

# Double- $\beta$ Decay

OMITTED FROM SUMMARY TABLE  
 A REVIEW GOES HERE – Check our WWW List of Reviews

## Half-life Measurements and Limits for Double- $\beta$ Decay

In most cases the transitions  $(Z,A) \rightarrow (Z-2,A) + 2e^- + (0 \text{ or } 2) \bar{\nu}_e$  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. For  $2\nu$  decay, which is well established, only measured half-lives are reported.

$t_{1/2}(10^{21} \text{ yr})$	CL%	ISOTOPE	TRANSITION	METHOD	DOCUMENT ID
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●					
$> 8.8 \times 10^{-5}$	90	$^{136}\text{Ce}$	$0\nu \quad \beta^+\text{EC}$	CeCl <sub>3</sub> scint.	1 BELLI 11
$(2.35 \pm 0.14 \pm 0.16)\text{E-2}$		$^{96}\text{Zr}$	$2\nu$	NEMO-3	2 ARGYRIADES 10
$> 9.2$	90	$^{96}\text{Zr}$	$0\nu$	NEMO-3	3 ARGYRIADES 10
$> 0.22$	90	$^{96}\text{Zr}$	$0^+ \rightarrow 0_1^+$	NEMO-3	4 ARGYRIADES 10
$0.69^{+0.10}_{-0.08} \pm 0.07$	68	$^{100}\text{Mo}$	$2\nu \quad 0^+ \rightarrow 0_1^+$	Ge coinc.	5 BELLI 10
$> 18.0$	90	$^{150}\text{Nd}$	$0\nu$	NEMO-3	6 ARGYRIADES 09
$(9.11^{+0.25}_{-0.22} \pm 0.63)\text{E-3}$		$^{150}\text{Nd}$	$2\nu$	NEMO-3	7 ARGYRIADES 09
$> 0.43$	90	$^{64}\text{Zn}$	$0\nu \quad \beta^+\text{EC}$	ZnWO <sub>4</sub> scint.	8 BELLI 09A
$> 0.11$	90	$^{64}\text{Zn}$	$0\nu \quad \text{ECEC}$	ZnWO <sub>4</sub> scint.	9 BELLI 09A
$> 4.1 \times 10^{-4}$	90	$^{120}\text{Te}$	$0\nu \quad \beta^+\text{EC}$	CdZnTe det.	10 DAWSON 09
$> 0.02$	90	$^{124}\text{Sn}$	$0\nu \quad \beta\beta$	tin liq. scint.	11 HWANG 09
$0.55^{+0.12}_{-0.09}$		$^{100}\text{Mo}$	$2\nu+0\nu \quad 0^+ \rightarrow 0_1^+$	Ge coincidence	12 KIDD 09
$> 3000$	90	$^{130}\text{Te}$	$0\nu$	TeO <sub>2</sub> bolometer	13 ARNABOLDI 08
$> 0.004$	90	$^{64}\text{Zn}$	$0\nu \quad 2\text{K}$	ZnWO <sub>4</sub> scint.	14 BELLI 08
$> 0.22$	90	$^{64}\text{Zn}$	$0\nu$	ZnWO <sub>4</sub> scint.	15 BELLI 08
$> 0.001$	90	$^{108}\text{Cd}$	$0\nu \quad 2\text{K}$	CdWO <sub>4</sub> scint.	16 BELLI 08B
$> 0.0013$	90	$^{114}\text{Cd}$	$2\nu \quad \beta\beta$	CdWO <sub>4</sub> scint.	17 BELLI 08B
$> 1.1$	90	$^{114}\text{Cd}$	$0\nu \quad \beta\beta$	CdWO <sub>4</sub> scint.	18 BELLI 08B
$> 58$	90	$^{48}\text{Ca}$	$0\nu$	CaF <sub>2</sub> scint.	19 UMEHARA 08
$0.57^{+0.13}_{-0.09} \pm 0.08$	68	$^{100}\text{Mo}$	$2\nu \quad 0^+ \rightarrow 0_1^+$	NEMO-3	20 ARNOLD 07
$> 89$	90	$^{100}\text{Mo}$	$0\nu \quad 0^+ \rightarrow 0_1^+$	NEMO-3	21 ARNOLD 07
$> 1.1$	90	$^{100}\text{Mo}$	$2\nu \quad 0^+ \rightarrow 2_1^+$	NEMO-3	22 ARNOLD 07
$> 160$	90	$^{100}\text{Mo}$	$0\nu \quad 0^+ \rightarrow 2^+$	NEMO-3	23 ARNOLD 07
$> 0.0019$	90	$^{74}\text{Se}$	$0\nu+2\nu$	$\gamma$ in Ge det.	24 BARABASH 07
$> 0.0055$	90	$^{74}\text{Se}$	$0\nu+2\nu \quad 0^+ \rightarrow 2_2^+$	$\gamma$ in Ge det.	25 BARABASH 07
$> (1.9-6.0) 10^{-4}$	90	$^{120}\text{Te}$	$0\nu$	$\gamma$ in Ge det.	26 BARABASH 07B
$> 1.9 \times 10^{-4}$	90	$^{120}\text{Te}$	$0\nu+2\nu$	$\gamma$ in Ge det.	27 BARABASH 07B
$> 7.5 \times 10^{-4}$	90	$^{120}\text{Te}$	$0\nu+2\nu \quad 0^+ \rightarrow 2^+$	$\gamma$ in Ge det.	28 BARABASH 07B
$> 1.19 \times 10^{-4}$	90	$^{64}\text{Zn}$	$0\nu$	CdZnTe calorim.	29 BLOXHAM 07
$> 1.21 \times 10^{-4}$	90	$^{120}\text{Te}$	$0\nu$	CdZnTe calorim.	30 BLOXHAM 07

