

Double- $\beta$  Decay

OMITTED FROM SUMMARY TABLE

For a discussion of the double- $\beta$  decay, see sections 14.9.2 and 14.9.3 of the review "14. Neutrino Masses, Mixing, and Oscillations."

See the related review(s):

[Neutrino Masses, Mixing, and Oscillations](#)

Half-life  $0\nu$  double- $\beta$  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.

| $t_{1/2}(10^{23} \text{ yr})$                                                 | CL% | ISOTOPE           | TRANSITION                      | METHOD       | DOCUMENT ID                |
|-------------------------------------------------------------------------------|-----|-------------------|---------------------------------|--------------|----------------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                   |                                 |              |                            |
| > 3                                                                           | 90  | $^{134}\text{Xe}$ |                                 | PandaX-4T    | <sup>1</sup> YAN 24        |
| >2300                                                                         | 90  | $^{136}\text{Xe}$ |                                 | KamLAND-Zen  | <sup>2</sup> ABE 23        |
| > 830                                                                         | 90  | $^{76}\text{Ge}$  |                                 | MAJORANA     | <sup>3</sup> ARNQUIST 23   |
| > 2.1                                                                         | 90  | $^{100}\text{Mo}$ | $\text{g.s.} \rightarrow 2_1^+$ | CUPID-Mo     | <sup>4</sup> AUGIER 23     |
| > 1.2                                                                         | 90  | $^{100}\text{Mo}$ | $\text{g.s.} \rightarrow 0_1^+$ | CUPID-Mo     | <sup>4</sup> AUGIER 23     |
| > 13                                                                          | 90  | $^{136}\text{Xe}$ |                                 | NEXT         | <sup>5</sup> NOVELLA 23    |
| > 220                                                                         | 90  | $^{130}\text{Te}$ |                                 | CUORE        | <sup>6</sup> ADAMS 22A     |
| > 36                                                                          | 90  | $^{128}\text{Te}$ |                                 | CUORE        | <sup>7</sup> ADAMS 22B     |
| > 12                                                                          | 90  | $^{136}\text{Xe}$ |                                 | XENON1T      | <sup>8</sup> APRILE 22A    |
| > 18                                                                          | 90  | $^{100}\text{Mo}$ |                                 | CUPID-Mo     | <sup>9</sup> AUGIER 22     |
| > 46                                                                          | 90  | $^{82}\text{Se}$  |                                 | CUPID-0      | <sup>10</sup> AZZOLINI 22  |
| > 1.8                                                                         | 90  | $^{82}\text{Se}$  | $\text{g.s.} \rightarrow 0_1^+$ | CUPID-0      | <sup>11</sup> AZZOLINI 22  |
| > 3.0                                                                         | 90  | $^{82}\text{Se}$  | $\text{g.s.} \rightarrow 2_1^+$ | CUPID-0      | <sup>12</sup> AZZOLINI 22  |
| > 3.2                                                                         | 90  | $^{82}\text{Se}$  | $\text{g.s.} \rightarrow 2_2^+$ | CUPID-0      | <sup>13</sup> AZZOLINI 22  |
| > 59                                                                          | 90  | $^{130}\text{Te}$ | $\text{g.s.} \rightarrow 0_1^+$ | CUORE        | <sup>14</sup> ADAMS 21A    |
| > 15                                                                          | 90  | $^{100}\text{Mo}$ |                                 | CUPID-Mo     | <sup>15</sup> ARMENGAUD 21 |
| > 39.9                                                                        | 90  | $^{76}\text{Ge}$  | $\text{g.s.} \rightarrow 0_1^+$ | MAJORANA-Dem | <sup>16</sup> ARNQUIST 21  |
| > 21.2                                                                        | 90  | $^{76}\text{Ge}$  | $\text{g.s.} \rightarrow 2_1^+$ | MAJORANA-Dem | <sup>17</sup> ARNQUIST 21  |
| > 9.7                                                                         | 90  | $^{76}\text{Ge}$  | $\text{g.s.} \rightarrow 2_2^+$ | MAJORANA-Dem | <sup>18</sup> ARNQUIST 21  |
| > 320                                                                         | 90  | $^{130}\text{Te}$ |                                 | CUORE        | <sup>19</sup> ADAMS 20A    |
| >1800                                                                         | 90  | $^{76}\text{Ge}$  |                                 | GERDA        | <sup>20</sup> AGOSTINI 20B |
| > 14                                                                          | 90  | $^{130}\text{Te}$ | $\text{g.s.} \rightarrow 0_1^+$ | CUORE-0      | <sup>21</sup> ALDUINO 19   |
| > 0.95                                                                        | 90  | $^{100}\text{Mo}$ |                                 | AMoRE        | <sup>22</sup> ALENKOV 19   |
| > 350                                                                         | 90  | $^{136}\text{Xe}$ |                                 | EXO-200      | <sup>23</sup> ANTON 19     |
| > 2.4                                                                         | 90  | $^{136}\text{Xe}$ |                                 | PANDAX-II    | <sup>24</sup> NI 19        |
| > 150                                                                         | 90  | $^{130}\text{Te}$ |                                 | CUORE        | <sup>25</sup> ALDUINO 18   |

|        |    |                                            |                              |                         |     |
|--------|----|--------------------------------------------|------------------------------|-------------------------|-----|
| > 2.5  | 90 | $^{82}\text{Se}$                           | NEMO-3                       | $^{26}\text{Arnold}$    | 18  |
| > 2.2  | 90 | $^{116}\text{Cd}$                          | AURORA                       | $^{27}\text{Barabash}$  | 18  |
| > 1.1  | 90 | $^{134}\text{Xe}$                          | EXO-200                      | $^{28}\text{Albert}$    | 17C |
| > 1    | 90 | $^{116}\text{Cd}$                          | NEMO-3                       | $^{29}\text{Arnold}$    | 17  |
| > 40   | 90 | $^{130}\text{Te}$                          | CUORICINO                    | $^{30}\text{Alduino}$   | 16  |
| > 260  | 90 | $^{136}\text{Xe}$ g.s. $\rightarrow 2_1^+$ | KamLAND-Zen                  | $^{31}\text{Asakura}$   | 16  |
| > 260  | 90 | $^{136}\text{Xe}$ g.s. $\rightarrow 2_2^+$ | KamLAND-Zen                  | $^{32}\text{Asakura}$   | 16  |
| > 240  | 90 | $^{136}\text{Xe}$ g.s. $\rightarrow 0_1^+$ | KamLAND-Zen                  | $^{33}\text{Asakura}$   | 16  |
| > 11   | 90 | $^{100}\text{Mo}$                          | NEMO-3                       | $^{34}\text{Arnold}$    | 15  |
| > 9.4  | 90 | $^{130}\text{Te}$ g.s. $\rightarrow 0_1^+$ | CUORICINO                    | $^{35}\text{Andreotti}$ | 12  |
| > 0.58 | 90 | $^{48}\text{Ca}$                           | $\text{CaF}_2$ scint.        | $^{36}\text{UmeHara}$   | 08  |
| > 0.89 | 90 | $^{100}\text{Mo}$ g.s. $\rightarrow 0_1^+$ | NEMO-3                       | $^{37}\text{Arnold}$    | 07  |
| > 1.6  | 90 | $^{100}\text{Mo}$ g.s. $\rightarrow 2^+$   | NEMO-3                       | $^{38}\text{Arnold}$    | 07  |
| > 1.1  | 90 | $^{128}\text{Te}$                          | Cryog. det.                  | $^{39}\text{Arnaboldi}$ | 03  |
| > 1.7  | 90 | $^{116}\text{Cd}$                          | $^{116}\text{CdWO}_4$ scint. | $^{40}\text{Danevich}$  | 03  |
| > 157  | 90 | $^{76}\text{Ge}$                           | Enriched HPGe                | $^{41}\text{Aalseth}$   | 02B |

<sup>1</sup> YAN 24 make use of 17.9 kg·yr of  $^{134}\text{Xe}$  isotope exposure in the PandaX-4T TPC, using natural xenon, to place a limit on the  $0\nu\beta\beta$  decay half-life of  $^{134}\text{Xe}$ .

