AVERAGE AND RECOMMENDED
HALF-LIFE VALUES FOR TWO
NEUTRINO DOUBLE BETA DECAY:
UPGRADE ’05

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Abstract

All existing “positive” results on two neutrino double beta decay in different nuclei were analyzed. Using the procedure recommended by the Particle Data Group, weighted average values for half-lives of $^{48}$Ca, $^{76}$Ge, $^{82}$Se, $^{96}$Zr, $^{100}$Mo, $^{100}$Mo - $^{100}$Ru ($0^+_1$), $^{116}$Cd, $^{150}$Nd, $^{150}$Nd - $^{150}$Sm ($0^+_1$) and $^{238}$U were obtained. Existing geochemical data were analyzed and recommended values for half-lives of $^{128}$Te, $^{130}$Te and $^{130}$Ba are proposed. We recommend the use of these results as presently the most precise and reliable values for half-lives.

1 Introduction

At present, the two neutrino double beta ($2\nu\beta\beta$) decay process has been detected in a total of 10 different nuclei. In $^{100}$Mo and $^{150}$Nd, this type of decay was also detected for the transition to the $0^+$ excited state of the daughter nucleus. For the case of the $^{130}$Ba nucleus, evidence for the two neutrino double electron capture process was observed via a geochemical experiment. All of these results were obtained in a few tens of geochemical experiments, more then twenty direct (counting) experiments, and in one radiochemical experiment. In direct experiments, for some nuclei there are as many as
seven independent positive results (e.g., $^{100}$Mo). In some experiments, the statistical error does not always play the primary role in overall half-life uncertainties. For example, the NEMO-3 experiment with $^{100}$Mo detected more than 219000 useful events [1], which results in a value for the statistical error of $\sim 0.2\%$. At the same time, the systematic error in many other experiments on $2\nu\beta\beta$ decay generally remains quite high ($\sim 10 - 30\%$) and very often cannot be determined very reliably. As a result, it is frequently quite difficult for the “user” to select the “best” half-life value among all existing results. In fact, however, using an averaging procedure, one can produce reliable and accurate half-life values for each isotope.

In the present work, a critical analysis of all “positive” experimental results has been performed, and averaged (or recommended) values for all isotopes have been obtained.

The first time that this type of work was done was in 2001, and the results were presented at MEDEX’01 [2]. In the present paper, new positive results obtained since 2001 have been added and analyzed.

2 Present experimental data

Experimental results on $2\nu\beta\beta$ decay in different nuclei are presented in Table 1. For direct experiments, the number of useful events and the signal-to-background ratio are presented.

3 Data analysis

To obtain an average of the available data, a standard weighted least-squares procedure, as recommended by the Particle Data Group [37], was used. The weighted average and the corresponding error were calculated, as follows:

$$\bar{x} \pm \delta \bar{x} = \frac{\sum w_i x_i}{\sum w_i} \pm \left(\sum w_i\right)^{-1/2}, \quad (1)$$

where $w_i = 1/(\delta x_i)^2$. Here, $x_i$ and $\delta x_i$ are, respectively, the value and error reported by the i-th experiment, and the summations run over the N experiments.

The following step is to calculate $\chi^2 = \sum w_i (\bar{x} - x_i)^2$ and compare it with $N - 1$, which is the expectation value of $\chi^2$ if the measurements are from a Gaussian distribution. If $\chi^2/(N - 1)$ is less than or equal to 1, and there are
Table 1: Present, “positive” $2\nu\beta\beta$ decay results. Here, N is the number of useful events, S/B is the signal-to-background ratio. *) After correction (see text). **) For HSD mechanism.

