Double-β Decay

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NEUTRINOLESS DOUBLE-β DECAY

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Observation of neutrinoless double-beta ($0\nu\beta\beta$) decay would signal violation of total lepton number conservation. The process can be mediated by an exchange of a light Majorana neutrino, or by an exchange of other particles. However, the existence of $0\nu\beta\beta$-decay requires a nonvanishing Majorana neutrino mass, no matter what the actual mechanism is. As long as only a limit on the lifetime is available, limits on the effective Majorana neutrino mass, on the lepton-number violating right-handed current or other possible mechanisms mediating $0\nu\beta\beta$ decay can be obtained, independently of the actual mechanism, by assuming that one of these "new physics" possibilities dominates. These limits are listed in the Double-β Decay Listings of the experimental measurements.

In the following we assume that the exchange of light Majorana neutrinos ($m_{\nu_i} \leq 10$ MeV) contributes dominantly to the decay rate. Besides a dependence on the phase space ($G^{0\nu}$) and the nuclear matrix element ($M^{0\nu}$), the observable $0\nu\beta\beta$-decay rate is proportional then to the square of the effective Majorana mass m_{ee}, $(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot m^2_{ee}$, with $m^2_{ee} = |\sum_i U^2_{ei} m_{\nu_i}|^2$. The sum contains, in general, complex CP-phases in U^2_{ei}, i.e., cancellations may occur. For three neutrino flavors there are two physical phases for Majorana neutrinos (η_1, η_2) and one for Dirac neutrinos (δ_{CP}). The relevant Majorana phases affect only processes to which lepton-number changing amplitudes contribute. Given the general 3×3 mixing matrix for Majorana neutrinos, one can construct other analogous lepton number violating quantities, $m_{\ell\ell'} = \sum_i U_{\ell i} U_{\ell' i} m_{\nu_i} (\ell \text{ or } \ell' \neq e)$. However, these are currently much less constrained than m_{ee}.

Nuclear structure calculations are needed to deduce m_{ee} from the decay rate. While $G^{0\nu}$ can be calculated accurately, the computation of $M^{0\nu}$ is subject to uncertainty. Comparing different nuclear model evaluations indicates a factor ∼2-3 spread in the calculated nuclear matrix elements. Nuclear structure calculation consistently overestimate Gamow-Teller (axial current) matrix elements. This inability of the nuclear models to reproduce Gamow-Teller decay rates is often parametrized in form of a modified coupling constant g_A. Many nuclear theorists interpret this shortcoming as evidence that important physics is missing in the modeling of weak nuclear transitions. It is not clear how these observed uncertainties impact $0\nu\beta\beta$-matrix elements. Nevertheless, this constitutes an additional element of uncertainty. Recent work, [1] shows how the discrepancy between experimental and theoretical axial current matrix elements might be resolved. However, application of this approach to the $0\nu\beta\beta$ decay remains to be accomplished. The particle physics quantities to be determined are thus nuclear model-dependent, so the half-life measurements are listed first. Where possible, we reference the nuclear matrix elements used in the subsequent analysis. Since rates for the conventional $2\nu\beta\beta$ decay serve to constrain the nuclear theory models, results for this process are also given.

Oscillation experiments utilizing atmospheric, accelerator, solar, and reactor produced neutrinos and anti-neutrinos show that at least some neutrinos are massive. However, so far the inverted mass ordering (i.e., whether $\Delta m^2_{31} < 0$) is disfavored only by 2-3 σ compared to the normal mass ordering (when

$\Delta m^2_{31} > 0$), while the absolute neutrino mass values or the properties of neutrinos under CPT-conjugation (Dirac or Majorana) remain undetermined. All confirmed oscillation experiments can be consistently described using three interacting neutrino species with two mass splittings and three mixing angles. (For values of the mixing angles and mass square differences see the corresponding tables.)

Based on the 3-neutrino analysis: $m^2_{ee} = |\cos^2\theta_{13}\cos^2\theta_{12}m_1 + e^{2i(\eta_2-\eta_1)}\cos^2\theta_{13}\sin^2\theta_{12}m_2 + e^{-2i(\eta_1+\delta_{CP})}\sin^2\theta_{13}m_3|^2$, valid for both mass orderings. Given the present knowledge of the neutrino oscillation parameters one can derive a relation between the effective Majorana mass and the mass of the lightest neutrino, as illustrated in Figure 14.11 in the Neutrino Masses, Mixing and Oscillations review. The three mass orderings allowed by the oscillation data: normal ($m_1 < m_2 \ll m_3$), inverted ($m_3 \ll m_1 < m_2$), and degenerate ($m_1 \approx m_2 \approx m_3$), result in different projections. The width of the colored bands reflects the uncertainty introduced by the unknown Majorana and Dirac phases as well as the experimental errors of the oscillation parameters. The latter causes only minor broadening of the bands. Because of the overlap of the different mass scenarios, a measurement of m_{ee} would not reveal which mass ordering is applicable, provided the value of m_{ee} is in the overlapping range.