<sup>2</sup> ABE 23 use the combined data set of the KamLAND-Zen 400 and 800 experiments, utilizing 745 kg of isotopically enriched xenon (90.9%  $^{136}\text{Xe}$ ), dissolved in liquid scintillator and an exposure of 970 kg·yr of  $^{136}\text{Xe}$ , to derive this limit on  $0\nu\beta\beta$  decay. A half-life sensitivity of  $1.5 \times 10^{26}$  yr is reported.

<sup>3</sup> ARNQUIST 23 use the final data set of the MAJORANA DEMONSTRATOR experiment, operating enriched in  $^{76}\text{Ge}$  detectors, to set this limit on the  $0\nu\beta\beta$  half-life of  $^{76}\text{Ge}$ . The exposure is 64.5 kg·yr. A median sensitivity of  $8.1 \times 10^{25}$  yr is reported.

<sup>4</sup> AUGIER 23 utilize the complete data, set collected by the CUPID-Mo bolometric calorimeter with particle ID and located at the LSM, to study various double beta decays of  $^{100}\text{Mo}$  to excited states of the daughter nucleus. An exposure of 1.47 kg·yr of  $^{100}\text{Mo}$  is available.

<sup>5</sup> NOVELLA 23 use data collected by the NEXT-White experiment to limit the  $0\nu\beta\beta$  half-life of  $^{136}\text{Xe}$ . The experiment contains 3.5 kg of enriched Xe and is based on a high-pressure gas TPC. Two different limits are reported, based on different data analysis approaches,  $> 5.5 \times 10^{23}$  yr and  $> 13 \times 10^{23}$  yr.

<sup>6</sup> ADAMS 22A use the CUORE TeO<sub>2</sub> experiment with an exposure of 288.8 kg·yr of  $^{130}\text{Te}$  to place a limit on its  $0\nu\beta\beta$  decay. The median sensitivity is reported as  $280 \times 10^{23}$  yr. Supersedes ADAMS 20A.

<sup>7</sup> ADAMS 22B use the CUORE bolometric calorimeter to place a limit on the  $0\nu\beta\beta$  decay half-life of  $^{128}\text{Te}$ .

<sup>8</sup> APRILE 22A use 36.16 kg·yr of  $^{136}\text{Xe}$  exposure of the XENON1T not enriched detector to establish the stated limit.

<sup>9</sup> AUGIER 22 use the final data set of the CUPID-Mo cryogenic calorimeter, utilizing enriched  $\text{Li}_2^{100}\text{MoO}_4$  and an isotope exposure of 1.47 kg·yr, to place a limit on the  $0\nu\beta\beta$  decay half-life.

<sup>10</sup> AZZOLINI 22 use the CUPID-0 scintillating cryogenic bolometer to set a limit on the  $0\nu\beta\beta$  half-life of  $^{82}\text{Se}$ . The analyzed isotope exposure is 8.82 kg·yr. A median sensitivity of  $7 \times 10^{24}$  yr is reported. Supersedes AZZOLINI 19.

<sup>11</sup> AZZOLINI 22 use CUPID-0 data with an isotope exposure of 8.82 kg·yr to set a limit on the  $0\nu\beta\beta$  decay to the first excited  $0^+$  state.

<sup>12</sup> AZZOLINI 22 use CUPID-0 data with an isotope exposure of 8.82 kg·yr to set a limit on the  $0\nu\beta\beta$  decay to the first excited  $2^+$  state.

- <sup>13</sup> AZZOLINI 22 use CUPID-0 data with an isotope exposure of 8.82 kg·yr to set a limit on the  $0\nu\beta\beta$  decay to the second excited  $2^+$  state.
- <sup>14</sup> ADAMS 21A et al. used 101.76 kg yr of  $^{130}\text{Te}$  exposure of the CUORE (LNGS) bolometric detector to place a limit on the decay to the first excited state of  $^{130}\text{Xe}$ , superseding ALDUINO 19 as the most restrictive bound on this particular decay.
- <sup>15</sup> ARMENGAUD 21 use the CUPID-Mo 4.2 kg array of enriched  $\text{Li}_2^{100}\text{MoO}_4$  scintillating bolometers, with 1.17 kg·yr exposure, to set this limit.
- <sup>16</sup> ARNQUIST 21 use the MAJORANA demonstrator to set this limit for the  $0\nu\beta\beta$  decay to the first excited  $0^+$  state, with a 41.9 kg yr isotopic exposure. The median sensitivity is  $39.9 \times 10^{23}$  yr.
- <sup>17</sup> ARNQUIST 21 use the MAJORANA demonstrator to set this limit for the  $0\nu\beta\beta$  decay to the first excited  $2^+$  state, with a 41.9 kg yr isotopic exposure. The median sensitivity is  $21.2 \times 10^{23}$  yr.
- <sup>18</sup> ARNQUIST 21 use the MAJORANA demonstrator to set this limit for the  $0\nu\beta\beta$  decay to the second excited  $2^+$  state, with a 41.9 kg yr isotopic exposure. The median sensitivity is  $18.6 \times 10^{23}$  yr.
- <sup>19</sup> ADAMS 20A use the CUORE detector to search for the  $0\nu\beta\beta$  decay of  $^{130}\text{Te}$ . The exposure was 372.5 kg·yr of  $\text{TeO}_2$  corresponding to 103.6 kg·yr of  $^{130}\text{Te}$ . The exclusion sensitivity is  $1.7 \times 10^{25}$ yr. Supersedes ALDUINO 18.
- <sup>20</sup> AGOSTINI 20B present the final data set of the GERDA experiment, searching for  $0\nu\beta\beta$  decay of  $^{76}\text{Ge}$  with isotopically enriched, high resolution Ge detectors. A final exposure of 127.2 kg·yr is reported. The experiment reports the lowest background and longest half life limit ever achieved by any double beta decay experiment. The reported experiment sensitivity equals the limit. Supersedes AGOSTINI 19.
- <sup>21</sup> 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  $^{130}\text{Te}$  to the first excited  $0^+$  state of  $^{130}\text{Xe}$ . Supersedes ANDREOTTI 12.
- <sup>22</sup> ALENKOV 19 report the  $0\nu\beta\beta$  decay half-life limit based on the 52.1 kg·d exposure of  $^{100}\text{Mo}$ , of a a cryogenic dual heat and light detector in the Yangyang underground laboratory. The median sensitivity is  $1.1 \times 10^{23}$  years.
- <sup>23</sup> 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  $5.0 \times 10^{25}$  yr. Supersedes ALBERT 18 and ALBERT 14B.
- <sup>24</sup> NI 19 use the PandaX-II dual phase TPC at CJPL to search for the  $0\nu\beta\beta$  decay of  $^{136}\text{Xe}$ . The half-life limit  $2.4 \times 10^{23}$  yr is obtained from 22.2 kg yr exposure with a sensitivity of  $1.9 \times 10^{23}$  yr.
- <sup>25</sup> ALDUINO 18 uses the CUORE detector to search for the  $0\nu\beta\beta$  decay of  $^{130}\text{Te}$ . The exposure is 86.3 kg·year of natural  $\text{TeO}_2$  corresponding to 24.0 kg·year for  $^{130}\text{Te}$ . The median sensitivity is  $0.7 \times 10^{25}$  yr. The limit is obtained combining the new data from CUORE with those of CUORE0 (9.8 kg·year of  $^{130}\text{Te}$ ) and Cuoricino (19.8 kg·year of  $^{130}\text{Te}$ ).
- <sup>26</sup> ARNOLD 18 use the NEMO-3 tracking detector to place a limit on the  $0\nu\beta\beta$  decay of  $^{82}\text{Se}$ . This is a slightly weaker limit than in BARABASH 11A, using the same detector. Supersedes ARNOLD 05A.
- <sup>27</sup> BARABASH 18 use 1.162 kg of  $^{116}\text{CdWO}_4$  scintillating crystals to obtain this limit. Supersedes DANEVICH 03 with analogous source and is more sensitive than ARNOLD 17.
- <sup>28</sup> ALBERT 17C uses the EXO-200 detector that contains  $19.098 \pm 0.014\%$  admixture of  $^{134}\text{Xe}$  to search for the  $0\nu$  and  $2\nu\beta\beta$  decay modes. The exposure is 29.6 kg·year. The median sensitivity is  $1.9 \times 10^{21}$  years.
- <sup>29</sup> ARNOLD 17 use the NEMO-3 tracking calorimeter, containing 410 g of enriched  $^{116}\text{Cd}$  exposed for 5.26 yr, to determine the half-life limit. Supersedes BARABASH 11A.