| Nucleus | N  | $T_{1/2}, \text{y}$                                                                 | S/B | Ref., year |
|---------|----|-------------------------------------------------------------------------------------|-----|------------|
| $^{48}\text{Ca}$ | ~100 | $[4.3^{+2.4}_{-1.1} \text{(stat)} \pm 1.4 \text{(syst)}] \cdot 10^{19}$ 4.2$^{+3.3}_{-1.3} \cdot 10^{19}$ | 1/5 | [3], 1996  |
|         | 5   | $\text{Average value: } 4.2^{+2.1}_{-1.0} \cdot 10^{19}$                          | 5/0 | [4], 2000  |
| $^{76}\text{Ge}$ | ~4000 | $(0.9 \pm 0.1) \cdot 10^{21}$ 1.1$^{+0.6}_{-0.3} \cdot 10^{21}$ 0.93$^{+0.2}_{-0.1} \cdot 10^{21}$ 1.2$^{+0.2}_{-0.1} \cdot 10^{21}$ | ~1/8 | [5], 1990  |
|         | 758 |                                     | ~1/6 | [6], 1991  |
|         | 132 |                                     | ~4   | [7], 1991  |
|         | 132 |                                     | ~4   | [8], 1994  |
|         | ~3000 | $[1.45 \pm 0.15] \cdot 10^{21}$ 1.74$^{+0.01}_{-0.01} \text{(stat)} \pm 0.18 \text{(syst)} \cdot 10^{21}$ | ~1.5 | [9], 1999  |
|         | ~8000 |                                     | ~1.5 | [10], 2003 |
| $^{82}\text{Se}$ | 149.1 | $0.83 \pm 0.10\text{(stat)} \pm 0.07\text{(syst)} \cdot 10^{20}$ 1.08$^{+0.26}_{-0.06} \cdot 10^{20}$ | 2.3 | [11], 1998 |
|         | 89.6 |                                     | ~8   | [12], 1992 |
|         | 2750 |                                     | 4    | [13], 2005 |
|         |      | $[0.96 \pm 0.03\text{(stat)} \pm 0.1\text{(syst)}] \cdot 10^{20}$ 1.3$^{+0.05}_{-0.05} \cdot 10^{20}$ (geochem.) |      | [14], 1986 |
| $^{96}\text{Zr}$ | 26.7 | $[2.1^{+0.8}_{-0.4}\text{(stat)} \pm 0.2\text{(syst)}] \cdot 10^{19}$ 2.0$^{+0.3}_{-0.2} \text{(stat)} \pm 0.2\text{(syst)} \cdot 10^{19}$ 3.9$^{+0.9}_{-0.9} \cdot 10^{19}$ (geochem.) 0.94$^{+0.32}_{-0.32} \cdot 10^{19}$ (geochem.) | 1.9 | [15], 1999 |
|         | 72   |                                     | 0.9  | [16], 2005 |
|         |      | $\text{Average value: } (0.92 \pm 0.07) \cdot 10^{20}$                          |      | [17], 1993 |
|         |      |                                     |      | [18], 2001 |
| $^{100}\text{Mo}$ | ~500 | $11.5^{+3.0}_{-2.0} \cdot 10^{18}$ 11.6$^{+3.4}_{-0.8} \cdot 10^{18}$ 7.3$^{+0.35}_{-0.35} \text{(stat)} \pm 0.8\text{(syst)} \cdot 10^{18}$ 7.6$^{+2.2}_{-1.4} \cdot 10^{18}$ | 1/7 | [19], 1991 |
|         | 67   |                                     | 7    | [20], 1991 |
|         | 1433 |                                     | 3    | [21], 1995 |
|         | 175  |                                     | 1/2  | [22], 1997 |
|         | 377  |                                     | 10   | [23], 2001 |
|         | 800  |                                     | 1/9  | [24], 2005 |
|         | 219000 |                                     | 40   | [25], 2004 |
|         |      | $\text{Average value: } (7.1 \pm 0.4) \cdot 10^{18}$                          |      |            |
Table 1: continued.