$> 2.68 \times 10^{-6}$	90	$^{120}\text{Te}$	$0\nu$		CdZnTe calorim.	31 BLOXHAM	07
$> 9.72 \times 10^{-6}$	90	$^{120}\text{Te}$	$0\nu$	$0^+ \rightarrow 2^+_1$	CdZnTe calorim.	32 BLOXHAM	07
$22300^{+4400}_{-3100}$	68	$^{76}\text{Ge}$	$0\nu$		Enriched HPGe	33 KLAPDOR-K...	06A
$> 1800$	90	$^{130}\text{Te}$	$0\nu$		Cryog. det.	34 ARNABOLDI	05
$> 460$	90	$^{100}\text{Mo}$	$0\nu$		NEMO-3	35 ARNOLD	05A
$> 100$	90	$^{82}\text{Se}$	$0\nu$		NEMO-3	36 ARNOLD	05A
$(7.11 \pm 0.02 \pm 0.54)\text{E-3}$		$^{100}\text{Mo}$	$2\nu$		NEMO-3	37 ARNOLD	05A
$(9.6 \pm 0.3 \pm 1.0)\text{E-2}$		$^{82}\text{Se}$	$2\nu$		NEMO-3	38 ARNOLD	05A
$> 550$	90	$^{130}\text{Te}$	$0\nu$		Cryog. det.	39 ARNABOLDI	04
$> 310$	90	$^{100}\text{Mo}$	$0\nu$		NEMO-3	40 ARNOLD	04
$> 140$	90	$^{82}\text{Se}$	$0\nu$		NEMO-3	41 ARNOLD	04
$(7.68 \pm 0.02 \pm 0.54)\text{E-3}$		$^{100}\text{Mo}$	$2\nu$		NEMO-3	42 ARNOLD	04
$(10.3 \pm 0.3 \pm 0.7)\text{E-2}$		$^{82}\text{Se}$	$2\nu$		NEMO-3	43 ARNOLD	04
$0.14^{+0.04}_{-0.02} \pm 0.03$	68	$^{150}\text{Nd}$	$0\nu+2\nu$	$0^+ \rightarrow 0^+_1$	$\gamma$ in Ge det.	44 BARABASH	04
$11900^{+29900}_{-5000}$	99.7	$^{76}\text{Ge}$	$0\nu$		Enriched HPGe	45 KLAPDOR-K...	04A
$> 14$	90	$^{48}\text{Ca}$	$0\nu$		$\text{CaF}_2$ scint.	46 OGAWA	04
$> 210$	90	$^{130}\text{Te}$	$0\nu$		Cryog. det.	47 ARNABOLDI	03
$> 31$	90	$^{130}\text{Te}$	$0\nu$	$0^+ \rightarrow 2^+$	Cryog. det.	48 ARNABOLDI	03
$0.61 \pm 0.14^{+0.29}_{-0.35}$	90	$^{130}\text{Te}$	$2\nu$		Cryog. det.	49 ARNABOLDI	03
$> 110$	90	$^{128}\text{Te}$	$0\nu$		Cryog. det.	50 ARNABOLDI	03
$(0.029^{+0.004}_{-0.003})$		$^{116}\text{Cd}$	$2\nu$		$^{116}\text{CdWO}_4$ scint.	51 DANEVICH	03
$> 170$	90	$^{116}\text{Cd}$	$0\nu$		$^{116}\text{CdWO}_4$ scint.	52 DANEVICH	03
$> 29$	90	$^{116}\text{Cd}$	$0\nu$	$0^+ \rightarrow 2^+$	$^{116}\text{CdWO}_4$ scint.	53 DANEVICH	03
$> 14$	90	$^{116}\text{Cd}$	$0\nu$	$0^+ \rightarrow 0^+_1$	$^{116}\text{CdWO}_4$ scint.	54 DANEVICH	03
$> 6$	90	$^{116}\text{Cd}$	$0\nu$	$0^+ \rightarrow 0^+_2$	$^{116}\text{CdWO}_4$ scint.	55 DANEVICH	03
$1.74 \pm 0.01^{+0.18}_{-0.16}$		$^{76}\text{Ge}$	$2\nu$		Enriched HPGe	56 DOERR	03
$> 15700$	90	$^{76}\text{Ge}$	$0\nu$		Enriched HPGe	57 AALSETH	02B
$> 58$	90	$^{134}\text{Xe}$	$0\nu$		Liquid Xe Scint.	58 BERNABEI	02D
$> 1200$	90	$^{136}\text{Xe}$	$0\nu$		Liquid Xe Scint.	59 BERNABEI	02D
$15000^{+168000}_{-7500}$		$^{76}\text{Ge}$	$0\nu$		Enriched HPGe	60 KLAPDOR-K...	02D
$(7.2 \pm 0.9 \pm 1.8)\text{E-3}$		$^{100}\text{Mo}$	$2\nu$		Liq. Ar ioniz.	61 ASHITKOV	01
$> 4.9$	90	$^{100}\text{Mo}$	$0\nu$		Liq. Ar ioniz.	62 ASHITKOV	01
$> 1.3$	90	$^{160}\text{Gd}$	$0\nu$		$\text{Gd}_2\text{SiO}_5:\text{Ce}$	63 DANEVICH	01
$> 1.3$	90	$^{160}\text{Gd}$	$0\nu$	$0^+ \rightarrow 2^+$	$\text{Gd}_2\text{SiO}_5:\text{Ce}$	64 DANEVICH	01
$0.59^{+0.17}_{-0.11} \pm 0.06$		$^{100}\text{Mo}$	$0\nu+2\nu$	$0^+ \rightarrow 0^+_1$	Ge coinc.	65 DEBRAECKEL	01
$> 55$	90	$^{100}\text{Mo}$	$0\nu, \langle m_\nu \rangle$		ELEGANT V	66 EJIRI	01
$> 42$	90	$^{100}\text{Mo}$	$0\nu, \langle \lambda \rangle$		ELEGANT V	66 EJIRI	01
$> 49$	90	$^{100}\text{Mo}$	$0\nu, \langle \eta \rangle$		ELEGANT V	66 EJIRI	01
$> 19000$	90	$^{76}\text{Ge}$	$0\nu$		Enriched HPGe	67 KLAPDOR-K...	01
$1.55 \pm 0.001^{+0.19}_{-0.15}$	90	$^{76}\text{Ge}$	$2\nu$		Enriched HPGe	68 KLAPDOR-K...	01
$(9.4 \pm 3.2)\text{E-3}$	90	$^{96}\text{Zr}$	$0\nu+2\nu$		Geochem	69 WIESER	01
$0.042^{+0.033}_{-0.013}$		$^{48}\text{Ca}$	$2\nu$		Ge spectrometer	70 BRUDANIN	00
$0.021^{+0.008}_{-0.004} \pm 0.002$		$^{96}\text{Zr}$	$2\nu$		NEMO-2	71 ARNOLD	99
$> 1.0$	90	$^{96}\text{Zr}$	$0\nu$		NEMO-2	71 ARNOLD	99
$(8.3 \pm 1.0 \pm 0.7)\text{E-2}$		$^{82}\text{Se}$	$2\nu$		NEMO-2	72 ARNOLD	98