30 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.

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

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

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

34 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  $^{100}\text{Mo}$ . Supersedes ARNOLD 2005A and BARABASH 11A.

35 ANDREOTTI 12 use high resolution  $\text{TeO}_2$  bolometric calorimeter to search for the  $0\nu\beta\beta$  decay of  $^{130}\text{Te}$  leading to the excited  $0_1^+$  state at 1793.5 keV.

36 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.

37 Limit on  $0\nu$ -decay to the first excited  $0_1^+$ -state of daughter nucleus using NEMO-3 tracking calorimeter. Supersedes DASSIE 95.

38 Limit on  $0\nu$ -decay to the first excited  $2^+$ -state of daughter nucleus using NEMO-3 tracking calorimeter.

39 Supersedes ALESSANDRELLO 00. Array of  $\text{TeO}_2$  crystals in high resolution cryogenic calorimeter. Some enriched in  $^{128}\text{Te}$ . Ground state to ground state decay.

40 Limit on  $0\nu\beta\beta$  decay of  $^{116}\text{Cd}$  using enriched  $\text{CdWO}_4$  scintillators. Supersedes DANEVICH 00.

41 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.

Half-life measurements of the two-neutrino double- $\beta$  decay

The measured half-life values for the transitions  $(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}_e$  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 measurements with the smallest (or comparable) uncertainty for each transition.

| $t_{1/2}(10^{20} \text{ yr})$                                                 |                  |                    |  | ISOTOPE           | TRANSITION              | METHOD   | DOCUMENT ID |     |
|-------------------------------------------------------------------------------|------------------|--------------------|--|-------------------|-------------------------|----------|-------------|-----|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |                  |                    |  |                   |                         |          |             |     |
| 109                                                                           | ± 14             | ± 5                |  | $^{124}\text{Xe}$ | $2\nu\text{DEC}$        | LZ       | 1 AALBERS   | 24C |
| 20.22                                                                         | ± 0.18           | ± 0.38             |  | $^{76}\text{Ge}$  |                         | GERDA    | 2 AGOSTINI  | 23  |
| 1.11                                                                          | + 0.19<br>− 0.14 | + 0.17<br>− 0.15   |  | $^{150}\text{Nd}$ | $0^+ \rightarrow 0_1^+$ | NEMO-3   | 3 AGUERRE   | 23  |
| 7.5                                                                           | ± 0.8            | + 0.4<br>− 0.3     |  | $^{100}\text{Mo}$ | $0^+ \rightarrow 0_1^+$ | CUPID-Mo | 4 AUGIER    | 23  |
| 0.0707                                                                        | ± 0.0002         | ± 0.0011           |  | $^{100}\text{Mo}$ |                         | CUPID-Mo | 5 AUGIER    | 23A |
| 0.869                                                                         | ± 0.005          | + 0.009<br>− 0.006 |  | $^{82}\text{Se}$  |                         | CUPID-0  | 6 AZZOLINI  | 23A |
| 21.6                                                                          | + 6.2<br>− 4.0   | + 4.0<br>− 2.9     |  | $^{136}\text{Xe}$ |                         | NEXT     | 7 NOVELLA   | 23  |
| 21900                                                                         | ± 700            |                    |  | $^{128}\text{Te}$ |                         | CUORE    | 8 ADAMS     | 22B |
| 110                                                                           | ± 20             | ± 10               |  | $^{124}\text{Xe}$ |                         | XENON1T  | 9 APRILE    | 22A |
| 118                                                                           | ± 13             | ± 14               |  | $^{124}\text{Xe}$ |                         | XENONnT  | 10 APRILE   | 22B |