|          |       |            |            |            |            |            |            |            |            |
|----------|-------|------------|------------|------------|------------|------------|------------|------------|------------|
|          |       |            |            |            |            |            |            |            |            |
| $^{100}$Mo - $^{100}$Ru ($0^+_1$) | 66    | $6.1^{+0.8}_{-0.7} \cdot 10^{20}$ | $[9.3^{+2.8}_{-1.7}(\text{stat}) \pm 1.4(\text{syst})] \cdot 10^{20}$ | $5.9^{+1.7}_{-1.1}(\text{stat}) \pm 0.6(\text{syst})] \cdot 10^{20}$ | 1/7 | 25 | 1995 |
|          |       |            |            |            |            |            |            |            |            |
|          |       |            |            |            |            |            |            |            |            |
| $^{116}$Cd | ~ 180 | $2.6^{+0.9}_{-0.5} \cdot 10^{19}$ | $[2.9 \pm 0.06(\text{stat})^{+0.4}_{-0.3}(\text{syst})] \cdot 10^{19}$ | $[3.2 \pm 0.3(\text{stat}) \pm 0.2(\text{syst})] \cdot 10^{19}$ | 1/4 | 28 | 1995 |
|          |       |            |            |            |            |            |            |            |            |
|          |       |            |            |            |            |            |            |            |            |
|          |       |            |            |            |            |            |            |            |            |
| $^{128}$Te | ~ 220 | $2.1 \cdot 10^{24}$ | $[7.7 \pm 0.4] \cdot 10^{24}$ | $[0.9 \pm 0.1] \cdot 10^{24}$ | 1/4 | 29 | 2003 |
|          |       |            |            |            |            |            |            |            |            |
| $^{130}$Te | ~ 0.8 | $0.8 \cdot 10^{21}$ | $[2.7 \pm 0.1] \cdot 10^{21}$ | $[0.9 \pm 0.1] \cdot 10^{21}$ | 1/4 | 30 | 1996 |
|          |       |            |            |            |            |            |            |            |            |
| $^{150}$Nd | 23    | $18.8^{+6.9}_{-3.9}(\text{stat}) \pm 1.9(\text{syst})] \cdot 10^{18}$ | $[6.75^{+0.37}_{-0.42}(\text{stat}) \pm 0.68(\text{syst})] \cdot 10^{18}$ | $[9.7 \pm 0.7(\text{stat}) \pm 1.0(\text{syst})] \cdot 10^{18}$ | 1/5 | 31 | 1991 |
|          |       |            |            |            |            |            |            |            |            |
| $^{150}$Nd - $^{150}$Sm ($0^+_1$) | 186   | $1.4^{+0.4}_{-0.2}(\text{stat}) \pm 0.3(\text{syst})] \cdot 10^{20}$ | $[1.4^{+0.4}_{-0.2}(\text{stat}) \pm 0.3(\text{syst})] \cdot 10^{20}$ | $[1.4^{+0.4}_{-0.2}(\text{stat}) \pm 0.3(\text{syst})] \cdot 10^{20}$ | 1/5 | 32 | 1993 |
| $^{238}$U | ~ 2.0 | $2.0 \pm 0.6$ | $[2.0 \pm 0.6] \cdot 10^{21}$ | $[2.0 \pm 0.6] \cdot 10^{21}$ | 1/5 | 33 | 1995 |
| $^{130}$Ba | ~ 2.2 | $2.2 \pm 0.5$ | $[2.2 \pm 0.5] \cdot 10^{21}$ | $[2.2 \pm 0.5] \cdot 10^{21}$ | 1/5 | 34 | 1995 |
| ECEC(2ν) |       |            |            |            |            |            |            |            |            |

Average value: $(6.8 \pm 1.2) \cdot 10^{20}$
no known problems with the data, we accept the results. If $\chi^2/(N-1)$ is very large, we may choose not to use the average at all. Alternatively, we may quote the calculated average, while making an educated guess of the error, using a conservative estimate designed to take into account known problems with the data. Finally, if $\chi^2/(N-1)$ is larger than 1 but not greatly so, we may still average the data, but can increase the quoted error, $\delta \bar{x}$ in Equation 1, by a scale factor $S$ defined as

$$S = [\chi^2/(N-1)]^{1/2}. \quad (2)$$

For averages, we add the statistical and systematic errors in quadrature and use this combined error as $\delta x_i$. In some cases only the results obtained with high enough signal-to-background ratio were used.

