0^+_1$	γ in HPGe	[31] BLUM	92
$>$ 0.6	90	^{100}Mo	0ν+2ν	$0^+ \rightarrow 2^+_2$	γ in HPGe	[31] BLUM	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
$>$ 0.15	68	^{100}Mo	2ν	$0^+ \rightarrow 2^+_1$	Spect	[32] KUDOMI	92
$>$ 1.1	68	^{100}Mo	0ν	$0^+ \rightarrow 2^+_1$	Spect	[32] KUDOMI	92
$>$ 0.08	68	^{100}Mo	2ν	$0^+ \rightarrow 0^+_1$	Spect	[32] KUDOMI	92
$>$ 0.56	68	^{100}Mo	0ν	$0^+ \rightarrow 0^+_1$	Spect	[32] KUDOMI	92
$>$ 0.051	68	^{100}Mo	2ν	$0^+ \rightarrow 4^+_1$	Spect	[32] KUDOMI	92

> 0.63	68	^{100}Mo	0ν	$0^+ \rightarrow 4^+_1$	Spect	[32] KUDOMI	92
> 0.065	68	^{100}Mo	2ν	$0^+ \rightarrow 2^+_2$	Spect	[32] KUDOMI	92
> 0.12	68	^{100}Mo	0ν	$0^+ \rightarrow 2^+_2$	Spect	[32] KUDOMI	92
> 330	90	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	HPGe	[33] REUSSER	92
> 65	90	^{76}Ge	0ν	$0^+ \rightarrow 2^+$	HPGe	[33] REUSSER	92
$0.92^{+0.07}_{-0.04}$		^{76}Ge	2ν	$0^+ \rightarrow 0^+$	Enriched HPGe	[34] AVIGNONE	91
> 12	95	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	Prop cntr	[28,35] BELLOTTI	91
> 10	95	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	Prop cntr	[29,35] BELLOTTI	91
> 3.3	95	^{136}Xe	0ν	$0^+ \rightarrow 2^+$	Prop cntr	[35] BELLOTTI	91
> 0.16	95	^{136}Xe	2ν		Prop cntr	BELLOTTI	91
> 4.7	68	^{100}Mo	0ν		Spect	EJIRI	91
$0.0115^{+0.0030}_{-0.0020}$		^{100}Mo	2ν		Spect	EJIRI	91
2.0 ± 0.6		^{238}U			Radiochem	[36] TURKEVICH	91
> 9.5	76	^{48}Ca	0ν		CaF_2 scint.	YOU	91
> 0.14	68	^{100}Mo	$0\nu+2\nu$	$0^+ \rightarrow 2^+$	γ in HPGe	BARABASH	90
> 0.042	68	^{100}Mo	$0\nu+2\nu$	$0^+ \rightarrow 0^+_1$	γ in HPGe	BARABASH	90
> 0.17	68	^{116}Cd	$0\nu+2\nu$	$0^+ \rightarrow 2^+$	γ in HPGe	BARABASH	90
$1.12^{+0.48}_{-0.26}$		^{76}Ge	2ν	$0^+ \rightarrow 0^+$	HPGe	[37] MILEY	90
>1300	68	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	Enriched Ge(Li)	[38] VASENKO	90
0.9 ± 0.1		^{76}Ge	2ν		Enriched Ge(Li)	VASENKO	90
> 0.40	68	^{100}Mo	0ν	$0^+ \rightarrow 2^+$	Si(Li)	ALSTON-...	89
> 3.3	68	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	Ion chamber	[28] BARABASH	89
> 2.9	68	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	Ion chamber	[29] BARABASH	89
> 1.5	68	^{136}Xe	0ν	$0^+ \rightarrow 2^+$	Ion chamber	BARABASH	89
> 0.084	68	^{136}Xe	2ν	$0^+ \rightarrow 0^+$	Ion chamber	BARABASH	89
> 1.3	68	^{116}Cd	0ν		$^{116}CdWO_4$ scint	DANEVICH	89
> 60	68	^{76}Ge	0ν	$0^+ \rightarrow 2^+$	HPGe	[39] MORALES	88
> 4.7	68	^{128}Te		$0^+ \rightarrow 2^+$	Ge(Li)	[24] BELLOTTI	87
> 4.5	68	^{130}Te		$0^+ \rightarrow 2^+$	Ge(Li)	[24] BELLOTTI	87
> 500	68	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	HPGe	CALDWELL	87
> 330	68	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	HPGe	BELLOTTI	86
> 27	68	^{76}Ge	0ν	$0^+ \rightarrow 2^+$	HPGe	BELLOTTI	86
> 2.3	68	^{76}Ge	0ν		Ge(Li)	[40] HUBERT	85
> 17	90	^{76}Ge	0ν		Intrinsic Ge	AVIGNONE	83
> 800	95	^{128}Te			Geochem	[41] KIRSTEN	83
2.60 ± 0.28		^{130}Te			Geochem	[41] KIRSTEN	83

[22] ARNOLD 95 final result, $(0.0375^{+0.0035}_{-0.0021}) \times 10^{21}$ y, has been submitted for publication to Z. Phys.