|        |        |                |        |                  |                                          |                       |                          |     |
|--------|--------|----------------|--------|------------------|------------------------------------------|-----------------------|--------------------------|-----|
| 23.4   | +<br>− | 0.8<br>4.6     | +<br>− | 3.0<br>1.7       | $^{136}\text{Xe}$                        | NEXT                  | <sup>11</sup> NOVELLA    | 22  |
| 8.76   | +<br>− | 0.09<br>0.07   | +<br>− | 0.14<br>0.17     | $^{130}\text{Te}$                        | CUORE                 | <sup>12</sup> ADAMS      | 21  |
| 180    | ±      | 50             | ±      | 10               | $^{124}\text{Xe } 2\nu\text{DEC}$        | XENON1T               | <sup>13</sup> APRILE     | 19E |
| 0.0680 | ±      | 0.0001         | +<br>− | 0.0038<br>0.0040 | $^{100}\text{Mo}$                        | NEMO-3                | <sup>14</sup> ARNOLD     | 19  |
| 0.939  | ±      | 0.017          | ±      | 0.058            | $^{82}\text{Se}$                         | NEMO-3                | <sup>15</sup> ARNOLD     | 18  |
| 0.263  | +<br>− | 0.011<br>0.012 |        |                  | $^{116}\text{Cd}$                        | AURORA                | <sup>16</sup> BARABASH   | 18  |
| > 0.87 |        |                |        |                  | $^{134}\text{Xe}$                        | EXO-200               | <sup>17</sup> ALBERT     | 17C |
| 8.2    | ±      | 0.2            | ±      | 0.6              | $^{130}\text{Te}$                        | CUORE-0               | <sup>18</sup> ALDUINO    | 17  |
| 0.274  | ±      | 0.004          | ±      | 0.018            | $^{116}\text{Cd}$                        | NEMO-3                | <sup>19</sup> ARNOLD     | 17  |
| 0.64   | +<br>− | 0.07<br>0.06   | +<br>− | 0.12<br>0.09     | $^{48}\text{Ca}$                         | NEMO-3                | <sup>20</sup> ARNOLD     | 16  |
| 0.0934 | ±      | 0.0022         | +<br>− | 0.0062<br>0.0060 | $^{150}\text{Nd}$                        | NEMO-3                | <sup>21</sup> ARNOLD     | 16A |
| 19.26  | ±      | 0.94           |        |                  | $^{76}\text{Ge}$                         | GERDA                 | <sup>22</sup> AGOSTINI   | 15A |
| 0.0693 | ±      | 0.0004         |        |                  | $^{100}\text{Mo}$                        | NEMO-3                | <sup>23</sup> ARNOLD     | 15  |
| 21.65  | ±      | 0.16           | ±      | 0.59             | $^{136}\text{Xe}$                        | EXO-200               | <sup>24</sup> ALBERT     | 14  |
| 92     | +<br>− | 55<br>26       | ±      | 13               | $^{78}\text{Kr}$                         | BAKSAN                | <sup>25</sup> GAVRILYAK  | 13  |
| 23.8   | ±      | 0.2            | ±      | 1.4              | $^{136}\text{Xe}$                        | KamLAND-Z             | <sup>26</sup> GANDO      | 12A |
| 7.0    | ±      | 0.9            | ±      | 1.1              | $^{130}\text{Te}$                        | NEMO-3                | <sup>27</sup> ARNOLD     | 11  |
| 0.235  | ±      | 0.014          | ±      | 0.016            | $^{96}\text{Zr}$                         | NEMO-3                | <sup>28</sup> ARGYRIADES | 10  |
| 6.9    | +<br>− | 1.0<br>0.8     | ±      | 0.7              | $^{100}\text{Mo } 0^+ \rightarrow 0_1^+$ | Ge coinc.             | <sup>29</sup> BELLI      | 10  |
| 5.7    | +<br>− | 1.3<br>0.9     | ±      | 0.8              | $^{100}\text{Mo } 0^+ \rightarrow 0_1^+$ | NEMO-3                | <sup>30</sup> ARNOLD     | 07  |
| 0.96   | ±      | 0.03           | ±      | 0.10             | $^{82}\text{Se}$                         | NEMO-3                | <sup>31</sup> ARNOLD     | 05A |
| 0.29   | +<br>− | 0.04<br>0.03   |        |                  | $^{116}\text{Cd}$                        | CdWO <sub>4</sub> sc. | <sup>32</sup> DANEVICH   | 03  |

<sup>1</sup> AALBERS 24C report the observation of  $^{124}\text{Xe } 2\nu\text{DEC}$ . 1.39 kg·yr of isotopic exposure of the LZ dark matter experiment, collected during the first science run, were analyzed. The same capture fractions as used in APRILE 22A were assumed.

<sup>2</sup> AGOSTINI 23 report an updated value for the  $2\nu \beta\beta$  half-life of  $^{76}\text{Ge}$ ; the final result of the GERDA Phase II experiment. A subset of the data, corresponding to an exposure of exposure is 11.8 kg·yr, is utilized. This is one of the most precise measurements of  $2\nu \beta\beta$  decay reported in the literature. An effective nuclear matrix element of  $0.101 \pm 0.001$  is derived from this result.

<sup>3</sup> AGUERRE 23 report the results of a 5.25 yr search for the  $2\nu \beta\beta$  decay to the excited  $0^+ \rightarrow 0_1^+$  state of the daughter nucleus, using the NEMO-3 tracking calorimeter. 36.6g of  $^{150}\text{Nd}$  isotope were available for the measurement of this decay rate.

<sup>4</sup> AUGIER 23 utilize the complete data, set collected by the CUPID-Mo bolometric calorimeter with particle ID and located at the LSM, to measure the  $^{100}\text{Mo } 2\nu\beta\beta$  half-life to excited  $0_1^+$  state of the daughter nucleus. An exposure of 1.47 kg·yr of  $^{100}\text{Mo}$  is available.

<sup>5</sup> AUGIER 23A use full data set collected by the CUPID-Mo experiment to derive an improved  $2\nu \beta\beta$  g.s. to g.s. half-life of  $^{100}\text{Mo}$ . An exposure of 1.48 kg·yr of  $^{100}\text{Mo}$  is utilized. Supersedes ARMENGAUD 20.

<sup>6</sup> AZZOLINI 23A report an improved measurement of the  $2\nu \beta\beta$  decay with an exposure of 8.82 kg·yr of  $^{82}\text{Se}$ , collected with the CUPID-0 detector. Supersedes AZZOLINI 19B.

- 7 NOVELLA 23 used the NEXT-White experiment, with a fiducial mass of 3.5 kg of enriched xenon, to measure the  $2\nu\beta\beta$  g.s. to g.s. half-life of  $^{136}\text{Xe}$ . The experiment is based on a high-pressure gas TPC. Supersedes NOVELLA 22.
- 8 ADAMS 22B derive the  $2\nu\beta\beta$  half-life of  $^{128}\text{Te}$  from data of the CUORE bolometric calorimeter and the half-life ratio for  $^{130}\text{Te} / ^{128}\text{Te}$  reported in BERNATOWICZ 92.
- 9 APRILE 22A report an improved  $^{124}\text{Xe}$   $2\nu\text{DEC}$  half-life measurement for  $^{124}\text{Xe}$ , using data collected by the XENON1T detector with an isotopically not enriched Xe target. The analyzed  $^{124}\text{Xe}$  exposure is 0.87 kg·yr. The statistical significance of the signal is 7.0 sigma. The stated half-life considers captures from the K shell up to the N5 shell. This result supersedes APRILE 19E, which exclusively considered captures from the K shell.
- 10 APRILE 22B use data collected by the XENONnT dark matter experiment to derive an improved  $^{124}\text{Xe}$   $2\nu\text{DEC}$  half-life measurement for  $^{124}\text{Xe}$ . This result supersedes APRILE 22A.
- 11 NOVELLA 22 report on a high-pressure gas TPC at Canfranc underground laboratory, filled with 3.5 kg (fiducial) xenon gas, used to measure the  $2\nu\beta\beta$  decay of  $^{136}\text{Xe}$ . Topological track reconstruction is utilized in the data analysis. The measurement is based on comparing runs with isotopically enriched and depleted xenon. Other measurements with smaller error exist.
- 12 ADAMS 21 use 102.7 kg yr of  $^{130}\text{Te}$  exposure, collected by the CUORE bolometric detector at LNGS, to perform a measurement of the  $2\nu\beta\beta$  decay of  $^{130}\text{Te}$ . The dataset is more than 10-times that collected by the CUORE-0 experiment. The result has been revised in ADAMS 23A. Supersedes ALDUINO 17.
- 13 APRILE 19E report first measurement of two-neutrino double electron capture in  $^{124}\text{Xe}$  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.
- 14 ARNOLD 19 use the NEMO-3 tracking calorimeter with 34.3 kg y exposure to determine the  $2\nu\beta\beta$  half-life of  $^{100}\text{Mo}$ . Supersedes ARNOLD 15.
- 15 ARNOLD 18 use the NEMO-3 tracking detector to determine the  $2\nu\beta\beta$  half-life of  $^{82}\text{Se}$ . 0.93 kg of  $^{82}\text{Se}$  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  $2\sigma$ . Supersedes ARNOLD 05A.
- 16 BARABASH 18 use 1.162 kg of  $^{116}\text{CdWO}_4$  scintillating crystals to obtain this value. Supersedes DANEVICH 03 with analogous source and agrees with ARNOLD 17 with the NEMO-3 detector.
- 17 ALBERT 17C uses the EXO-200 detector that contains  $19.098 \pm 0.014\%$  admixture of  $^{134}\text{Xe}$  to search for the  $2\nu\beta\beta$  decay mode. The exposure is 29.6 kg·year. The median sensitivity is  $1.2 \times 10^{21}$  years.
- 18 ALDUINO 17 use the CUORE-0 detector containing 10.8 kg of  $^{130}\text{Te}$  in 52 crystals of  $\text{TeO}_2$ . The exposure was 9.3 kg yr of  $^{130}\text{Te}$ . This is a more accurate rate determination than in ARNOLD 11 and BARABASH 11A.
- 19 ARNOLD 17 use the NEMO-3 tracking calorimeter, containing 410 grams of enriched  $^{116}\text{Cd}$  exposed for 5.26 years, to determine the half-life value.
- 20 ARNOLD 16 use the NEMO-3 detector and a source of 6.99 g of  $^{48}\text{Ca}$ . 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.
- 21 ARNOLD 16A use the NEMO-3 tracking calorimeter, containing 36.6 g of  $^{150}\text{Nd}$  exposed for 1918.5 days, to determine the half-life. Supersedes ARGYRIADES 09.
- 22 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  $^{76}\text{Ge}$ .
- 23 ARNOLD 15 use the NEMO-3 tracking calorimeter with 34.3 kg yr exposure to determine the  $2\nu\beta\beta$ -half life of  $^{100}\text{Mo}$ . Supersedes ARNOLD 05A and ARNOLD 04.