3.1. $^{48}$Ca. There are two independent experiments in which $2\nu\beta\beta$ decay of $^{48}$Ca was observed [3, 4]. The results are in good agreement, yet the associated errors are quite large. The weighted average value is:

$$T_{1/2} = 4.2^{+2.1}_{-1.0} \cdot 10^{19} \text{y}.$$  

3.2. $^{76}$Ge. Let us consider the results of five experiments. First of all, however, a few additional comments are necessary:

1) Recently, the result of the Heidelberg-Moscow group was corrected again. Instead of the previously published value $T_{1/2} = [1.55^{+0.01}_{-0.00}(\text{stat})^{+0.19}_{-0.15}(\text{syst})] \cdot 10^{21} \text{y}$ [38], a new value $T_{1/2} = [1.74^{+0.01}_{-0.01}(\text{stat})^{+0.18}_{-0.16}(\text{syst})] \cdot 10^{21} \text{y}$ has been presented. It is the latter value that has been used in our present analysis. At the same time, using an independent analysis, the Moscow part of the Collaboration obtained a value similar to the result of Ref. [10], namely $T_{1/2} = [1.78^{+0.01}_{-0.00}(\text{stat})^{+0.08}_{-0.10}(\text{syst})] \cdot 10^{21} \text{y}$ [39].

2) In Ref. [7], the value $T_{1/2} = 0.92^{+0.07}_{-0.04} \cdot 10^{21} \text{y}$ was presented. However, after a more careful analysis, this result has been changed to a value of $T_{1/2} = 1.2^{+0.2}_{-0.1} \cdot 10^{21} \text{y}$ [32], which was used in our analysis.

3) The results presented in Ref. [5] do not agree with the more recent and more precise experiments [10, 11]. Furthermore, the error presented in [5] appears to be too small, especially taking into account the fact that the signal-to-background ratio in this experiment is equal to $\sim 1/10$. It has been mentioned before [10] that the half-life value in this work can be $\sim 1.5 - 2$ times higher because the thickness of the dead layer in the Ge(Li) detectors used can be different for crystals made from enriched Ge, rather than natural
Ge. With no uniformity of the external background, this effect can have an appreciable influence on the final result.

Finally, in calculating the average, only the results of experiments with signal-to-background ratios greater than 1 were used (i.e., the results of Refs. [10, 8, 9]). The weighted average value is:

$$T_{1/2} = (1.5 \pm 0.1) \cdot 10^{21} y.$$ 

3.3. $^{82}\text{Se}$. There are three independent counting experiments and many geochemical measurements ($\sim 20$). The geochemical data are neither in good agreement with each other nor in good agreement with the data from direct measurements. Formally, the accuracy of geochemical measurements is typically on the level of a few percent and sometimes even better. Nevertheless, the possibility of existing large systematic errors cannot be excluded (see discussion in Ref. [11]). It is mentioned in Ref. [12] that if the weak interaction constant $G_F$ is time-dependent, then the half-life values obtained in geochemical experiments will depend on the age of the samples. Thus, to obtain a “present” half-life value for $^{82}\text{Se}$, only the results of the direct measurements [1, 11, 12] were used. The result of Ref. [13] is the preliminary result of [12], hence it has not been used in our analysis. It is interesting to note that the “lower” error in Ref. [12] appears to be too small. Indeed, it is even smaller than the statistical error, and that is why we use here a more realistic value of 15% as an estimation of this error. As a result, the weighted average value is:

$$T_{1/2} = (0.92 \pm 0.07) \cdot 10^{20} y.$$ 

3.4. $^{96}\text{Zr}$. There are two “positive” geochemical results [16, 17] and two results from direct NEMO-2 [14] and NEMO-3 [15] experiments. Taking into account the comment in section 3.3, we use the values from Refs. [14, 15] to obtain a “present” weighted half-life value for $^{96}\text{Zr}$ of:

$$T_{1/2} = (2.0 \pm 0.3) \cdot 10^{19} y.$$ 

3.5. $^{100}\text{Mo}$. Formally, there are seven positive results\(^1\) from direct experiments and one recent result from a geochemical experiment. However, we do not consider the preliminary result of M. Moe et al. [19] and instead use their

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\(^1\)We do not consider the result of Ref. [44] because a possible high background contribution to the “effect” was not excluded in this experiment.
final result [22], plus we do not use the geochemical result (again, see comment in section 3.3). Finally, in calculating the average, only the results of experiments with signal-to-background ratios greater than 1 were used (i.e., the results of Refs. [20, 22, 1]). In addition, here we have used the corrected half-life value from Ref. [20]. First of all, the original result was decreased by 15% because the calculated efficiency (by MC) was overestimated (see Ref. [43]). Secondly, the half-life value was decreased by 10% taking into account that, for the special case of $^{100}$Mo we have to deal with the Single State Dominance (SSD) mechanism (see discussion in [1, 46]). The following weighted average value for this half-life is obtained:

$$T_{1/2} = (7.1 \pm 0.4) \cdot 10^{18} \text{y}.$$  

In framework of High State Dominance (HSD) mechanism (see [47, 48]) the following average value can be obtained, $T_{1/2} = (7.6 \pm 0.4) \cdot 10^{18} \text{y}$.

3.6. $^{100}$Mo - $^{108}$Ru ($0^+_1$; 1130.29 keV). The transition to the 0$^+$ excited state of $^{100}$Ru was detected in three independent experiments. The results are in good agreement, and the weighted average value for half-life is:

$$T_{1/2} = (6.8 \pm 1.2) \cdot 10^{20} \text{y}.$$  

3.7. $^{116}$Cd. There are three independent “positive” results that are in good agreement with each other when taking into account the corresponding error bars. Again, we use here the corrected result for the half-life value from Ref. [30]. The original half-life value was decreased by 15% (see remark in section 3.5). The weighted average value is:

$$T_{1/2} = (3.0 \pm 0.2) \cdot 10^{19} \text{y}.$$  

If the SSD mechanism is realised for the case of $^{116}$Cd as well, then the adjusted half-life value is $T_{1/2} = (2.8 \pm 0.2) \cdot 10^{19} \text{y}$.

3.8. $^{128}$Te and $^{130}$Te. There are only geochemical data for these isotopes.\(^2\) Although the half-life ratio for these isotopes has been obtained with good accuracy ($\sim 3\%$) [32], the absolute values for $T_{1/2}$ of the individual nuclei are different from one experiment to the next. One group of authors [31, 30, 51] gives $T_{1/2} \approx 0.8 \cdot 10^{21} \text{y}$ for $^{130}$Te and $T_{1/2} \approx 2 \cdot 10^{24} \text{y}$ for $^{128}$Te, whereas

\(^2\)Recently, the first indication of a positive result for $^{130}$Te in a direct experiment was published, $T_{1/2} = [6.1 \pm 1.4(\text{stat})^{+2.3}_{-2.5}(\text{syst})] \cdot 10^{20} \text{y}$ [49]. This result is in agreement with the “lower” geochemical value, but is not very precise or reliable.
another group claims \( T_{1/2} \approx (2.5 - 2.7) \times 10^{21} \) y and \( T_{1/2} \approx 7.7 \times 10^{24} \) y, respectively. Furthermore, as a rule, experiments with “young” samples (\( \sim 100 \) million years) result in half-life values of \(^{130}\text{Te} \) in the range of \( \sim (0.7 - 0.9) \times 10^{21} \) y, while for “old” samples (\( > 1 \) billion years), half-life values in the range of \( \sim (2.5 - 2.7) \times 10^{21} \) y have been produced. It was even assumed that the difference in half-life values could be connected with a variation of the weak interaction constant \( G_F \) with time [42].