> 9.5	90	$^{82}\text{Se}$	$0\nu$		NEMO-2	$^{73}\text{ARNOLD}$	98
> 2.8	90	$^{82}\text{Se}$	$0\nu$	$0^+ \rightarrow 2^+$	NEMO-2	$^{74}\text{ARNOLD}$	98
$(7.6^{+2.2}_{-1.4})\text{E-3}$		$^{100}\text{Mo}$	$2\nu$		Si(Li)	$^{75}\text{ALSTON-...}$	97
$(6.82^{+0.38}_{-0.53} \pm 0.68)\text{E-3}$		$^{100}\text{Mo}$	$2\nu$		TPC	$^{76}\text{DESILVA}$	97
$(6.75^{+0.37}_{-0.42} \pm 0.68)\text{E-3}$		$^{150}\text{Nd}$	$2\nu$		TPC	$^{77}\text{DESILVA}$	97
> 1.2	90	$^{150}\text{Nd}$	$0\nu$		TPC	$^{78}\text{DESILVA}$	97
$(3.75 \pm 0.35 \pm 0.21)\text{E-2}$		$^{116}\text{Cd}$	$2\nu$	$0^+ \rightarrow 0^+$	NEMO 2	$^{79}\text{ARNOLD}$	96
$0.043^{+0.024}_{-0.011} \pm 0.014$		$^{48}\text{Ca}$	$2\nu$		TPC	$^{80}\text{BALYSH}$	96
$0.79 \pm 0.10$		$^{130}\text{Te}$	$0\nu+2\nu$		Geochem	$^{81}\text{TAKAOKA}$	96
$0.61^{+0.18}_{-0.11}$		$^{100}\text{Mo}$	$0\nu+2\nu$	$0^+ \rightarrow 0^+_1$	$\gamma$ in HPGe	$^{82}\text{BARABASH}$	95
$(9.5 \pm 0.4 \pm 0.9)\text{E-3}$		$^{100}\text{Mo}$	$2\nu$		NEMO 2	DASSIE	95
> 0.6	90	$^{100}\text{Mo}$	$0\nu$	$0^+ \rightarrow 0^+_1$	NEMO 2	DASSIE	95
$0.026^{+0.009}_{-0.005}$		$^{116}\text{Cd}$	$2\nu$	$0^+ \rightarrow 0^+$	ELEGANT IV	EJIRI	95
$0.017^{+0.010}_{-0.005} \pm 0.0035$		$^{150}\text{Nd}$	$2\nu$	$0^+ \rightarrow 0^+$	TPC	ARTEMEV	93
$0.039 \pm 0.009$		$^{96}\text{Zr}$	$0\nu+2\nu$		Geochem	KAWASHIMA	93
$2.7 \pm 0.1$		$^{130}\text{Te}$	$0\nu+2\nu$		Geochem	BERNATOW...	92
$7200 \pm 400$		$^{128}\text{Te}$	$0\nu+2\nu$		Geochem	$^{83}\text{BERNATOW...}$	92
> 27	68	$^{82}\text{Se}$	$0\nu$	$0^+ \rightarrow 0^+$	TPC	ELLIOTT	92
$0.108^{+0.026}_{-0.006}$		$^{82}\text{Se}$	$2\nu$	$0^+ \rightarrow 0^+$	TPC	ELLIOTT	92
$2.0 \pm 0.6$		$^{238}\text{U}$	$0\nu+2\nu$		Radiochem	$^{84}\text{TURKEVICH}$	91
> 9.5	76	$^{48}\text{Ca}$	$0\nu$		CaF <sub>2</sub> scint.	YOU	91
$0.12 \pm 0.01 \pm 0.04$	68	$^{82}\text{Se}$	$0\nu+2\nu$		Geochem.	$^{85}\text{LIN}$	88
$0.75 \pm 0.03 \pm 0.23$	68	$^{130}\text{Te}$	$0\nu+2\nu$		Geochem.	$^{86}\text{LIN}$	88
$1800 \pm 700$	68	$^{128}\text{Te}$	$0\nu+2\nu$		Geochem.	$^{87}\text{LIN}$	88B
$2.60 \pm 0.28$		$^{130}\text{Te}$	$0\nu+2\nu$		Geochem	$^{88}\text{KIRSTEN}$	83

<sup>1</sup> BELLI 11 use 6.9g CeCl<sub>3</sub> scintillation detector to search for  $\beta\beta$  decay of isotopes of Ce. They also obtain limits of various modes of the  $2\nu$  decay.

<sup>2</sup> ARGYRIADES 10 use  $9.4 \pm 0.2$  g of  $^{96}\text{Zr}$  in NEMO-3 detector and identify its  $2\nu\beta\beta$  decay. The result is in agreement and supersedes ARNOLD 99.

<sup>3</sup> ARGYRIADES 10 use  $9.4 \pm 0.2$  g of  $^{96}\text{Zr}$  in NEMO-3 detector and obtain a limit of the  $0\nu\beta\beta$  decay. The result is in agreement and supersedes ARNOLD 99.

<sup>4</sup> ARGYRIADES 10 use  $9.4 \pm 0.2$  g of  $^{96}\text{Zr}$  in NEMO-3 detector and obtain a limit of the  $0\nu\beta\beta$  decay into the first excited  $0^+_1$  state in  $^{96}\text{Mo}$ .

<sup>5</sup> BELLI 10 use enriched  $^{100}\text{Mo}$  with 4 HP Ge detectors to record the 590.8 and 539.5 keV  $\gamma$  rays from the decay of the  $0^+_1$  state in  $^{100}\text{Ru}$  both in singles and coincidences. This result confirms the measurement of KIDD 09 and ARNOLD 07 and supersedes them.

<sup>6</sup> ARGYRIADES 09 use the NEMO-3 tracking calorimeter containing 36.5 g of  $^{150}\text{Nd}$ , a total exposure of 924.7 days, to derive a limit for the  $0\nu\beta\beta$  half-life. Supersedes DESILVA 97.

<sup>7</sup> ARGYRIADES 09 use the NEMO-3 tracking calorimeter containing 36.5 g of  $^{150}\text{Nd}$ , 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.

<sup>8</sup> BELLI 09A use ZnWO<sub>4</sub> scintillating crystals to search for various modes of  $\beta\beta$  decay. This work improves the limits for different modes of  $^{64}\text{Zn}$  decay into the ground state of  $^{64}\text{Ni}$ , in this case for the  $0\nu\beta^+\text{EC}$  mode. Supersedes BELLI 08.

<sup>9</sup> BELLI 09A use ZnWO<sub>4</sub> scintillating crystals to search for various modes of  $\beta\beta$  decay. This work improves the limits for different modes of  $^{64}\text{Zn}$  decay into the ground state of  $^{64}\text{Ni}$ , in this case for the  $0\nu\text{ECEC}$  mode. Supersedes BELLI 08.