- <sup>24</sup> ALBERT 14 use the EXO-200 tracking detector for a re-measurement of the  $2\nu\beta\beta$ -half life of  $^{136}\text{Xe}$ . A nuclear matrix element of  $0.0218 \pm 0.0003 \text{ MeV}^{-1}$  is derived from this data. Supersedes ACKERMAN 11.
- <sup>25</sup> GAVRILYAK 13 use a proportional counter filled with Kr gas to search for the  $2\nu 2K$  decay of  $^{78}\text{Kr}$ . Data with the enriched and depleted Kr were used to determine signal and background. A  $2.5\sigma$  excess of events obtained with the enriched sample is interpreted as an indication for the presence of this decay.
- <sup>26</sup> GANDO 12A use a modification of the existing KamLAND detector. The  $\beta\beta$  decay source/detector is 13 tons of enriched  $^{136}\text{Xe}$ -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.
- <sup>27</sup> ARNOLD 11 use enriched  $^{130}\text{Te}$  in the NEMO-3 detector to measure the  $2\nu\beta\beta$  decay rate. This result is in agreement with, but more accurate than ARNABOLDI 03.
- <sup>28</sup> ARGYRIADES 10 use  $9.4 \pm 0.2 \text{ g}$  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>29</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>30</sup> 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.
- <sup>31</sup> 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.
- <sup>32</sup> DANEVICH 03 is calorimetric measurement of  $2\nu\beta\beta$  ground state decay of  $^{116}\text{Cd}$  using enriched  $\text{CdWO}_4$  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- $\beta$ Decay

$\langle m_{ee} \rangle = |\sum U_{ei}^2 m_{\nu_i}|$ ,  $i = 1, 2, 3$ . It is assumed that  $\nu_i$  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. ● ● ● |                   |             |                           |
| $< 0.036\text{--}0.156$                                                       | $^{136}\text{Xe}$ | KamLAND-Zen | <sup>1</sup> ABE 23       |
| $< 0.113\text{--}0.269$                                                       | $^{76}\text{Ge}$  | MAJORANA    | <sup>2</sup> ARNQUIST 23  |
| $< 0.48\text{--}3.19$                                                         | $^{136}\text{Xe}$ | NEXT        | <sup>3</sup> NOVELLA 23   |
| $< 0.09\text{--}0.305$                                                        | $^{130}\text{Te}$ | CUORE       | <sup>4</sup> ADAMS 22A    |
| $< 0.8\text{--}2.5$                                                           | $^{136}\text{Xe}$ | XENON1T     | <sup>5</sup> APRILE 22A   |
| $< 0.28\text{--}0.49$                                                         | $^{100}\text{Mo}$ | CUPID-Mo    | <sup>6</sup> AUGIER 22    |
| $< 0.263\text{--}0.545$                                                       | $^{82}\text{Se}$  | CUPID-0     | <sup>7</sup> AZZOLINI 22  |
| $< 0.31\text{--}0.54$                                                         | $^{100}\text{Mo}$ | CUPID-Mo    | <sup>8</sup> ARMENGAUD 21 |
| $< 0.075\text{--}0.35$                                                        | $^{130}\text{Te}$ | CUORE       | <sup>9</sup> ADAMS 20A    |

|               |                   |                                         |                          |                |
|---------------|-------------------|-----------------------------------------|--------------------------|----------------|
| < 0.079–0.180 | <sup>76</sup> Ge  | GERDA                                   | <sup>10</sup> AGOSTINI   | <sup>20B</sup> |
| < 1.2–2.1     | <sup>100</sup> Mo | AMoRE                                   | <sup>11</sup> ALENKOV    | 19             |
| < 0.093–0.286 | <sup>136</sup> Xe | EXO-200                                 | <sup>12</sup> ANTON      | 19             |
| < 1.3–3.5     | <sup>136</sup> Xe | PANDAX-II                               | <sup>13</sup> NI         | 19             |
| < 0.11–0.52   | <sup>130</sup> Te | CUORE                                   | <sup>14</sup> ALDUINO    | 18             |
| < 1.2–3.0     | <sup>82</sup> Se  | NEMO-3                                  | <sup>15</sup> ARNOLD     | 18             |
| < 1.0–1.7     | <sup>116</sup> Cd | AURORA                                  | <sup>16</sup> BARABASH   | 18             |
| < 1.4–2.5     | <sup>116</sup> Cd | NEMO-3                                  | <sup>17</sup> ARNOLD     | 17             |
| < 0.27–0.76   | <sup>130</sup> Te | CUORICINO                               | <sup>18</sup> ALDUINO    | 16             |
| < 1.6–5.3     | <sup>150</sup> Nd | NEMO-3                                  | <sup>19</sup> ARNOLD     | 16A            |
| < 0.33–0.62   | <sup>100</sup> Mo | NEMO-3                                  | <sup>20</sup> ARNOLD     | 15             |
| < 7.2–19.5    | <sup>96</sup> Zr  | NEMO-3                                  | <sup>21</sup> ARGYRIADES | 10             |
| < 3.5–22      | <sup>48</sup> Ca  | CaF <sub>2</sub> scint.                 | <sup>22</sup> UMEHARA    | 08             |
| < 1.5–1.7     | <sup>116</sup> Cd | <sup>116</sup> CdWO <sub>4</sub> scint. | <sup>23</sup> DANEVICH   | 03             |

<sup>1</sup> ABE 23 utilize 745 kg of <sup>136</sup>Xe isotope exposure from the combined data set of the KamLAND-Zen 400 and 800 to derive a limit on  $\langle m_{\beta\beta} \rangle$ . The range reflects the author's assessment of the variability of the theoretically calculated nuclear matrix elements.