Analogous plots depict the relation of m_{ee} with the summed neutrino mass $m_{tot} = m_1 + m_2 + m_3$, constrained by observational cosmology, and m_{ee} as a function of the average mass $m^{eff}_{\nu_e} = [\Sigma|U_{ei}|^2 m^2_{\nu_i}]^{1/2}$ determined through the analysis of the electron energy distribution in low energy beta decays. (See Fig. 1 of [2].) The oscillation data thus allow to test whether observed values of m_{ee} and m_{tot} or $m^{eff}_{\nu_e}$ are consistent within the 3 neutrino framework. The rather large intrinsic width of the $\beta\beta$-decay constraints essentially does not allow to positively identify the mass ordering, and thus the sign of Δm^2_{31}, even in combination with these other observables. Naturally, if a value of $0 < m_{ee} \leq 0.01$ eV is ever established, then the normal mass ordering becomes the only possible scenario.

It should be noted that systematic uncertainties of the nuclear matrix elements and possible quenching of the axial current matrix elements are sometimes not folded into the mass limits reported by $\beta\beta$-decay experiments. Taking this additional uncertainty into account would further widen the projections. The plots are based on a 3-neutrino analysis. If it turns out that additional, i.e. sterile light neutrinos exist, the allowed regions would be modified substantially.

If neutrinoless double-beta decay is observed, it will be possible to fix a range of absolute values of the masses m_{ν_i}. Unlike the direct neutrino mass measurements, however, a limit on m_{ee} does not allow one to constrain the individual mass values m_{ν_i} even when the mass differences Δm^2_{ij} are known.

Neutrino oscillation data imply the existence of a lower limit ~ 0.014 eV for the Majorana neutrino mass for the inverted mass ordering pattern, while m_{ee} could, by fine tuning, vanish in the case of the normal mass ordering. Several new double-beta searches have been proposed to probe the interesting m_{ee} mass range, with the prospect of full coverage of the inverted mass ordering region within the next decade.

The $0\nu\beta\beta$ decay mechanism discussed so far is not the only way in which the decay can occur. Numerous other possible scenarios have been proposed, however, all of them requiring new physics. It will be a challenging task to decide which mechanism was responsible once $0\nu\beta\beta$ decay is observed. LHC experiments may reveal corresponding signatures for new physics of lepton number violation. If lepton-number violating right-handed weak current interactions exist, its strength can be characterized by the phenomenological coupling constants η and λ (η describes the coupling between the right-handed lepton current and left-handed quark current while λ describes the coupling when both currents are right-handed). The $0\nu\beta\beta$ decay rate then depends on $\langle\eta\rangle = \eta\sum_i U_{ei}V_{ei}$ and $\langle\lambda\rangle = \lambda\sum_i U_{ei}V_{ei}$ that vanish for massless or unmixed neutrinos ($V_{\ell j}$ is a matrix analogous to $U_{\ell j}$ but describing the mixing with the hypothetical right-handed neutrinos). The observation of the single electron spectra could, in principle, allow to distinguish this mechanism of $0\nu\beta\beta$ from the light Majorana neutrino exchange driven mode. The limits on $\langle\eta\rangle$ and $\langle\lambda\rangle$ are listed in a separate table. The reader is cautioned that a number of earlier experiments did not distinguish between η and λ. In addition, see the section on Majoron searches for additional limits set by these experiments.

References

1. P. Gysbers *et al.*, Nature Phys. **15**, 5 (2019); [arXiv:1903.00047].
2. M.J. Dolinski, A.W.P. Poon and W. Rodejohann, Ann. Rev. Nucl. Part. Sci. **49**, 219 (2019); [arXiv:1902.04097].

Half-life 0ν double-β decay

In most cases the transitions (Z,A) $\rightarrow$ (Z+2,A) $+ 2e^-$ to the 0^+ ground state of the final nucleus are listed. We also list transitions that decrease the nuclear charge ($2e^+$, e^+ CC and double EC) and transitions to an excited state of the final nucleus (0_i^+, 2^+, and 2_i^+). In the following Listings only the best or comparable limits for the half-lives of each transition are reported and only those with about $T_{1/2} > 10^{23}$ years that are relevant for particle physics.

$t_{1/2}(10^{23}$ yr)	CL%	ISOTOPE	TRANSITION	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>900	90	^{76}Ge		GERDA	[1] AGOSTINI	19