- 10 DAWSON 09 use an array of  $^{16}\text{CdZnTe}$  detectors that contain nine  $\beta\beta$ -decay candidate nuclei. Several lifetime limits were obtained, of which the  $\beta^+\text{EC}$  decay of  $^{120}\text{Te}$  exceeds the previous best limit. Supersedes BARABASH 07B and BLOXHAM 07.
- 11 HWANG 09 use a tin loaded liquid scintillator to search for the  $0\nu\beta\beta$ -decay of  $^{124}\text{Sn}$ . They report the most stringent limit for this nuclide.
- 12 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.
- 13 ARNABOLDI 08 use high resolution  $\text{TeO}_2$  bolometer calorimeter to search for double beta decay of  $^{130}\text{Te}$ . Supersedes ARNABOLDI 05.
- 14 BELLI 08 use  $\text{ZnWO}_4$  scintillation calorimeter to search for neutrinoless double K-shell electron capture decay of  $^{64}\text{Zn}$ . Slightly weaker limit is obtained for capture from other shells. The half-life limit for the  $2\nu$  mode is  $6.2 \times 10^{18}$  years.
- 15 BELLI 08 use  $\text{ZnWO}_4$  scintillation calorimeter to search for neutrinoless  $\beta^+$  plus electron capture decay of  $^{64}\text{Zn}$ . The half-life limit for the  $2\nu$  mode is  $2.1 \times 10^{20}$  years.
- 16 BELLI 08B use  $\text{CdWO}_4$  scintillation calorimeter to search for  $0\nu$  and  $2\nu$  decay with 2K electron captures of  $^{108}\text{Cd}$ . The absence of signal at  $2\times\text{K}$  electron binding energy (48.8 keV) is used to derive the half-life limit. Search for  $\gamma$  at 223 keV gives half-life limit for the  $0\nu$  mode of  $1.0 \times 10^{18}$  years.
- 17 BELLI 08B use  $\text{CdWO}_4$  scintillation calorimeter to search for  $2\nu\beta\beta$  decay of  $^{114}\text{Cd}$ .
- 18 BELLI 08B use  $\text{CdWO}_4$  scintillation calorimeter to search for  $0\nu\beta\beta$  decay of  $^{114}\text{Cd}$ .
- 19 UMEHARA 08 use  $\text{CaF}_2$  scintillation calorimeter to search for double beta decay of  $^{48}\text{Ca}$ . Limit is significantly more stringent than quoted sensitivity:  $18 \times 10^{21}$  years.
- 20 First exclusive measurement of  $2\nu$ -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.
- 21 Limit on  $0\nu$ -decay to the first excited  $0_1^+$ -state of daughter nucleus using NEMO-3 tracking calorimeter. Supersedes DASSIE 95.
- 22 Limit on  $2\nu$ -decay to the first excited  $2^+$ -state of daughter nucleus using NEMO-3 tracking calorimeter.
- 23 Limit on  $0\nu$ -decay to the first excited  $2^+$ -state of daughter nucleus using NEMO-3 tracking calorimeter.
- 24 BARABASH 07 use Ge calorimeter to search for  $\gamma$ -radiation following double electron capture or  $\beta^+$  plus electron capture decays of  $^{74}\text{Sr}$  to the ground state of  $^{74}\text{Ge}$ . 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.
- 25 BARABASH 07 use Ge calorimeter to search for  $\gamma$ -radiation following double electron capture decay of  $^{74}\text{Sr}$  into the second excited  $2^+$ -state of  $^{74}\text{Ge}$ . That transition has been considered due to a possible resonance enhancement. The  $2\nu$  mode would be suppressed for this decay by its extremely small phase space factor.
- 26 BARABASH 07B use Ge calorimeter to search for  $\gamma$ -radiation following the double electron capture decay of  $^{120}\text{Te}$ . This limit is based on the search for the bremsstrahlung radiation. Various limits, for the capture from different atomic shells, are reported that cover the range of half-lives shown.
- 27 BARABASH 07B use Ge calorimeter to search for the 511 keV positron annihilation radiation following the  $\beta^+$  plus electron capture decay of  $^{120}\text{Te}$ .
- 28 BARABASH 07B use Ge calorimeter to search for  $\gamma$ -radiation following the double electron capture decay of  $^{120}\text{Te}$  into the excited  $2^+$  state of  $^{120}\text{Sn}$ . This limit is based on the search for the  $\gamma$ -radiation from the excited  $2^+$  state.
- 29 BLOXHAM 07 use  $\text{CdZnTe}$  solid state detectors to search for the decays of the various double beta detector components, here for double electron capture  $^{64}\text{Zn}$  decay.

- 30 BLOXHAM 07 use CdZnTe solid state detectors to search for the decays of the various double beta detector components, here for  $\beta^+$  plus electron capture  $^{120}\text{Te}$  decay.
- 31 BLOXHAM 07 use CdZnTe solid state detectors to search for the decays of the various double beta detector components, here for double electron capture  $^{120}\text{Te}$  decay.
- 32 BLOXHAM 07 use CdZnTe solid state detectors to search for the decays of the various double beta detector components, here for double electron capture  $^{120}\text{Te}$  decay to the first excited  $2^+$ -state.
- 33 KLAPDOR-KLEINGROTHAUS 06A present re-analysis of data originally published in KLAPDOR-KLEINGROTHAUS 04A. Modified pulse shape analysis leads the authors to claim improved  $6\sigma$  statistical evidence for observation of  $0\nu$ -decay, compared to  $4.2\sigma$  in KLAPDOR-KLEINGROTHAUS 04A. Analysis of the systematic uncertainty is not presented. Supersedes KLAPDOR-KLEINGROTHAUS 04A.
- 34 Supersedes ARNABOLDI 04. Bolometric  $\text{TeO}_2$  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  $^{130}\text{Te}$  exposure.
- 35 NEMO-3 tracking calorimeter containing 6.9 kg of enriched  $^{100}\text{Mo}$  is used in ARNOLD 05A. A limit for  $0\nu\beta\beta$  half-life of  $^{100}\text{Mo}$  is reported. Supersedes ARNOLD 04.
- 36 NEMO-3 tracking calorimeter is used in ARNOLD 05A to place limit on  $0\nu\beta\beta$  half-life of  $^{82}\text{Se}$ . Detector contains 0.93 kg of enriched  $^{82}\text{Se}$ . Supersedes ARNOLD 04.
- 37 ARNOLD 05A use the NEMO-3 tracking calorimeter to determine the  $2\nu\beta\beta$  half-life of  $^{100}\text{Mo}$  with high statistics and low background (389 days of data taking). Supersedes ARNOLD 04.
- 38 ARNOLD 05A use the NEMO-3 tracking detector to determine the  $2\nu\beta\beta$  half-life of  $^{82}\text{Se}$  with high statistics and low background (389 days of data taking). Supersedes ARNOLD 04.
- 39 Supersedes ARNABOLDI 03. Bolometric  $\text{TeO}_2$  detector array Cuoricino used for high resolution search for  $0\nu\beta\beta$  decay.
- 40 ARNOLD 04 use the NEMO-3 tracking detector to determine the limit for  $0\nu\beta\beta$  half-life of  $^{100}\text{Mo}$ . This represents an improvement, by a factor of  $\sim 6$ , when compared with EJIRI 01.
- 41 ARNOLD 04 use the NEMO-3 tracking detector to determine the limit for  $0\nu\beta\beta$  half-life of  $^{82}\text{Se}$ . This represents an improvement, by a factor of  $\sim 10$ , when compared with ELLIOTT 92. It supersedes the limit of ARNOLD 98 for this decay using NEMO-2.
- 42 ARNOLD 04 use the NEMO-3 tracking detector to determine the  $2\nu\beta\beta$  half-life of  $^{100}\text{Mo}$  with high statistics and low background. The half-life 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.
- 43 ARNOLD 04 use the NEMO-3 tracking detector to determine the  $2\nu\beta\beta$  half-life of  $^{82}\text{Se}$ . The half-life is in agreement with ARNOLD 98 with NEMO-2 which it supersedes.
- 44 BARABASH 04 perform an inclusive measurement of the  $\beta\beta$  decay of  $^{150}\text{Nd}$  into the first excited ( $0_1^+$ ) state of  $^{150}\text{Sm}$ . Gamma radiation emitted in decay of the excited state is detected.
- 45 Supersedes KLAPDOR-KLEINGROTHAUS 02D. Authors present new analysis of event excess seen in Heidelberg-Moscow experiment at  $\beta\beta$ -decay energy. Enhanced statistics leads to a  $4.2\sigma$  evidence for observation of  $0\nu\beta\beta$ -decay and a finite Majorana neutrino mass. Stated error is purely statistical. No systematic errors are mentioned in the paper. More details can be found in KLAPDOR-KLEINGROTHAUS 04C.
- 46  $\text{CaF}_2$  scintillation calorimeter ELEGANT VI used to set limit on  $0\nu\beta\beta$ -decay rate of  $^{48}\text{Ca}$ . The stated half-life limit benefits from a downward fluctuation on the number of background events. The experimental sensitivity is  $5.9 \times 10^{21}$  yr. at 90 % CL. Replaces YOU 91 as the most stringent experiment using  $^{48}\text{Ca}$ .
- 47 Supersedes ALESSANDRELLO 00. Array of  $\text{TeO}_2$  crystals in high resolution cryogenic calorimeter. Some enriched in  $^{130}\text{Te}$ . Ground state to ground state decay.
- 48 Decay into first excited state of daughter nucleus.