We will estimate the absolute half-life values for \(^{130}\text{Te} \) and \(^{128}\text{Te} \) using only very well-known ratios from geochemical measurements and the “present” half-life value of \(^{82}\text{Se} \) (see section 3.3). The first ratio is given by

\[
\frac{T_{1/2}^{(130}\text{Te})}{T_{1/2}^{(128}\text{Te})} = (3.52 \pm 0.11) \times 10^{-4} \text{[32]},
\]

while the second ratio is given by

\[
\frac{T_{1/2}^{(130}\text{Te})}{T_{1/2}^{(82}\text{Se})} = 9.9 \pm 0.6. \text{ This latter value is the weighted average value from three experiments with minerals containing both elements (Te and Se): 7.3 \pm 0.9 [52], 12.5 \pm 0.9 [13] and 10 \pm 2 [53]. It is significant that the gas retention age problem has no effect on the half-life ratios. Now, using the “present” \(^{82}\text{Se} \) half-life value \( T_{1/2} = (0.92 \pm 0.07) \times 10^{20} \) y and the value 9.9\( \pm 0.6 \) for the \( T_{1/2}^{(130}\text{Te})/T_{1/2}^{(82}\text{Se}) \) ratio, one can obtain the half-life value for \(^{130}\text{Te} \):
\]

\[
T_{1/2} = (0.9 \pm 0.1) \times 10^{21} \text{y}.
\]

Using \( T_{1/2}^{(130}\text{Te})/T_{1/2}^{(128}\text{Te}) = (3.52 \pm 0.11) \times 10^{-4} \) [32], one can obtain the half-life value for \(^{128}\text{Te} \):

\[
T_{1/2} = (2.5 \pm 0.3) \times 10^{24} \text{y}.
\]

3.9. \(^{150}\text{Nd} \). The half-life value was measured in three independent experiments \[33, 22, 15\]. However, only the latter two results are in good agreement. Using Equation 1, and three existing values one can obtain \( T_{1/2} = (7.8 \pm 0.4) \times 10^{18} \) y. Taking into account the fact that \( \chi^2 > 1 \) and \( S = 2.2 \) (see Equation 2) we finally obtain:

\[
T_{1/2} = (7.8 \pm 0.7) \times 10^{18} \text{y}.
\]

3.10. \(^{150}\text{Nd} - ^{150}\text{Sm} \) \((0^+; 740.4 \) keV\)). There is only one positive result from a direct (counting) experiment [34]:

\[
T_{1/2} = (1.4^{+0.5}_{-0.3}) \times 10^{20} \text{y}.
\]

3.11. \(^{238}\text{U} \). There is only one positive result from a radiochemical experiment [35]:

\[
T_{1/2} = (2.0 \pm 0.6) \times 10^{21} \text{y}.
\]
3.12. $^{130}$Ba (ECEC). There is only one positive result from a geochemical experiment [36]:

$$T_{1/2} = (2.2 \pm 0.5) \cdot 10^{21} \text{y}.$$ 

4 Conclusion

In summary, all “positive” $2\nu\beta\beta$-decay results were analyzed and average values for half-lives were calculated. For the cases of $^{128}$Te, $^{130}$Te, and $^{130}$Ba, so-called “recommended” values have been proposed. We strongly recommend the use of these values as presently the most precise and reliable. In particular, the accurate experimental $2\nu\beta\beta$-decay rates can be used to adjust the most relevant parameter in the framework of the QRPA model, namely the strength of the particle-particle interaction ($g_{pp}$). Once accomplished, these values can be used in NME calculations for neutrinoless double beta decay [51].

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