[23] 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, but also see DASSIE 95).

[24] BELLOTTI 87 searches for γ rays for 2^+ state decays in corresponding Xe isotopes. Limit for ^{130}Te case argues for dominant $0^+ \rightarrow 0^+$ transition in known decay of this isotope.

[25] GEORGADZE 95 result for this and other modes are also give in DANEVICH 95. Result for 2ν decay omitted because of authors' caveats.

[26] ALESSANDRELLO 94 state that their present limit excludes a significant contribution from the 0ν channel of ^{130}Te even if the large lifetime obtained in the geochemical experiment of BERNATOWICZ 92 is assumed.

[27] In PIEPKE 94, the studied excited states of ^{116}Sn have energies above the ground state of 1.2935 MeV for the 2^+ state, 1.7568 MeV for the 0_1^+ state, and 2.0273 for the 0_2^+ state.

[28] Limit in the case of a transition induced by a Majorana mass.

[29] Limit for lepton-number violating right-handed current-induced (RHC) decay.

[30] 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.

[31] BLUM 92 reports lifetime limits for the decay of ^{100}Mo to several excited states of ^{100}Ru. Limits for decay to the 0_1^+ state are about 30% higher if decay to the 2^+ states are assumed negligible. Uses 99.5% enriched ^{100}Mo.

[32] KUDOMI 92 reports lifetime limits for 0ν and 2ν decays to four excited states of the daughter ^{100}Ru. The limits were obtained from searches for the two individual electrons in coincidence with photons from the decays of the excited states. The experiment was performed in the Kamioka underground laboratory. See EJIRI 91 for the group's ground-state transition measurement.

[33] REUSSER 92 contains the final results for the search for neutrinoless double beta decay of ^{76}Ge in the Gotthard tunnel underground laboratory. Supersedes FISHER 89.

[34] AVIGNONE 91 reports confirmation of the MILEY 90 and VASENKO 90 observations of $2\nu\beta\beta$ decay of ^{76}Ge. Error is 2σ.

[35] BELLOTTI 91 uses difference between natural and enriched ^{136}Xe runs to obtain $\beta\beta 0\nu$ limits, leading to "less stringent, but safer limits."

[36] 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.

[37] MILEY 90 claims only "suggestive evidence" for the decay. Error is 2σ.

[38] VASENKO 90 limit based on background statistics. Maximum likelihood solution is >2000.

[39] MORALES 88 notes a 2.5 sigma coincidence rate between electrons with energy 1483.7 ± 0.5 keV in the Ge detector and photons with energy 558 ± 15 keV in the NaI detector, close to the region where neutrinoless $0^+ \rightarrow 2^+$ ^{76}Ge decay should be expected. However, a further study reported in MORALES 91 rejects this peak at the 95% CL.

[40] HUBERT 85 gives lifetime limits on neutrinoless double β decay of ^{76}Ge to excited states of ^{76}Se.

[41] 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_{1j}, not $|U_{1j}|^2$, occurs in the sum. The possibility of cancellations has been stressed.