- 49 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.
- 50 Supersedes ALESSANDRELLO 00. Array of TeO<sub>2</sub> crystals in high resolution cryogenic calorimeter. Some enriched in <sup>128</sup>Te. Ground state to ground state decay.
- 51 Calorimetric measurement of 2ν ground state decay of <sup>116</sup>Cd using enriched CdWO<sub>4</sub> scintillators. Agrees with EJIRI 95 and ARNOLD 96. Supersedes DANEVICH 00.
- 52 Limit on 0ν decay of <sup>116</sup>Cd using enriched CdWO<sub>4</sub> scintillators. Supersedes DANEVICH 00.
- 53 Limit on 0ν decay of <sup>116</sup>Cd into first excited 2<sup>+</sup> state of daughter nucleus using enriched CdWO<sub>4</sub> scintillators. Supersedes DANEVICH 00.
- 54 Limit on 0ν decay of <sup>116</sup>Cd into first excited 0<sup>+</sup> state of daughter nucleus using enriched CdWO<sub>4</sub> scintillators. Supersedes DANEVICH 00.
- 55 Limit on 0ν decay of <sup>116</sup>Cd into second excited 0<sup>+</sup> state of daughter nucleus using enriched CdWO<sub>4</sub> scintillators. Supersedes DANEVICH 00.
- 56 Results of the Heidelberg-Moscow experiment (KLAPDOR-KLEINGROTHAUS 01 and GUENTHER 97) are reanalyzed using a new simulation of the complete background spectrum. The ββ2ν-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.
- 57 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.
- 58 BERNABEI 02D report a limit for the 0ν, 0<sup>+</sup> → 0<sup>+</sup> decay of <sup>134</sup>Xe, present in the source at 17%, by considering the maximum number of events for this mode compatible with the fitted smooth background.
- 59 BERNABEI 02D report a limit for the 0ν, 0<sup>+</sup> → 0<sup>+</sup> decay of <sup>136</sup>Xe, by considering the maximum number of events for this mode compatible with the fitted smooth background. The quoted sensitivity is 450 × 10<sup>21</sup> yr. The Feldman and Cousins method is used to obtain the quoted limit.
- 60 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. GROMOV 06 analysis of the background supports the assignment of the weak γ transitions near 2040 keV to the decay of <sup>214</sup>Bi as claimed in KLAPDOR-KLEINGROTHAUS 04A and KLAPDOR-KLEINGROTHAUS 04C, and in earlier works.
- 61 ASHITKOV 01 result for 2ν of <sup>100</sup>Mo is in agreement with other determinations of that halflife.
- 62 ASHITKOV 01 result for 0ν of <sup>100</sup>Mo is less stringent than EJIRI 01.
- 63 DANEVICH 01 place limit on 0ν decay of <sup>160</sup>Gd using Gd<sub>2</sub>SiO<sub>5</sub>:Ce crystal scintillators. The limit is more stringent than KOBAYASHI 95.
- 64 DANEVICH 01 place limits on 0ν decay of <sup>160</sup>Gd into excited 2<sup>+</sup> state of daughter nucleus using Gd<sub>2</sub>SiO<sub>5</sub>:Ce crystal scintillators.

- <sup>65</sup> 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.
- <sup>66</sup> 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.
- <sup>67</sup> 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.
- <sup>68</sup> 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 larger systematic error than their previous result.
- <sup>69</sup> WIESER 01 reports an inclusive geochemical measurement of  $^{96}\text{Zr}$   $\beta\beta$  half life. Their result agrees within  $2\sigma$  with ARNOLD 99 but only marginally, within  $3\sigma$ , with KAWASHIMA 93.
- <sup>70</sup> BRUDANIN 00 determine the  $2\nu$  half-life of  $^{48}\text{Ca}$ . Their value is less accurate than BALYSH 96.
- <sup>71</sup> ARNOLD 99 measure directly the  $2\nu$  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.
- <sup>72</sup> ARNOLD 98 measure the  $2\nu$  decay of  $^{82}\text{Se}$  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.
- <sup>73</sup> ARNOLD 98 determine the limit for  $0\nu$  decay to the ground state of  $^{82}\text{Se}$  using the NEMO-2 tracking detector. The half-life limit is in agreement, but less stringent, than ELLIOTT 92.
- <sup>74</sup> ARNOLD 98 determine the limit for  $0\nu$  decay to the excited  $2^+$  state of  $^{82}\text{Se}$  using the NEMO-2 tracking detector.
- <sup>75</sup> ALSTON-GARNJOST 97 report evidence for  $2\nu$  decay of  $^{100}\text{Mo}$ . This decay has been also observed by EJIRI 91, DASSIE 95, and DESILVA 97.
- <sup>76</sup> DESILVA 97 result for  $2\nu$  decay of  $^{100}\text{Mo}$  is in agreement with ALSTON-GARNJOST 97 and DASSIE 95. This measurement has the smallest errors.
- <sup>77</sup> DESILVA 97 result for  $2\nu$  decay of  $^{150}\text{Nd}$  is in marginal agreement with ARTEMEV 93. It has smaller errors.
- <sup>78</sup> DESILVA 97 do not explain whether their efficiency for  $0\nu$  decay of  $^{150}\text{Nd}$  was calculated under the assumption of a  $\langle m_\nu \rangle$ ,  $\langle \lambda \rangle$ , or  $\langle \eta \rangle$  driven decay.
- <sup>79</sup> ARNOLD 96 measure the  $2\nu$  decay of  $^{116}\text{Cd}$ . This result is in agreement with EJIRI 95, but has smaller errors. Supersedes ARNOLD 95.
- <sup>80</sup> BALYSH 96 measure the  $2\nu$  decay of  $^{48}\text{Ca}$ , using a passive source of enriched  $^{48}\text{Ca}$  in a TPC.
- <sup>81</sup> TAKAOKA 96 measure the geochemical half-life of  $^{130}\text{Te}$ . 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.
- <sup>82</sup> BARABASH 95 cannot distinguish  $0\nu$  and  $2\nu$ , but it is inferred indirectly that the  $0\nu$  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).
- <sup>83</sup> BERNATOWICZ 92 finds  $^{128}\text{Te}/^{130}\text{Te}$  activity ratio from slope of  $^{128}\text{Xe}/^{132}\text{Xe}$  vs  $^{130}\text{Xe}/^{132}\text{Xe}$  ratios during extraction, and normalizes to lead-dated ages for the  $^{130}\text{Te}$  lifetime. The authors state that their results imply that "(a) the double beta decay of  $^{128}\text{Te}$  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  $^{128}\text{Te}$   $^{130}\text{Te}$ ] by 1 or 2 orders of magnitude, pointing to a real suppression in the  $2\nu$  decay rate of these isotopes. (c) Despite [this], most  $\beta\beta$ -models predict a *ratio* of  $2\nu$  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  $^{128}\text{Xe}$  production corrections.