$>$ 14	90	^{130}Te	g.s $\to 0^+_1$	CUORE-0	[2] ALDUINO	19
$>$ 0.95	90	^{100}Mo		AMoRE	[3] ALENKOV	19
$>$ 270	90	^{76}Ge		MAJORANA	[4] ALVIS	19
$>$ 350	90	^{136}Xe		EXO-200	[5] ANTON	19
$>$ 35	90	^{82}Se		CUPID-0	[6] AZZOLINI	19
$>$ 2.4	90	^{136}Xe		PANDAX-II	[7] NI	19
$>$ 190	90	^{76}Ge		MAJORANA	[8] AALSETH	18
$>$ 800	90	^{76}Ge		GERDA	[9] AGOSTINI	18
$>$ 180	90	^{136}Xe		EXO-200	[10] ALBERT	18
$>$ 150	90	^{130}Te		CUORE	[11] ALDUINO	18
$>$ 2.5	90	^{82}Se		NEMO-3	[12] ARNOLD	18
$>$ 24	90	^{82}Se		CUPID-0	[13] AZZOLINI	18
$>$ 0.81	90	^{82}Se	g.s $\to 0^+_1$	CUPID-0	[14] AZZOLINI	18A
$>$ 2.2	90	^{116}Cd		AURORA	[15] BARABASH	18
$>$ 530	90	^{76}Ge		GERDA	[16] AGOSTINI	17
$>$ 1.1	90	^{134}Xe		EXO-200	[17] ALBERT	17C
$>$ 1	90	^{116}Cd		NEMO-3	[18] ARNOLD	17
$>$ 40	90	^{130}Te		CUORE(CINO)	[19] ALDUINO	16
$>$ 260	90	^{136}Xe	g.s.$\to 2^+_1$	KamLAND-Zen	[20] ASAKURA	16
$>$ 260	90	^{136}Xe	g.s.$\to 2^+_2$	KamLAND-Zen	[21] ASAKURA	16
$>$ 240	90	^{136}Xe	g.s.$\to 0^+_1$	KamLAND-Zen	[22] ASAKURA	16
$>$1070	90	^{136}Xe		KamLAND-Zen	[23] GANDO	16
$>$ 11	90	^{100}Mo		NEMO-3	[24] ARNOLD	15
$>$ 110	90	^{136}Xe		EXO-200	[25] ALBERT	14B
$>$ 9.4	90	^{130}Te	$0^+ \to 0^+_1$	CUORICINO	[26] ANDREOTTI	12
$>$ 3.6	90	^{82}Se		NEMO-3	[27] BARABASH	11A
$>$ 30	90	^{130}Te		CUORICINO	[28] ARNABOLDI	08
$>$ 0.58	90	^{48}Ca		CaF_2 scint.	[29] UMEHARA	08
$>$ 0.89	90	^{100}Mo	$0^+ \to 0^+_1$	NEMO-3	[30] ARNOLD	07
$>$ 1.6	90	^{100}Mo	$0^+ \to 2^+$	NEMO-3	[31] ARNOLD	07
$>$ 1	90	^{82}Se		NEMO-3	[32] ARNOLD	05A
$>$ 1.1	90	^{128}Te		Cryog. det.	[33] ARNABOLDI	03
$>$ 1.7	90	^{116}Cd		$^{116}CdWO_4$ scint.	[34] DANEVICH	03
$>$ 157	90	^{76}Ge		Enriched HPGe	[35] AALSETH	02B
$>$ 190	90	^{76}Ge		Enriched HPGe	[36] KLAPDOR-K...	01

[1] AGOSTINI 19 use 82.4 kg·yr of data, collected by the GERDA experiment, to search for the $0\nu\ \beta\beta$ decay of ^{76}Ge. High resolution Ge-calorimeters, made from isotopically enriched Ge, are used. A median sensitivity of 1.1×10^{26} yr is reported. Supersedes AGOSTINI 18.

[2] ALDUINO 19 use the combined data of the CUORICINO and CUORE-0 experiments to place a lower limit on the half life of the $0\nu\ \beta\beta$ decay of ^{130}Te to the first excited 0^+ state of ^{130}Xe. Supersedes ANDREOTTI 12.

[3] ALENKOV 19 report the $0\nu\ \beta\beta$ decay half-life limit based on the 52.1 kg·d exposure of ^{100}Mo, of a a cryogenic dual heat and light detector in the Yangyang underground laboratory. The median sensitivity is 1.1×10^{23} years.

[4] ALVIS 19 use the MAJORANA Demonstrator with enriched in ^{76}Ge detectors to set this limit on $0\nu\ \beta\beta$ half-life of ^{76}Ge. The exposure is 26.0 kg yr. The sensitivity is 4.8×10^{25} yr.

[5] ANTON 19 uses he complete dataset of the EXO-200 detector to search for the $0\nu\ \beta\beta$ decay. The exposure is 234.1 kg yr. The median sensitivity is 5.0×10^{25} yr. Supersedes ALBERT 18 and ALBERT 14B.

[6] AZZOLINI 19 use the CPID-0 scintillating cryogenic bolometer to set this limit on $0\nu\ \beta\beta$ half-life of ^{82}Se. The exposure is 5.29 kg yr. The sensitivity is 5×10^{24} yr.

[7] NI 19 use the PandaX-II dual phase TPC at CJPL to search for the $0\nu\ \beta\beta$ decay of ^{136}Xe. The half-life limit 2.4×10^{23} yr is obtained from 22.2 kg yr exposure with a sensitivity of 1.9×10^{23} yr.

[8] AALSETH 18 uses the MAJORANA Demonstrator to search for the $0\nu\ \beta\beta$ decay. The exposure is 9.95 kg·year. The median sensitivity is 2.1×10^{25} yr.

[9] AGOSTINI 18 uses the GERDA detector to search for the $0\nu\ \beta\beta$ decay. The exposure is 46.7 kg·year. The median sensitivity is 5.8×10^{25} yr. Supersedes AGOSTINI 17.

[10] ALBERT 18 uses the EXO-200 detector to search for the $0\nu\ \beta\beta$ decay. The exposure is 177.6 kg·year. The median sensitivity is 3.7×10^{25} years.

[11] ALDUINO 18 uses the CUORE detector to search for the $0\nu\ \beta\beta$ decay of ^{130}Te. The exposure is 86.3 kg·year of natural TeO_2 corresponding to 24.0 kg·year for ^{130}Te. The median sensitivity is 0.7×10^{25} yr. The limit is obtained combining the new data from CUORE with those of CUORE0 (9.8 kg·year of ^{130}Te) and Cuoricino (19.8 kg·year of ^{130}Te).