<sup>2</sup> ARNQUIST 23 use the final data set of the MAJORANA DEMONSTRATOR experiment, with 64.5 kg·yr of isotop exposure, to derive an upper limit for  $\langle m_{\beta\beta} \rangle$ . The range reflects the author's assessment of the variability of the theoretically calculated nuclear matrix elements.

<sup>3</sup> NOVELLA 23 use data collected with the NEXT-White experiment to derive a range of upper limits for  $\langle m_{\beta\beta} \rangle$ . The range reflects the author's assessment of the variability of the theoretically calculated nuclear matrix elements and both half-life limits stated in NOVELLA 23.

<sup>4</sup> ADAMS 22A use 1038.4 kg·yr of TeO<sub>2</sub> exposure collected by the CUORE experiment to determine this range of limits. The range reflects the uncertainty of nuclear matrix element calculations needed for the conversion of half-life to neutrino mass.

<sup>5</sup> APRILE 22A use data taken with the XENON1T detector to limit the Majorana neutrino mass. 36.16 kg·yr of <sup>136</sup>Xe exposure were utilized. The reported range of limits is due to uncertainties in the nuclear matrix elements.

<sup>6</sup> AUGIER 22 use the final data set of the CUPID-Mo cryogenic calorimeter with an isotop exposure of 1.47 kg·y to derive a range of neutrino mass limits. The range reflects the authors' estimate of the spread of nuclear matrix element calculations.

<sup>7</sup> AZZOLINI 22 use 8.82 kg·yr of isotopic exposure of the CPID-0 scintillating cryogenic bolometer to set this range of neutrino mass limits. The range reflects the authors' estimate of the spread of nuclear matrix element calculations.

<sup>8</sup> ARMENGAUD 21 use the CUPID-Mo demonstrator, with 1.17 kg·yr exposure of <sup>100</sup>Mo, to set this limit. The range reflects the estimated uncertainty of the calculated nuclear matrix elements.

<sup>9</sup> ADAMS 20A use the data of CUORE (372.5 kg·yr exposure of TeO<sub>2</sub>) to obtain this limit.

<sup>10</sup> AGOSTINI 20B use the final data set of the GERDA experiment, representing an exposure of 127.2 kg·yr to derive an upper limit for  $\langle m_{\beta\beta} \rangle$ . Isotopically enriched Ge detectors were used. The range reflects the variability of the theoretically calculated nuclear matrix elements. Supersedes AGOSTINI 19.

<sup>11</sup> ALENKOV 19 report the range of the effective masses  $\langle m_{\beta\beta} \rangle$  corresponding to the  $0\nu\beta\beta$  decay half-life limit. It is based on the 52.1 kg·d exposure of <sup>100</sup>Mo, in the Yangyang underground laboratory. The median sensitivity is  $1.1 \times 10^{23}$  years. The range of  $\langle m_{\beta\beta} \rangle$  reflects the uncertainty of nuclear matrix elements.

<sup>12</sup> 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.



- <sup>13</sup>NI 19 use the PandaX-II dual phase TPC at CJPL to search for the  $0\nu\beta\beta$  decay of  $^{136}\text{Xe}$  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  $1.9 \times 10^{23}$  yr.
- <sup>14</sup>ALDUINO 18 use the combined data of CUORE, CUORE0, and Cuoricino to obtain this limit.
- <sup>15</sup>ARNOLD 18 use the NEMO-3 tracking detector to constrain the  $0\nu\beta\beta$  decay of  $^{82}\text{Se}$ . 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.
- <sup>16</sup>BARABASH 18 use 1.162 kg of  $^{116}\text{CdWO}_4$  scintillating crystals to obtain these limits. The spread reflects the estimated uncertainty in the nuclear matrix element. Supersedes DANEVICH 03.
- <sup>17</sup>ARNOLD 17 utilize NEMO-3 data, taken with enriched  $^{116}\text{Cd}$  to limit the effective Majorana neutrino mass. The reported range results from the use of different nuclear matrix elements. Supersedes BARABASH 11A.
- <sup>18</sup>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. Supersedes ALFONSO 15.
- <sup>19</sup>ARNOLD 16A limit is derived from 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. Supersedes ARGYRADES 09.
- <sup>20</sup>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  $^{100}\text{Mo}$ . The spread range reflects different nuclear matrix elements. Supersedes ARNOLD 14 and BARABASH 11A.
- <sup>21</sup>ARGYRADES 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>22</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>23</sup>Limit for  $\langle m_{\nu} \rangle$  is based on the nuclear matrix elements of STAUDT 90 and ARNOLD 96. Supersedes DANEVICH 00.

### Limits on Lepton-Number Violating ( $V+A$ ) Current Admixture

Considering that a number of experiments earlier than 1989 did not distinguish between  $\lambda$  and  $\eta$ , we list only results from that year on.  $\langle \lambda \rangle = \lambda \sum U_{ej} V_{ej}$  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. ● ● ● |     |                                  |     |                   |                              |                               |
| $< 2.2\text{--}2.6$                                                           | 90  | $< 1.7\text{--}2.1$              | 90  | $^{82}\text{Se}$  | NEMO-3                       | <sup>1</sup> ARNOLD 18        |
| $< 1.8\text{--}22$                                                            | 90  | $< 1.6\text{--}21$               | 90  | $^{116}\text{Cd}$ | AURORA                       | <sup>2</sup> BARABASH 18      |
| $< 0.9\text{--}1.3$                                                           | 90  | $< 0.5\text{--}0.8$              | 90  | $^{100}\text{Mo}$ | NEMO-3                       | <sup>3</sup> ARNOLD 14        |
| $< 120$                                                                       | 90  |                                  |     | $^{100}\text{Mo}$ | $0^+ \rightarrow 2^+$        | <sup>4</sup> ARNOLD 07        |
| $0.692^{+0.058}_{-0.056}$                                                     | 68  | $0.305^{+0.026}_{-0.025}$        | 68  | $^{76}\text{Ge}$  | Enriched HPGe                | <sup>5</sup> KLAPDOR-K... 06A |
| $< 2.5$                                                                       | 90  |                                  |     | $^{100}\text{Mo}$ | $0\nu$ , NEMO-3              | <sup>6</sup> ARNOLD 05A       |
| $< 3.8$                                                                       | 90  |                                  |     | $^{82}\text{Se}$  | $0\nu$ , NEMO-3              | <sup>7</sup> ARNOLD 05A       |
| $< 1.5\text{--}2.0$                                                           | 90  |                                  |     | $^{100}\text{Mo}$ | $0\nu$ , NEMO-3              | <sup>8</sup> ARNOLD 04        |
| $< 3.2\text{--}3.8$                                                           | 90  |                                  |     | $^{82}\text{Se}$  | $0\nu$ , NEMO-3              | <sup>9</sup> ARNOLD 04        |
| $< 1.6\text{--}2.4$                                                           | 90  | $< 0.9\text{--}5.3$              | 90  | $^{130}\text{Te}$ | Cryog. det.                  | <sup>10</sup> ARNABOLDI 03    |
| $< 2.2$                                                                       | 90  | $< 2.5$                          | 90  | $^{116}\text{Cd}$ | $^{116}\text{CdWO}_4$ scint. | <sup>11</sup> DANEVICH 03     |

|           |    |           |    |                   |               |                           |    |
|-----------|----|-----------|----|-------------------|---------------|---------------------------|----|
| < 3.2–4.7 | 90 | < 2.4–2.7 | 90 | <sup>100</sup> Mo | ELEGANT V     | <sup>12</sup> EJIRI       | 01 |
| < 1.1     | 90 | <0.64     | 90 | <sup>76</sup> Ge  | Enriched HPGe | <sup>13</sup> GUENTHER    | 97 |
| < 4.4     | 90 | <2.3      | 90 | <sup>136</sup> Xe | TPC           | <sup>14</sup> VUILLEUMIER | 93 |
|           |    | <5.3      |    | <sup>128</sup> Te | Geochem       | <sup>15</sup> BERNATOW... | 92 |