- 84 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  $^{238}\text{U}$  transition in the same range as deduced for  $^{130}\text{Te}$  and  $^{76}\text{Ge}$ . 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.
- 85 Result agrees with direct determination of ELLIOTT 92.
- 86 Inclusive half life inferred from mass spectroscopic determination of abundance of  $\beta\beta$ -decay product  $^{130}\text{Te}$  in mineral kitkaite ( $\text{NiTeSe}$ ). 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.
- 87 Ratio of inclusive double beta half lives of  $^{128}\text{Te}$  and  $^{130}\text{Te}$  determined from minerals melonite ( $\text{NiTe}_2$ ) and altaite ( $\text{PbTe}$ ) 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  $^{130}\text{Te}$  (LIN 88) to infer the half life of  $^{128}\text{Te}$ . No estimate of the systematic uncertainty of this method is given. The directly determined half life ratio agrees with BERNATOWICZ 92. However, the inferred  $^{128}\text{Te}$  half life disagrees with KIRSTEN 83 and BERNATOWICZ 92.
- 88 KIRSTEN 83 reports "2 $\sigma$ " error. References are given to earlier determinations of the  $^{130}\text{Te}$  lifetime.

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

$\langle m_\nu \rangle = |\sum U_{1j}^2 m_{\nu_j}|$ , where the sum goes from 1 to  $n$  and where  $n$  = number of neutrino generations, and  $\nu_j$  is a Majorana neutrino. Note that  $U_{ej}^2$ , 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. ● ● ●					
< 7.2–19.5	90	$^{96}\text{Zr}$	$0\nu$	NEMO-3	89 ARGYRIADES 10
< 4.0–6.8	90	$^{150}\text{Nd}$	$0\nu$	NEMO-3	90 ARGYRIADES 09
< 0.19–0.68	90	$^{130}\text{Te}$	$0\nu$	$\text{TeO}_2$ bolometer	91 ARNABOLDI 08
< 3.5–22	90	$^{48}\text{Ca}$	$0\nu$	$\text{CaF}_2$ scint.	92 UMEHARA 08
< 9.3–60	90	$^{100}\text{Mo}$	$0^+ \rightarrow 0_1^+$	NEMO-3	93 ARNOLD 07
< 6500	90	$^{100}\text{Mo}$	$0^+ \rightarrow 2^+$	NEMO-3	94 ARNOLD 07
$0.32 \pm 0.03$	68	$^{76}\text{Ge}$	$0\nu$	Enriched HPGe	95 KLAPDOR-K...06A
< 0.2–1.1	90	$^{130}\text{Te}$		Cryog. det.	96 ARNABOLDI 05
< 0.7–2.8	90	$^{100}\text{Mo}$	$0\nu$	NEMO-3	97 ARNOLD 05A
< 1.7–4.9	90	$^{82}\text{Se}$	$0\nu$	NEMO-3	98 ARNOLD 05A
< 0.37–1.9	90	$^{130}\text{Te}$		Cryog. det.	99 ARNABOLDI 04
< 0.8–1.2	90	$^{100}\text{Mo}$	$0\nu$	NEMO-3	100 ARNOLD 04
< 1.5–3.1	90	$^{82}\text{Se}$	$0\nu$	NEMO-3	100 ARNOLD 04
0.1–0.9	99.7	$^{76}\text{Ge}$		Enriched HP Ge	101 KLAPDOR-K...04A
< 7.2–44.7	90	$^{48}\text{Ca}$		$\text{CaF}_2$ scint.	102 OGAWA 04
< 1.1–2.6	90	$^{130}\text{Te}$		Cryog. det.	103 ARNABOLDI 03



< 1.5–1.7	90	$^{116}\text{Cd}$	$0\nu$	$^{116}\text{CdWO}_4$ scint.	104	DANEVICH	03
< 0.33–1.35	90			Enriched HPGe	105	AALSETH	02B
< 2.9	90	$^{136}\text{Xe}$	$0\nu$	Liquid Xe Scint.	106	BERNABEI	02D
$0.39^{+0.17}_{-0.28}$		$^{76}\text{Ge}$	$0\nu$	Enriched HPGe	107	KLAPDOR-K...	02D
< 2.1–4.8	90	$^{100}\text{Mo}$	$0\nu$	ELEGANT V	108	EJIRI	01
< 0.35	90	$^{76}\text{Ge}$		Enriched HPGe	109	KLAPDOR-K...	01
< 23	90	$^{96}\text{Zr}$		NEMO-2	110	ARNOLD	99
< 1.1–1.5		$^{128}\text{Te}$		Geochem	111	BERNATOW...	92
< 5	68	$^{82}\text{Se}$		TPC	112	ELLIOTT	92
< 8.3	76	$^{48}\text{Ca}$	$0\nu$	$\text{CaF}_2$ scint.		YOU	91