[12] ARNOLD 18 use the NEMO-3 tracking detector to place a limit on the $0\nu\beta\beta$ decay of ^{82}Se. This is a slightly weaker limit than in BARABASH 11A, using the same detector. Supersedes ARNOLD 05A.

[13] AZZOLINI 18 uses CUPID-0 detector, a novel scintillating cryogenic calorimeter, operated in the LNGS. This results replaces BARABASH 11A (NEMO-3) as the most stringent limit on the $0\nu\ \beta\beta$-decay of ^{82}Se.

[14] AZZOLINI 18A data collected by CUPID-0 based on scintillating bolometers is used to derive a new most stringent limit on the $0\nu\beta\beta$-decay of ^{82}Se to the 0^+_1 state of ^{82}Kr.

[15] BARABASH 18 use 1.162 kg of $^{116}CdWO_4$ scintillating crystals to obtain this limit. Supersedes DANEVICH 03 with analogous source and is more sensitive than ARNOLD 17.

[16] AGOSTINI 17 result corresponds to data collected with GERDA phase 1 and first release of phase 2 for a total of 343 mol-yr exposure. Supersedes AGOSTINI 13A. The median sensitivity is 4.0 10^{25} yr.

[17] ALBERT 17C uses the EXO-200 detector that contains $19.098 \pm 0.014\%$ admixture of ^{134}Xe to search for the 0ν and $2\nu\ \beta\beta$ decay modes. The exposure is 29.6 kg·year. The median sensitivity is 1.9×10^{21} years.

[18] ARNOLD 17 use the NEMO-3 tracking calorimeter, containing 410 g of enriched ^{116}Cd exposed for 5.26 yr, to determine the half-life limit. Supersedes BARABASH 11A.

[19] ALDUINO 16 report result obtained with 9.8 kg y of data collected with the CUORE-0 bolometer, combined with data from the CUORICINO. Supersedes ALFONSO 15.

[20] ASAKURA 16 use the KamLAND-Zen liquid scintillator calorimeter (^{136}Xe 89.5 kg yr) to place a limit on the $0\nu\beta\beta$-decay into the first excited state of the daughter nuclide.

[21] ASAKURA 16 use the KamLAND-Zen liquid scintillator calorimeter (^{136}Xe 89.5 kg yr) to place a limit on the $0\nu\beta\beta$-decay into the second excited state of the daughter nuclide.

[22] ASAKURA 16 use the KamLAND-Zen liquid scintillator calorimeter (^{136}Xe 89.5 kg yr) to place a limit on the $0\nu\beta\beta$-decay into the third excited state of the daughter nuclide.

[23] GANDO 16 use the the KamLAND detector to search for the 0ν decay of ^{136}Xe. With a significant background reduction, the combination of results of the first (270.7 days) and the second phase (263.8 days) of the experiment leads to about six fold improvement over the previous limit. Supersedes GANDO 13A. The sensitivity is 5.6 10^{25} yr.

[24] ARNOLD 15 use the NEMO-3 tracking calorimeter with 34.3 kg yr exposure to determine the limit of $0\nu\beta\beta$-half life of ^{100}Mo. Supersedes ARNOLD 2005A and BARABASH 11A.

[25] ALBERT 14B use 100 kg yr of exposure of the EXO-200 tracking calorimeter to place a lower limit on the $0\nu\beta\beta$-half life of ^{136}Xe. Supersedes AUGER 12.

[26] ANDREOTTI 12 use high resolution TeO_2 bolometric calorimeter to search for the $0\nu\beta\beta$ decay of ^{130}Te leading to the excited 0^1_+ state at 1793.5 keV.

[27] BARABASH 11A use the NEMO-3 detector to measure $2\nu\beta\beta$ rates and place limits on $0\nu\beta\beta$ half lives for various nuclides. Supersedes ARNOLD 05A, ARNOLD 04, ARNOLD 98, and ELLIOTT 92.

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

[29] UMEHARA 08 use CaF_2 scintillation calorimeter to search for double beta decay of ^{48}Ca. Limit is significantly more stringent than quoted sensitivity: 18×10^{21} years.

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

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

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

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

[34] Limit on $0\nu\beta\beta$ decay of ^{116}Cd using enriched $CdWO_4$ scintillators. Supersedes DANEVICH 00.

[35] 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.

[36] 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.

Half-life measurements of the two-neutrino double-β decay

The measured half-life values for the transitions (Z,A) $\rightarrow$ (Z+2,A) + $2e^-$ + $2\overline{\nu}_e$ to the 0^+ ground state of the final nucleus are listed. We also list the transitions to an excited state of the final nucleus (0^+_i, etc.). We report only the measuremetnts with the smallest (or comparable) uncertainty for each transition.