- <sup>1</sup> ARNOLD 18 use the NEMO03 tracking detector, with 0.93 kg of <sup>82</sup>Se mass and 5.25 y exposure to obtain the limits for the hypothetical right-handed currents. Supersedes ARNOLD 05A.
- <sup>2</sup> BARABASH 18 use 1.162 kg of <sup>116</sup>CdWO<sub>4</sub> scintillating crystals to obtain this limits for the hypothetical right-handed currents in the  $0\nu\beta\beta$  decay of <sup>116</sup>Cd.
- <sup>3</sup> 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 <sup>100</sup>Mo.
- <sup>4</sup> ARNOLD 07 use NEMO-3 half life limit for  $0\nu$ -decay of <sup>100</sup>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.
- <sup>5</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 MUTO 89 to determine  $\langle\lambda\rangle$  and  $\langle\eta\rangle$ . Uncertainty of nuclear matrix element is not reflected in stated errors.
- <sup>6</sup> ARNOLD 05A derive limit for  $\langle\lambda\rangle$  based on <sup>100</sup>Mo data collected with NEMO-3 detector. No limit for  $\langle\eta\rangle$  is given. Supersedes ARNOLD 04.
- <sup>7</sup> ARNOLD 05A derive limit for  $\langle\lambda\rangle$  based on <sup>82</sup>Se data collected with NEMO-3 detector. No limit for  $\langle\eta\rangle$  is given. Supersedes ARNOLD 04.
- <sup>8</sup> 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.
- <sup>9</sup> 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.
- <sup>10</sup> Supersedes ALESSANDRELLO 00. Cryogenic calorimeter search. Reported a range reflecting uncertainty in nuclear matrix element calculations.
- <sup>11</sup> Limits for  $\langle\lambda\rangle$  and  $\langle\eta\rangle$  are based on nuclear matrix elements of STAUDT 90. Supersedes DANEVICH 00.
- <sup>12</sup> 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.
- <sup>13</sup> GUENTHER 97 limits use the matrix elements of STAUDT 90. Supersedes BALYSH 95 and BALYSH 92.
- <sup>14</sup> VUILLEUMIER 93 uses the matrix elements of MUTO 89. Based on a half-life limit  $2.6 \times 10^{23}$  y at 90%CL.
- <sup>15</sup> 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

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| YAN      | 24  | PRL 132 152502          | X. Yan <i>et al.</i>        | (PandaX-4T Collab.)   |
| ABE      | 23  | PRL 130 051801          | S. Abe <i>et al.</i>        | (KamLAND-Zen Collab.) |
| ADAMS    | 23A | PRL 131 249902 (errat.) | D.Q. Adams <i>et al.</i>    | (CUORE Collab.)       |
| AGOSTINI | 23  | PRL 131 142501          | M. Agostini <i>et al.</i>   | (GERDA Collab.)       |
| AGUERRE  | 23  | EPJ C83 1117            | X. Aguerre <i>et al.</i>    | (NEMO-3 Collab.)      |
| ARNQUIST | 23  | PRL 130 062501          | I.J. Arnquist <i>et al.</i> | (MAJORANA Collab.)    |
| AUGIER   | 23  | PR C107 025503          | C. Augier <i>et al.</i>     | (CUPID-Mo Collab.)    |
| AUGIER   | 23A | PRL 131 162501          | C. Augier <i>et al.</i>     | (CUPID-Mo Collab.)    |
| AZZOLINI | 23A | PRL 131 222501          | O. Azzolini <i>et al.</i>   | (CUPID-0 Collab.)     |
| NOVELLA  | 23  | JHEP 2309 190           | P. Novella <i>et al.</i>    | (NEXT Collab.)        |
| ADAMS    | 22A | NAT 604 53              | D.Q. Adams <i>et al.</i>    | (CUORE Collab.)       |