- <sup>89</sup> ARGYRIADES 10 use  $^{96}\text{Zr}$  and the NEMO-3 tracking detector to obtain the reported mass limit. The range reflects the fluctuation of the nuclear matrix elements considered.
- <sup>90</sup> ARGYRIADES 09 limit is based on data taken with the NEMO-3 detector and  $^{150}\text{Nd}$ . A range of nuclear matrix elements that include the effect of nuclear deformation have been used.
- <sup>91</sup> Limit was obtained using high resolution  $\text{TeO}_2$  bolometer calorimeter to search for double beta decay of  $^{130}\text{Te}$ . Reported range of limits reflects spread of matrix element calculations used. Supersedes ARNABOLDI 05.
- <sup>92</sup> Limit was obtained using  $\text{CaF}_2$  scintillation calorimeter to search for double beta decay of  $^{48}\text{Ca}$ . Reported range of limits reflects spread of QRPA and SM matrix element calculations used. Supersedes OGAWA 04.
- <sup>93</sup> ARNOLD 07 use NEMO-3 half life limit for  $0\nu$ -decay of  $^{100}\text{Mo}$  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.
- <sup>94</sup> ARNOLD 07 use NEMO-3 half life limit for  $0\nu$ -decay of  $^{100}\text{Mo}$  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.
- <sup>95</sup> Re-analysis of data originally published in KLAPDOR-KLEINGROTHAUS 04A. Modified pulse shape analysis leads the authors to claim  $6\sigma$  statistical evidence for observation of  $0\nu$ -decay. Authors use matrix element of STAUDT 90. Uncertainty of nuclear matrix element is not reflected in stated error. Supersedes KLAPDOR-KLEINGROTHAUS 04A.
- <sup>96</sup> Supersedes ARNABOLDI 04. Reported range of limits due to use of different nuclear matrix element calculations.
- <sup>97</sup> Mass limits reported in ARNOLD 05A are derived from  $^{100}\text{Mo}$  data, obtained by the NEMO-3 collaboration. The range reflects the spread of matrix element calculations considered in this work. Supersedes ARNOLD 04.
- <sup>98</sup> Neutrino mass limits based on  $^{82}\text{Se}$  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.
- <sup>99</sup> Supersedes ARNABOLDI 03. Reported range of limits due to use of different nuclear matrix element calculations.
- <sup>100</sup> ARNOLD 04 limit is based on the nuclear matrix elements of SIMKOVIC 99, STOICA 01 and CIVITARESE 03.
- <sup>101</sup> 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  $\langle m \rangle$  becomes (0.2–0.6) eV at the  $3\sigma$  level.
- <sup>102</sup> Calorimetric  $\text{CaF}_2$  scintillator. Range of limits reflects authors' estimate of the uncertainty of the nuclear matrix elements. Replaces YOU 91 as the most stringent limit based on  $^{48}\text{Ca}$ .

- 103 Supersedes ALESSANDRELLO 00. Cryogenic calorimeter search. Reported a range reflecting uncertainty in nuclear matrix element calculations.
- 104 Limit for  $\langle m_\nu \rangle$  is based on the nuclear matrix elements of STAUDT 90 and ARNOLD 96. Supersedes DANEVICH 00.
- 105 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.
- 106 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.
- 107 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.
- 108 The range of the reported  $\langle m_\nu \rangle$  values reflects the spread of the nuclear matrix elements. On axis value assuming  $\langle \lambda \rangle = \langle \eta \rangle = 0$ .
- 109 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  $m_\nu$ . It supersedes BAUDIS 99B.
- 110 ARNOLD 99 limit based on the nuclear matrix elements of STAUDT 90.
- 111 BERNATOWICZ 92 finds these majorana neutrino mass limits assuming that the measured geochemical decay width is a limit on the  $0\nu$  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.
- 112 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			$^{100}\text{Mo}$	$0^+ \rightarrow 2^+$	113 ARNOLD 07
$0.692^{+0.058}_{-0.056}$	68	$0.305^{+0.026}_{-0.025}$	68	$^{76}\text{Ge}$	Enriched HPGe	114 KLAPDOR-K... 06A
< 2.5	90			$^{100}\text{Mo}$	$0\nu$ , NEMO-3	115 ARNOLD 05A
< 3.8	90			$^{82}\text{Se}$	$0\nu$ , NEMO-3	116 ARNOLD 05A
< 1.5–2.0	90			$^{100}\text{Mo}$	$0\nu$ , NEMO-3	117 ARNOLD 04
< 3.2–3.8	90			$^{82}\text{Se}$	$0\nu$ , NEMO-3	118 ARNOLD 04
< 1.6–2.4	90	< 0.9–5.3	90	$^{130}\text{Te}$	Cryog. det.	119 ARNABOLDI 03
< 2.2	90	<2.5	90	$^{116}\text{Cd}$	$^{116}\text{CdWO}_4$ scint.	120 DANEVICH 03
< 3.2–4.7	90	< 2.4–2.7	90	$^{100}\text{Mo}$	ELEGANT V	121 EJIRI 01
< 1.1	90	<0.64	90	$^{76}\text{Ge}$	Enriched HPGe	122 GUENTHER 97
< 4.4	90	<2.3	90	$^{136}\text{Xe}$	TPC	123 VUILLEUMIER 93
		<5.3		$^{128}\text{Te}$	Geochem	124 BERNATOW... 92

- 113 ARNOLD 07 use NEMO-3 half life limit for  $0\nu$ -decay of  $^{100}\text{Mo}$  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.
- 114 Re-analysis of data originally published in KLAPDOR-KLEINGROTHAUS 04A. Modified pulse shape analysis leads the authors to claim  $6\sigma$  statistical evidence for observation of  $0\nu$ -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.
- 115 ARNOLD 05A derive limit for  $\langle\lambda\rangle$  based on  $^{100}\text{Mo}$  data collected with NEMO-3 detector. No limit for  $\langle\eta\rangle$  is given. Supersedes ARNOLD 04.
- 116 ARNOLD 05A derive limit for  $\langle\lambda\rangle$  based on  $^{82}\text{Se}$  data collected with NEMO-3 detector. No limit for  $\langle\eta\rangle$  is given. Supersedes ARNOLD 04.
- 117 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.
- 118 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.
- 119 Supersedes ALESSANDRELLO 00. Cryogenic calorimeter search. Reported a range reflecting uncertainty in nuclear matrix element calculations.
- 120 Limits for  $\langle\lambda\rangle$  and  $\langle\eta\rangle$  are based on nuclear matrix elements of STAUDT 90. Supersedes DANEVICH 00.
- 121 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.
- 122 GUENTHER 97 limits use the matrix elements of STAUDT 90. Supersedes BALYSH 95 and BALYSH 92.
- 123 VUILLEUMIER 93 uses the matrix elements of MUTO 89. Based on a half-life limit  $2.6 \times 10^{23}$  y at 90%CL.
- 124 BERNATOWICZ 92 takes the measured geochemical decay width as a limit on the  $0\nu$  width, and uses the SUHONEN 91 coefficients to obtain the least restrictive limit on  $\eta$ . Further details of the experiment are given in BERNATOWICZ 93.

---

### Double- $\beta$ Decay REFERENCES

BELLI	11	JPG 38 015103	P. Belli <i>et al.</i>	(INFN Gran Sasso)
ARGYRIADES	10	NP A847 168	J. Argyriades <i>et al.</i>	(NEMO-3 Collab.)
BELLI	10	NP A846 143	P. Belli <i>et al.</i>	(INFN Gran Sasso)
ARGYRIADES	09	PR C80 032501R	J. Argyriades <i>et al.</i>	(NEMO-3 Collab.)
BELLI	09A	NP A826 256	P. Belli <i>et al.</i>	
DAWSON	09	PR C80 025502	J.V. Dawson <i>et al.</i>	
HWANG	09	ASP 31 412	M.J. Hwang <i>et al.</i>	
KIDD	09	NP A821 251	M. Kidd <i>et al.</i>	
ARNABOLDI	08	PR C78 035502	C. Arnaboldi <i>et al.</i>	
BELLI	08	PL B658 193	P. Belli <i>et al.</i>	(INFN Gran Sasso)
BELLI	08B	EPJ A36 167	P. Belli <i>et al.</i>	
UMEHARA	08	PR C78 058501	S. Umehara <i>et al.</i>	
ARNOLD	07	NP A781 209	R. Arnold <i>et al.</i>	(NEMO-3 Collab.)
BARABASH	07	NP A785 371	A.S. Barabash <i>et al.</i>	
BARABASH	07B	JPG 34 1721	A.S. Barabash <i>et al.</i>	
BLOXHAM	07	PR C76 025501	T. Bloxham <i>et al.</i>	(COBRA Collab.)
GROMOV	06	PPNL 3 157	K. Gromov <i>et al.</i>	
KLAPDOR-K...	06A	MPL A21 1547	H.V. Klapdor-Kleingrothaus, I.V. Krivosheina	
ARNABOLDI	05	PRL 95 142501	C. Arnaboldi <i>et al.</i>	(CUORICINO Collab.)
ARNOLD	05A	PRL 95 182302	R. Arnold <i>et al.</i>	(NEMO-3 Collab.)
AALSETH	04	PR D70 078302	C.E. Aalseth <i>et al.</i>	
ARNABOLDI	04	PL B584 260	C. Arnaboldi <i>et al.</i>	
ARNOLD	04	JETPL 80 377	R. Arnold <i>et al.</i>	(NEMO3 Detector Collab.)