$t_{1/2}(10^{21}$ yr)			ISOTOPE	TRANSITION	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
18	±5	±1	^{124}Xe	2νDEC	XENON1T	[1] APRILE	19E
0.00680	±0.00001	$^{+0.00038}_{-0.00040}$	^{100}Mo		NEMO-3	[2] ARNOLD	19
0.0939	±0.0017	±0.0058	^{82}Se		NEMO-3	[3] ARNOLD	18

0.0263	$^{+0.0011}_{-0.0012}$		^{116}Cd		AURORA	[4] BARABASH	18
> 0.87			^{134}Xe		EXO-200	[5] ALBERT	17C
0.82	±0.02	±0.06	^{130}Te		CUORE-0	[6] ALDUINO	17
0.00690	±0.00015	±0.00037	^{100}Mo		CUPID	[7] ARMENGAUD	17
0.0274	±0.0004	±0.0018	^{116}Cd		NEMO-3	[8] ARNOLD	17
0.064	$^{+0.007}_{-0.006}$	$^{+0.012}_{-0.009}$	^{48}Ca		NEMO-3	[9] ARNOLD	16
0.00934	±0.00022	$^{+0.00062}_{-0.00060}$	^{150}Nd		NEMO-3	[10] ARNOLD	16A
1.926	±0.094		^{76}Ge		GERDA	[11] AGOSTINI	15A
0.00693	±0.00004		^{100}Mo		NEMO-3	[12] ARNOLD	15
2.165	±0.016	±0.059	^{136}Xe		EXO-200	[13] ALBERT	14
9.2	$^{+5.5}_{-2.6}$	±1.3	^{78}Kr		BAKSAN	[14] GAVRILYAK	13
2.38	±0.02	±0.14	^{136}Xe		KamLAND-Zen	[15] GANDO	12A
0.7	±0.09	±0.11	^{130}Te		NEMO-3	[16] ARNOLD	11
0.0235	±0.0014	±0.0016	^{96}Zr		NEMO-3	[17] ARGYRIADES	10
0.69	$^{+0.10}_{-0.08}$	±0.07	^{100}Mo	$0^+ \rightarrow 0^+_1$	Ge coinc.	[18] BELLI	10
0.57	$^{+0.13}_{-0.09}$	±0.08	^{100}Mo	$0^+ \rightarrow 0^+_1$	NEMO-3	[19] ARNOLD	07
0.096	±0.003	±0.010	^{82}Se		NEMO-3	[20] ARNOLD	05A
0.029	$^{+0.004}_{-0.003}$		^{116}Cd		^{116}CdWO$_4$ scint.	[21] DANEVICH	03

[1] APRILE 19E report first measurement of two-neutrino double electron capture in ^{124}Xe using the XENON1T detector with a 0.73 t-yr exposure. An excess of 126 $\pm$ 29 events is observed at 64.3 $\pm$ 0.6 keV decay energy, corresponding to $\sqrt{\Delta\chi^2} = 4.4$ with respect to the background-only hypothesis.

[2] ARNOLD 19 use the NEMO-3 tracking calorimeter with 34.3 kg y exposure to determine the $2\nu\ \beta\beta$ half-life of ^{100}Mo. Supersedes ARNOLD 15.

[3] ARNOLD 18 use the NEMO-3 tracking detector to determine the $2\nu\,\beta\beta$ half-life of ^{82}Se. 0.93 kg of ^{82}Se was observed for 5.25 y. The half-life value was obtained based on the single-state-dominance (SSD) hypothesis, preferred in this case by about 2 σ. Supersedes ARNOLD 05A.

[4] BARABASH 18 use 1.162 kg of ^{116}CdWO$_4$ scintillating crystals to obtain this value. Supersedes DANEVICH 03 with analogous source and agrees with ARNOLD 17 with the NEMO-3 detector.

[5] ALBERT 17C uses the EXO-200 detector that contains 19.098 $\pm$ 0.014% admixture of ^{134}Xe to search for the $2\nu\ \beta\beta$ decay mode. The exposure is 29.6 kg·year. The median sensitivity is 1.2×10^{21} years.

[6] ALDUINO 17 use the CUORE-0 detector containing 10.8 kg of ^{130}Te in 52 crystals of TeO$_2$. The exposure was 9.3 kg yr of ^{130}Te. This is a more accurate rate determination than in ARNOLD 11 and BARABASH 11A.

[7] ARMENGAUD 17 use 185.9 $\pm$ 0.1 g crystal of Li$_2$^{100}MoO$_4$ to determine the ^{100}Mo $2\nu\ \beta\beta$ half-life. The exposure was of 1303 $\pm$ 26 hours only, using novel technique.

[8] ARNOLD 17 use the NEMO-3 tracking calorimeter, containing 410 grams of enriched ^{116}Cd exposed for 5.26 years, to determine the half-life value.

[9] ARNOLD 16 use the NEMO-3 detector and a source of 6.99 g of ^{48}Ca. The half-life is based on 36.7 g year exposure. It is consistent, although somewhat longer, than the previous determinations of the half-life. Supersedes BARABASH 11A.

[10] ARNOLD 16A use the NEMO-3 tracking calorimeter, containing 36.6 g of ^{150}Nd exposed for 1918.5 days, to determine the half-life. Supersedes ARGYRIADES 09.

[11] AGOSTINI 15A use 17.9 kg yr exposure of the GERDA calorimeter to derive an improved measurement of the $2\nu\beta\beta$ decay half life of ^{76}Ge.

[12] ARNOLD 15 use the NEMO-3 tracking calorimeter with 34.3 kg yr exposure to determine the $2\nu\beta\beta$-half life of ^{100}Mo. Supersedes ARNOLD 05A and ARNOLD 04.

[13] ALBERT 14 use the EXO-200 tracking detector for a re-measurement of the $2\nu\beta\beta$-half life of ^{136}Xe. A nuclear matrix element of 0.0218 ± 0.0003 MeV^{-1} is derived from this data. Supersedes ACKERMAN 11.