|               |     |                               |                                                        |                             |
|---------------|-----|-------------------------------|--------------------------------------------------------|-----------------------------|
| ADAMS         | 22B | PRL 129 222501                | D.Q. Adams <i>et al.</i>                               | (CUORE Collab.)             |
| APRILE        | 22A | PR C106 024328                | E. Aprile <i>et al.</i>                                | (XENON1T Collab.)           |
| APRILE        | 22B | PRL 129 161805                | E. Aprile <i>et al.</i>                                | (XENONnT Collab.)           |
| AUGIER        | 22  | EPJ C82 1033                  | C. Augier <i>et al.</i>                                | (CUPID-Mo Collab.)          |
| AZZOLINI      | 22  | PRL 129 111801                | O. Azzolini <i>et al.</i>                              | (CUPID-0 Collab.)           |
| NOVELLA       | 22  | PR C105 055501                | P. Novella <i>et al.</i>                               | (NEXT Collab.)              |
| ADAMS         | 21  | PRL 126 171801                | D.Q. Adams <i>et al.</i>                               | (CUORE Collab.)             |
| Also          |     | PRL 131 249902 (errat.)       | D.Q. Adams <i>et al.</i>                               | (CUORE Collab.)             |
| ADAMS         | 21A | EPJ C81 567                   | D.Q. Adams <i>et al.</i>                               | (CUORE Collab.)             |
| ARMENGAUD     | 21  | PRL 126 181802                | E. Armengaud <i>et al.</i>                             | (CUPID-Mo Collab.)          |
| ARNQUIST      | 21  | PR C103 015501                | I.J. Arnquist <i>et al.</i>                            | (MAJORANA Collab.)          |
| ADAMS         | 20A | PRL 124 122501                | D.Q. Adams <i>et al.</i>                               | (CUORE Collab.)             |
| AGOSTINI      | 20B | PRL 125 252502                | M. Agostini <i>et al.</i>                              | (GERDA Collab.)             |
| ARMENGAUD     | 20  | EPJ C80 674                   | E. Armengaud <i>et al.</i>                             | (CUPID-Mo Collab.)          |
| AGOSTINI      | 19  | SCI 365 1445                  | M. Agostini <i>et al.</i>                              | (GERDA Collab.)             |
| ALDUINO       | 19  | EPJ C79 795                   | C. Alduino <i>et al.</i>                               | (CUORE Collab.)             |
| ALENKOV       | 19  | EPJ C79 791                   | V. Alenkov <i>et al.</i>                               | (AMoRE Collab.)             |
| ANTON         | 19  | PRL 123 161802                | G. Anton <i>et al.</i>                                 | (EXO-200 Collab.)           |
| APRILE        | 19E | NAT 568 532                   | E. Aprile <i>et al.</i>                                | (XENON1T Collab.)           |
| ARNOLD        | 19  | EPJ C79 440                   | R. Arnold <i>et al.</i>                                | (NEMO-3 Collab.)            |
| AZZOLINI      | 19  | PRL 123 032501                | O. Azzolini <i>et al.</i>                              | (CUPID-0 Collab.)           |
| AZZOLINI      | 19B | PRL 123 262501                | O. Azzolini <i>et al.</i>                              | (CUPID-0 Collab.)           |
| NI            | 19  | CP C43 113001                 | K. Ni <i>et al.</i>                                    | (PandaX-II Collab.)         |
| ALBERT        | 18  | PRL 120 072701                | J.B. Albert <i>et al.</i>                              | (EXO-200 Collab.)           |
| ALDUINO       | 18  | PRL 120 132501                | C. Alduino <i>et al.</i>                               | (CUORE Collab.)             |
| ARNOLD        | 18  | EPJ C78 821                   | R. Arnold <i>et al.</i>                                | (NEMO-3 Collab.)            |
| BARABASH      | 18  | PR D98 092007                 | A.S. Barabash <i>et al.</i>                            | (AURORA Collab.)            |
| ALBERT        | 17C | PR D96 092001                 | J.B. Albert <i>et al.</i>                              | (EXO-200 Collab.)           |
| ALDUINO       | 17  | EPJ C77 13                    | C. Alduino <i>et al.</i>                               | (CUORE Collab.)             |
| ARNOLD        | 17  | PR D95 012007                 | R. Arnold <i>et al.</i>                                | (NEMO-3 Collab.)            |
| ALDUINO       | 16  | PR C93 045503                 | C. Alduino <i>et al.</i>                               | (CUORE Collab.)             |
| ARNOLD        | 16  | PR D93 112008                 | R. Arnold <i>et al.</i>                                | (NEMO-3 Collab.)            |
| ARNOLD        | 16A | PR D94 072003                 | R. Arnold <i>et al.</i>                                | (NEMO-3 Collab.)            |
| ASAKURA       | 16  | NP A946 171                   | K. Asakura <i>et al.</i>                               | (KamLAND-Zen Collab.)       |
| AGOSTINI      | 15A | EPJ C75 416                   | M. Agostini <i>et al.</i>                              | (GERDA Collab.)             |
| ALFONSO       | 15  | PRL 115 102502                | K. Alfonso <i>et al.</i>                               | (CUORE Collab.)             |
| ARNOLD        | 15  | PR D92 072011                 | R. Arnold <i>et al.</i>                                | (NEMO-3 Collab.)            |
| ALBERT        | 14  | PR C89 015502                 | J. Albert <i>et al.</i>                                | (EXO-200 Collab.)           |
| ALBERT        | 14B | NAT 510 229                   | J.B. Albert <i>et al.</i>                              | (EXO-200 Collab.)           |
| ARNOLD        | 14  | PR D89 111101                 | R. Arnold <i>et al.</i>                                | (NEMO-3 Collab.)            |
| GAVRILYAK     | 13  | PR C87 035501                 | Yu.M. Gavriluk <i>et al.</i>                           |                             |
| ANDREOTTI     | 12  | PR C85 045503                 | E. Andreotti <i>et al.</i>                             | (CUORICINO Collab.)         |
| GANDO         | 12A | PR C85 045504                 | A. Gando <i>et al.</i>                                 | (KamLAND-Zen Collab.)       |
| ACKERMAN      | 11  | PRL 107 212501                | N. Ackerman <i>et al.</i>                              | (EXO Collab.)               |
| ARNOLD        | 11  | PRL 107 062504                | R. Arnold <i>et al.</i>                                | (NEMO-3 Collab.)            |
| BARABASH      | 11A | PAN 74 312                    | A.S. Barabash <i>et al.</i>                            | (NEMO-3 Collab.)            |
| ARGYRIADES    | 10  | Translated from YAF 74 330.   |                                                        |                             |
| BELLI         | 10  | NP A847 168                   | J. Argyriades <i>et al.</i>                            | (NEMO-3 Collab.)            |
| ARGYRIADES    | 09  | NP A846 143                   | P. Belli <i>et al.</i>                                 | (DAMA-INR Collab.)          |
| ARGYRIADES    | 09  | PR C80 032501                 | J. Argyriades <i>et al.</i>                            | (NEMO-3 Collab.)            |
| KIDD          | 09  | NP A821 251                   | M. Kidd <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.)            |
| KLAPDOR-K...  | 06A | MPL A21 1547                  | H.V. Klapdor-Kleingrothaus, I.V. Krivosheina           |                             |
| 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>                             |                             |
| ARNOLD        | 04  | JETPL 80 377                  | R. Arnold <i>et al.</i>                                | (NEMO-3 Collab.)            |
| KLAPDOR-K...  | 04A | Translated from ZETFP 80 429. |                                                        |                             |
| KLAPDOR-K...  | 04B | PL B586 198                   | H.V. Klapdor-Kleingrothaus <i>et al.</i>               |                             |
| OGAWA         | 04  | PR D70 078301                 | H.V. Klapdor-Kleingrothaus, A. Dietz, I.V. Krivosheina |                             |
| ARNABOLDI     | 03  | NP A730 215                   | I. Ogawa <i>et al.</i>                                 |                             |
| DANEVICH      | 03  | PL B557 167                   | C. Arnaboldi <i>et al.</i>                             |                             |
| AALSETH       | 02B | PR C68 035501                 | F.A. Danevich <i>et al.</i>                            |                             |
| DEBRAECKEL... | 01  | PR D65 092007                 | C.E. Aalseth <i>et al.</i>                             | (IGEX Collab.)              |
| EJIRI         | 01  | PRL 86 3510                   | L. De Braeckeeler <i>et al.</i>                        |                             |
| KLAPDOR-K...  | 01  | PR C63 065501                 | H. Ejiri <i>et al.</i>                                 |                             |
| KLAPDOR-K...  | 01B | EPJ A12 147                   | H.V. Klapdor-Kleingrothaus <i>et al.</i>               |                             |
| ALESSAND...   | 00  | MPL A16 2409                  | H.V. Klapdor-Kleingrothaus <i>et al.</i>               |                             |
| DANEVICH      | 00  | PL B486 13                    | A. Alessandrello <i>et al.</i>                         |                             |
| ARNOLD        | 99  | PR C62 045501                 | F.A. Danevich <i>et al.</i>                            |                             |
| GUENTHER      | 97  | NP A658 299                   | R. Arnold <i>et al.</i>                                | (NEMO Collab.)              |
|               |     | PR D55 54                     | M. Gunther <i>et al.</i>                               | (Heidelberg-Moscow Collab.) |

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|-------------|----|---------------|------------------------------------------------|-----------------------------|
| ARNOLD      | 96 | ZPHY C72 239  | R. Arnold <i>et al.</i>                        | (BCEN, CAEN, JINR+)         |
| BALYSH      | 95 | PL B356 450   | A. Balysh <i>et al.</i>                        | (Heidelberg-Moscow Collab.) |
| 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)                |
| SUHONEN     | 94 | PR C49 3055   | J. Suhonen, O. Civitarese                      |                             |
| BERNATOW... | 93 | PR C47 806    | T. Bernatowicz <i>et al.</i>                   | (WUSL, TATA)                |
| 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>                        | (MPIK, KIAE, SASSO)         |
| BERNATOW... | 92 | PRL 69 2341   | T. Bernatowicz <i>et al.</i>                   | (WUSL, TATA)                |
| SUHONEN     | 91 | NP A535 509   | J. Suhonen, S.B. Khadkikar, A. Faessler        | (JYV+)                      |
| TOMODA      | 91 | RPP 54 53     | T. Tomoda                                      |                             |
| 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, MPIK)                |

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