Translated from ZETFP 80 429.

BARABASH	04	JETPL 79 10	A.S. Barabash <i>et al.</i>
KLAPDOR-K...	04A	PL B586 198	H.V. Klapdor-Kleingrothaus <i>et al.</i>
KLAPDOR-K...	04B	PR D70 078301	H.V. Klapdor-Kleingrothaus, A. Dietz, I.V. Krivosheina
KLAPDOR-K...	04C	NIM A522 371	H.V. Klapdor-Kleingrothaus <i>et al.</i>
OGAWA	04	NP A730 215	I. Ogawa <i>et al.</i>
ARNABOLDI	03	PL B557 167	C. Arnaboldi <i>et al.</i>
CIVITARESE	03	NP A729 867	O. Civitarese, J. Suhonen
DANEVICH	03	PR C68 035501	F.A. Danevich <i>et al.</i>
DOERR	03	NIM A513 596	C. Doerr, H.V. Klapdor-Kleingrothaus
AALSETH	02	MPL A17 1475	C.E. Aalseth <i>et al.</i>
AALSETH	02B	PR D65 092007	C.E. Aalseth <i>et al.</i> (IGEX Collab.)
BERNABEI	02D	PL B546 23	R. Bernabei <i>et al.</i> (DAMA Collab.)
KLAPDOR-K...	02	hep-ph/0205228	H.V. Klapdor-Kleingrothaus
KLAPDOR-K...	02B	PPNL 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 <i>et al.</i>
		Translated from ZETFP 74 601.	
DANEVICH	01	NP A694 375	F.A. Danevich <i>et al.</i>
DEBRAECKEL...	01	PRL 86 3510	L. De Braeckeleer <i>et al.</i>
EJIRI	01	PR C63 065501	H. Ejiri <i>et al.</i>
KLAPDOR-K...	01	EPJ A12 147	H.V. Klapdor-Kleingrothaus <i>et al.</i>
KLAPDOR-K...	01B	MPL A16 2409	H.V. Klapdor-Kleingrothaus <i>et al.</i>
STOICA	01	NP A694 269	S. Stoica, H.V. Klapdor-Kleingrothaus
WIESER	01	PR C64 024308	M.E. Wieser, J.R. De Laeter
ALESSAND...	00	PL B486 13	A. Alessandrello <i>et al.</i>
BRUDANIN	00	PL B495 63	V.B. Brudanin <i>et al.</i>
DANEVICH	00	PR C62 045501	F.A. Danevich <i>et al.</i>
ARNOLD	99	NP A658 299	R. Arnold <i>et al.</i> (NEMO Collab.)
BAUDIS	99	PR D59 022001	L. Baudis <i>et al.</i> (Heidelberg-Moscow Collab.)
BAUDIS	99B	PRL 83 41	L. Baudis <i>et al.</i> (Heidelberg-Moscow Collab.)
SIMKOVIC	99	PR C60 055502	F. Simkovic <i>et al.</i>
ARNOLD	98	NP A636 209	R. Arnold <i>et al.</i> (NEMO-2 Collab.)
ALSTON-...	97	PR C55 474	M. Alston-Garnjost <i>et al.</i> (LBL, MTHO+)
DESILVA	97	PR C56 2451	A. de Silva <i>et al.</i> (UCI)
GUENTHER	97	PR D55 54	M. Gunther <i>et al.</i> (Heidelberg-Moscow Collab.)
ARNOLD	96	ZPHY C72 239	R. Arnold <i>et al.</i> (BCEN, CAEN, JINR+)
BALYSH	96	PRL 77 5186	A. Balysh <i>et al.</i> (KIAE, UCI, CIT)
EJIRI	96	NP A611 85	H. Ejiri <i>et al.</i> (OSAK)
TAKAOKA	96	PR C53 1557	N. Takaoka, Y. Motomura, K. Nagao (KYUSH, OKAY)
ARNOLD	95	JETPL 61 170	R.G. Arnold <i>et al.</i> (NEMO Collab.)
		Translated from ZETFP 61 168.	
BALYSH	95	PL B356 450	A. Balysh <i>et al.</i> (Heidelberg-Moscow Collab.)
BARABASH	95	PL B345 408	A.S. Barabash <i>et al.</i> (ITEP, SCUC, PNL+)
DASSIE	95	PR D51 2090	D. Dassie <i>et al.</i> (NEMO Collab.)
EJIRI	95	JPSJ 64 339	H. Ejiri <i>et al.</i> (OSAK, KIEV)
KOBAYASHI	95	NP A586 457	M. Kobayashi, M. Kobayashi (KEK, SAGA)
SUHONEN	94	PR C49 3055	J. Suhonen, O. Civitarese
ARTEMEV	93	JETPL 58 262	V.A. Artemiev <i>et al.</i> (ITEP, INRM)
		Translated from ZETFP 58 256.	
BERNATOW...	93	PR C47 806	T. Bernatowicz <i>et al.</i> (WUSL, TATA)
KAWASHIMA	93	PR C47 R2452	A. Kawashima, K. Takahashi, A. Masuda (TOKYC+)
VUILLEUMIER	93	PR D48 1009	J.C. Vuilleumier <i>et al.</i> (NEUC, CIT, VILL)
BALYSH	92	PL B283 32	A. Balysh <i>et al.</i> (MPIH, KIAE, SASSO)
BERNATOW...	92	PRL 69 2341	T. Bernatowicz <i>et al.</i> (WUSL, TATA)
BLUM	92	PL B275 506	D. Blum <i>et al.</i> (NEMO Collab.)
ELLIOTT	92	PR C46 1535	S.R. Elliott <i>et al.</i> (UCI)
EJIRI	91	PL B258 17	H. Ejiri <i>et al.</i> (OSAK)
MANUEL	91	JPG 17 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 <i>et al.</i> (BHEP, CAST+)
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)
LIN	88	NP A481 477	W.J. Lin <i>et al.</i>
LIN	88B	NP A481 484	W.J. Lin <i>et al.</i>
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)

---