[14] GAVRILYAK 13 use a proportional counter filled with Kr gas to search for the 2ν2K decay of ^{78}Kr. Data with the enriched and depleted Kr were used to determine signal and background. A 2.5σ excess of events obtained with the enriched sample is interpreted as an indication for the presence of this decay.

[15] GANDO 12A use a modification of the existing KamLAND detector. The $\beta\beta$ decay source/detector is 13 tons of enriched ^{136}Xe-loaded scintillator contained in an inner balloon. The $2\nu\beta\beta$ decay rate is derived from the fit to the spectrum between 0.5 and 4.8 MeV. This result is in agreement with ACKERMAN 11.

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

[17] ARGYRIADES 10 use 9.4 ± 0.2 g of ^{96}Zr in NEMO-3 detector and identify its $2\nu\beta\beta$ decay. The result is in agreement and supersedes ARNOLD 99.

[18] BELLI 10 use enriched ^{100}Mo with 4 HP Ge detectors to record the 590.8 and 539.5 keV γ rays from the decay of the 0_1^+ state in ^{100}Ru both in singles and coincidences. This result confirms the measurement of KIDD 09 and ARNOLD 07 and supersedes them.

[19] First exclusive measurement of 2ν-decay to the first excited 0_1^+-state of daughter nucleus. ARNOLD 07 use the NEMO-3 tracking calorimeter to detect all particles emitted in decay. Result agrees with the inclusive ($0\nu +\ 2\nu$) measurement of DEBRAECKELEER 01.

[20] ARNOLD 05A use the NEMO-3 tracking detector to determine the $2\nu\beta\beta$ half-life of ^{82}Se with high statistics and low background (389 days of data taking). Supersedes ARNOLD 04.

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

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

$\langle m_{\text{ee}} \rangle = |\Sigma U_{ei}^2 m_{\nu_i}|$, i = 1,2,3. It is assumed that ν_i are Majorana particles and that the transition is dominated by the known (light) neutrinos. Note that U_{ei}^2 and not $|U_{ei}|^2$ occur in the sum, and that consequently cancellations are possible. The experiments obtain the limits on $\langle m_\nu \rangle$ from the measured ones on $T_{1/2}$ using a range of nuclear matrix elements (NME), which is reflected in the spread of $\langle m_\nu \rangle$. Different experiments may choose different NME. All assume $g_A = 1.27$. In the following Listings, only the best or comparable limits for each isotope are reported. When not mentioned explicitly the transition is between ground states, but transitions between excited states are also reported.

VALUE (eV)	*ISOTOPE*	*METHOD*	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<$ 0.07–0.16	^{76}Ge	GERDA	[1] AGOSTINI	19
$<$ 1.2–2.1	^{100}Mo	AMoRE	[2] ALENKOV	19
$<$ 0.200–0.433	^{76}Ge	MAJORANA	[3] ALVIS	19
$<$ 0.093–0.286	^{136}Xe	EXO-200	[4] ANTON	19
$<$ 0.311–0.638	^{82}Se	CUPID-0	[5] AZZOLINI	19

$<$ 1.3–3.5	^{136}Xe	PANDAX-II	[6] NI	19
$<$ 0.24–0.52	^{76}Ge	MAJORANA Dem	[7] AALSETH	18
$<$ 0.12–0.26	^{76}Ge	GERDA	[8] AGOSTINI	18
$<$ 0.15–0.40	^{136}Xe	EXO-200	[9] ALBERT	18
$<$ 0.11–0.52	^{130}Te	CUORE	[10] ALDUINO	18
$<$ 1.2–3.0	^{82}Se	NEMO-3	[11] ARNOLD	18
$<$ 0.376–0.770	^{82}Se	CUPID-0	[12] AZZOLINI	18
$<$ 1.0–1.7	^{116}Cd	AURORA	[13] BARABASH	18
$<$ 0.15–0.33	^{76}Ge	GERDA	[14] AGOSTINI	17
$<$ 1.4–2.5	^{116}Cd	NEMO-3	[15] ARNOLD	17
$<$ 0.27–0.76	^{130}Te	CUORE(CINO)	[16] ALDUINO	16
$<$ 1.6–5.3	^{150}Nd	NEMO-3	[17] ARNOLD	16A
$<$ 0.061–0.165	^{136}Xe	KamLAND-Zen	[18] GANDO	16
$<$ 0.33–0.62	^{100}Mo	NEMO-3	[19] ARNOLD	15
$<$ 0.19–0.45	^{136}Xe	EXO-200	[20] ALBERT	14B
$<$ 0.89–2.43	^{82}Se	NEMO-3	[21] BARABASH	11A
$<$ 7.2–19.5	^{96}Zr	NEMO-3	[22] ARGYRIADES	10
$<$ 3.5–22	^{48}Ca	CaF_2 scint.	[23] UMEHARA	08
$<$ 0.2–1.1	^{130}Te	Cryog. det.	[24] ARNABOLDI	05
$<$ 0.37–1.9	^{130}Te	Cryog. det.	[25] ARNABOLDI	04
$<$ 1.5–1.7	^{116}Cd	$^{116}CdWO_4$ scint.	[26] DANEVICH	03
$<$ 0.350	^{76}Ge	Enriched HPGe	[27] KLAPDOR-K...	01
$<$8.3	^{48}Ca	CaF_2 scint.	YOU	91

[1] AGOSTINI 19 use 82.4 kg·yr of data collected by the isotopically enriched ^{76}Ge detectors of the GERDA experiment to derive an upper limit for $\langle m_{\beta\beta}\rangle$. The range reflects the variability of the theoretically calculated nuclear matrix elements. Supersedes AGOSTINI 18.