VALUE (eV)	*CL%*	*ISOTOPE*		*TRANSITION*	*METHOD*	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$<$ 0.65	90	^{76}Ge	0ν	$0^+ \to 0^+$	Enriched HPGe	BALYSH	95
$<$ 4.1	90	^{116}Cd	0ν		^{116}CdWO$_4$ scint	[42] DANEVICH	95
$<$ 6.6	68	^{100}Mo	0ν	$0^+ \to 0^+$	Si(Li)	[43] ALSTON-...	93
$<$ 2.8–4.3	90	^{136}Xe	0ν	$0^+ \to 0^+$	TPC	[44] VUILLEUMIER	93
$<$ 1.5	90	^{76}Ge			Enriched HPGe	[45] BALYSH	92
$<$ 1.1–1.5		^{128}Te			Geochem	[46] BERNATOW...	92
$<$ 5	68	^{82}Se			TPC	[47] ELLIOTT	92
$<$ 1.9–6.7	68	^{76}Ge		$0^+ \to 0^+$	HPGe	[48] REUSSER	92
$<$ 11–30	95	^{136}Xe	0ν	$0^+ \to 0^+$	Prop cntr	[49] BELLOTTI	91
$<$ 3.3–5.0		^{136}Xe	0ν	$0^+ \to 0^+$	TPC	[50] WONG	91
$<$ 8.3	76	^{48}Ca	0ν		CaF$_2$ scint.	YOU	91
$<$ 1.4–8	68	^{76}Ge	0ν	$0^+ \to 0^+$	Enriched Ge(Li)	[51] VASENKO	90
$<$4.3–28		^{136}Xe	0ν	$0^+ \to 0^+$	Prop chamber	[52] BELLOTTI	89
$<$12	68	^{116}Cd	0ν		^{116}CdWO$_4$ scint	[53] DANEVICH	89
$<$ 1.8		^{76}Ge	0ν	$0^+ \to 0^+$	HPGe	[54] CALDWELL	87
$<$ 2.7	68	^{76}Ge	0ν	$0^+ \to 0^+$	HPGe	BELLOTTI	86
$<$20	68	^{76}Ge	0ν		Ge(Li)	[55] HUBERT	85
$<$22		^{76}Ge	0ν	$0^+ \to 0^+$	Ge	FORSTER	84
$<$10	90	^{76}Ge	0ν		Intrinsic Ge	AVIGNONE	83
$<$ 5.6	95	^{128}Te			Geochem	KIRSTEN	83

[42] DANEVICH 95 is identical to GEORGADZE 95.

[43] ALSTON-GARNJOST 93 use the "conservative matrix elements of Engel *et al.* (ENGEL 88).

[44] VUILLEUMIER 93 mass range from parameter range in the Caltech calculations (ENGEL 88). On the basis of these calculations, the BALYSH 92 mass range would be $<$ 2.2–4.4 eV.

[45] BALYSH 92 uses the MUTO 89 matrix elements.

[46] BERNATOWICZ 92 finds these majoron 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.

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

[48] REUSSER 92 contains the final results for the search for neutrinoless double beta decay of ^{76}Ge in the Gotthard tunnel underground laboratory. Range comes from range of nuclear matrix elements used to relate neutrino mass to lifetime limit (ENGEL 88, HAXTON 84, and MUTO 89).

[49] BELLOTTI 91 range of limits comes from range of theoretical calculations considered. Analysis uses difference between natural and enriched ^{136}Xe runs to obtain the $\beta\beta0\nu$ limits, leading to "less stringent, but safer limits."

[50] WONG 91 uses the quasiparticle random phase approximation of ENGEL 88 to extract the above limit for the case of a transition caused by a Majorana neutrino mass.

[51] VASENKO 90 range comes from range of nuclear matrix elements of HAXTON 84, ENGEL 88. On the basis of the MUTO 89 matrix element, the limit will be $<$ 1.3 eV.

[52] BELLOTTI 89 gives model-dependent upper bounds on Majorana neutrino masses and on the admixture of right-handed lepton-number-violating currents.
[53] DANEVICH 89 uses calculations of GROTZ 86.
[54] CALDWELL 87 least stringent limit (using HAXTON 84) is listed. Limits given using other nuclear matrix element calculations are 1.5 eV and 0.7 eV.
[55] HUBERT 85 limit is obtained from analysis of data using theoretical calculations by HAXTON 81, HAXTON 82.

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. $\langle\lambda\rangle = \lambda\sum U_{1j}V_{1j}$ and $\langle\eta\rangle = \eta\sum U_{1j}V_{1j}$, where the sum is over the number of neutrino generations. This sum vanishes for massless or unmixed neutrinos.

$\langle\lambda\rangle$ (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. • • •							
<5.3	90	<5.9	90	^{116}Cd	$^{116}CdWO_4$ scint	[56] DANEVICH	95
<2.3	90	<1.5	90	^{76}Ge	Enriched HPGe	[57] BALYSH	92
		<5.3		^{128}Te	Geochem	[58] BERNATOW...	92
<3.6	68	<2.2	68	^{76}Ge	HPGe	[59] REUSSER	92
<9	68	<8	68	^{76}Ge	Ion chamber	BELLOTTI	89

[56] DANEVICH 95 is identical to GEORGADZE 95.
[57] BALYSH 92 uses the MUTO 89 matrix elements.
[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.
[59] REUSSER 92 uses the MUTO 89 matrix elements for this reduction.