[2] ALENKOV 19 report the range of the effective masses $\langle m_{\beta\beta}\rangle$ corresponding to the 0ν $\beta\beta$ decay half-life limit. It is based on the 52.1 kg·d exposure of ^{100}Mo, in the Yangyang underground laboratory. The median sensitivity is 1.1×10^{23} years. The range of $\langle m_{\beta\beta}\rangle$ reflects the uncertainty of nuclear matrix elements.

[3] ALVIS 19 use the MAJORANA Demonstrator with enriched in ^{76}Ge detectors to set this limit. The exposure is 26.0 kg yr. The sensitivity is 4.8×10^{25} yr.

[4] ANTON 19 uses the complete dataset of the EXO-200 experiment to obtain these limits. The spread reflect the uncertainty in the nuclear matrix elements. Supersedes ALBERT 18 and ALBERT 14B.

[5] AZZOLINI 19 use the CPID-0 scintillating cryogenic bolometer to set this limit. The exposure is 5.29 kg yr. The sensitivity is 5×10^{24} yr.

[6] NI 19 use the PandaX-II dual phase TPC at CJPL to search for the 0ν $\beta\beta$ decay of ^{136}Xe with 22.2 kg yr exposure. The range in the $m_{\beta\beta}$ limit of 1.3–3.5 eV reflects the range of the calculated nuclear matrix elements. The sensitivity is 1.9×10^{23} yr.

[7] AALSETH 18 uses the MAJORANA Demonstrator detector to establish this limit.

[8] AGOSTINI 18 uses the GERDA detector to establish this limit.

[9] ALBERT 18 uses the EXO-200 experiment to obtain this limit.

[10] ALDUINO 18 use the combined data of CUORE, CUORE0, and Cuoricino to obtain this limit.

[11] ARNOLD 18 use the NEMO-3 tracking detector to constrain the $0\nu\beta\beta$ decay of ^{82}Se. The limit on $\langle m_{\beta\beta}\rangle$ is obtained assuming light neutrino exchange; the range reflects different calculations of the nuclear matrix elements. This is a somewhat weaker limit than in BARABASH 11A using the same detector.

[12] AZZOLINI 18 uses data collected by the CUPID-0 scintillating cryogenic calorimeter, operated in the LNGS, to derive a range of limits on $\langle m_\nu \rangle$. The reported range reflects the spread of the nuclear matrix element calculations considered in this work. Use g_A= 1.269.

[13] BARABASH 18 use 1.162 kg of $^{116}CdWO_4$ scintillating crystals to obtain these limits. The spread reflects the estimated uncertainty in the nuclear matrix element. Supersedes DANEVICH 03.

[14] AGOSTINI 17 is based on 343 mol yr of data from GERDA phase 1 and phase 2 first part and the corresponding limit on $T_{1/2}$ using the different nuclear matrix elements mentioned by the authors. Supersedes AGOSTINI 13A.

[15] ARNOLD 17 utilize NEMO-3 data, taken with enriched ^{116}Cd to limit the effective Majorana neutrino mass. The reported range results from the use of different nuclear matrix elements. Supersedes BARABASH 11A.

[16] ALDUINO 16 place a limit on the effective Majorana neutrino mass using the combined data of the CUORE-0 and CUORICINO experiments. The range reflects the authors' evaluation of the variability of the nuclear matrix elements. Supersededs ALFONSO 15.

[17] ARNOLD 16A limit is derived from data taken with the NEMO-3 detector and ^{150}Nd. A range of nuclear matrix elements that include the effect of nuclear deformation have been used. Supersedes ARGYRIADES 09.

[18] GANDO 16 result is based on the 2016 KamLAND-Zen half-life limit. The stated range reflects different nuclear matrix elements, an unquenched $g_A = 1.27$ is used. Supersedes GANDO 13A.

[19] ARNOLD 15 use the NEMO-3 tracking calorimeter with 34.3 kg yr exposure to determine the neutrino mass limit based on the $0\nu\beta\beta$-half life of ^{100}Mo. The spread range reflects different nuclear matrix elements. Supersedes ARNOLD 14 and BARABASH 11A.

[20] ALBERT 14B is based on 100 kg yr of exposure of the EXO-200 tracking calorimeter. The mass range reflects the nuclear matrix element calculations. Supersedes AUGER 12.

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

[22] ARGYRIADES 10 use ^{96}Zr and the NEMO-3 tracking detector to obtain the reported mass limit. The range reflects the fluctuation of the nuclear matrix elements considered.

[23] Limit was obtained using CaF_2 scintillation calorimeter to search for double beta decay of ^{48}Ca. Reported range of limits reflects spread of QRPA and SM matrix element calculations used. Supersedes OGAWA 04.

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

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

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

[27] 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.

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. • • •							
< 2.2–2.6	90	< 1.7–2.1	90	^{82}Se	NEMO-3	[1] ARNOLD	18

$<$ 1.8–22	90	$<$ 1.6–21	90	^{116}Cd	AURORA	[2] BARABASH	18
$<$ 0.9–1.3	90	$<$ 0.5–0.8	90	^{100}Mo	NEMO-3	[3] ARNOLD	14
$<$120	90			^{100}Mo	$0^+ \rightarrow 2^+$	[4] ARNOLD	07
$0.692^{+0.058}_{-0.056}$	68	$0.305^{+0.026}_{-0.025}$	68	^{76}Ge	Enriched HPGe	[5] KLAPDOR-K...	06A
$<$ 2.5	90			^{100}Mo	0ν, NEMO-3	[6] ARNOLD	05A
$<$ 3.8	90			^{82}Se	0ν, NEMO-3	[7] ARNOLD	05A
$<$ 1.5–2.0	90			^{100}Mo	0ν, NEMO-3	[8] ARNOLD	04
$<$ 3.2–3.8	90			^{82}Se	0ν, NEMO-3	[9] ARNOLD	04
$<$ 1.6–2.4	90	$<$ 0.9–5.3	90	^{130}Te	Cryog. det.	[10] ARNABOLDI	03
$<$ 2.2	90	$<$2.5	90	^{116}Cd	$^{116}CdWO_4$ scint.	[11] DANEVICH	03
$<$ 3.2–4.7	90	$<$ 2.4–2.7	90	^{100}Mo	ELEGANT V	[12] EJIRI	01
$<$ 1.1	90	$<$0.64	90	^{76}Ge	Enriched HPGe	[13] GUENTHER	97
$<$ 4.4	90	$<$2.3	90	^{136}Xe	TPC	[14] VUILLEUMIER	93
		$<$5.3		^{128}Te	Geochem	[15] BERNATOW...	92

[1] ARNOLD 18 use the NEMO03 tracking detector, with 0.93 kg of ^{82}Se mass and 5.25 y exposure to obtain the limits for the hypothetical right-handed currents. Supersedes ARNOLD 05A.

[2] BARABASH 18 use 1.162 kg of $^{116}CdWO_4$ scintillating crystals to obtain this limits for the hypothetical right-handed currents in the $0\nu\beta\beta$ decay of ^{116}Cd.

[3] ARNOLD 14 is based on 34.7 kg yr of exposure of the NEMO-3 tracking calorimeter. The reported range limit on $\langle\lambda\rangle$ and $\langle\eta\rangle$ reflects the nuclear matrix element uncertainty in ^{100}Mo.

[4] ARNOLD 07 use NEMO-3 half life limit for 0ν-decay of ^{100}Mo to the first excited 2^+-state of daughter nucleus to limit the right-right handed admixture of weak currents $\langle\lambda\rangle$. This limit is not competitive when compared to the decay to the ground state.

[5] Re-analysis of data originally published in KLAPDOR-KLEINGROTHAUS 04A. Modified pulse shape analysis leads the authors to claim 6σ statistical evidence for observation of 0ν-decay. Authors use matrix element of MUTO 89 to determine $\langle\lambda\rangle$ and $\langle\eta\rangle$. Uncertainty of nuclear matrix element is not reflected in stated errors.

[6] ARNOLD 05A derive limit for $\langle\lambda\rangle$ based on ^{100}Mo data collected with NEMO-3 detector. No limit for $\langle\eta\rangle$ is given. Supersedes ARNOLD 04.

[7] ARNOLD 05A derive limit for $\langle\lambda\rangle$ based on ^{82}Se data collected with NEMO-3 detector. No limit for $\langle\eta\rangle$ is given. Supersedes ARNOLD 04.

[8] 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.

[9] 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.

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

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

[12] 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.

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

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

[15] BERNATOWICZ 92 takes the measured geochemical decay width as a limit on the 0ν width, and uses the SUHONEN 91 coefficients to obtain the least restrictive limit on η. Further details of the experiment are given in BERNATOWICZ 93.

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ALENKOV	19	EPJ C79 791	V. Alenkov *et al.*	(AMoRE Collab.)
ALVIS	19	PR C100 025501	S.I. Alvis *et al.*	(MAJORANA Collab.)
ANTON	19	PRL 123 161802	G. Anton *et al.*	(EXO-200 Collab.)
APRILE	19E	NAT 568 532	E. Aprile *et al.*	(XENON1T Collab.)
ARNOLD	19	EPJ C79 440	R. Arnold *et al.*	(NEMO-3 Collab.)
AZZOLINI	19	PRL 123 032501	O. Azzolini *et al.*	(CUPID-0 Collab.)
NI	19	CP C43 113001	K. Ni *et al.*	(PandaX-II Collab.)
AALSETH	18	PRL 120 132502	C.E. Aalseth *et al.*	(MAJORANA Collab.)
AGOSTINI	18	PRL 120 132503	M. Agostini *et al.*	(GERDA Collab.)
ALBERT	18	PRL 120 072701	J.B. Albert *et al.*	(EXO-200 Collab.)
ALDUINO	18	PRL 120 132501	C. Alduino *et al.*	(CUORE Collab.)
ARNOLD	18	EPJ C78 821	R. Arnold *et al.*	(NEMO-3 Collab.)
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AALSETH	02B	PR D65 092007	C.E. Aalseth *et al.*	(IGEX Collab.)
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ARNOLD	99	NP A658 299	R. Arnold *et al.*	(NEMO Collab.)
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