AVERAGE (RECOMMENDED) HALF-LIFE VALUES FOR TWO NEUTRINO DOUBLE BETA DECAY

A.S. Barabash

Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117259 Moscow, Russia

Abstract

All existing "positive" results on two neutrino double beta decay in different nuclei were analyzed. Using procedure recommended by Particle Data Group weighted average values for half-lives of $^{48}$Ca, $^{76}$Ge, $^{82}$Se, $^{90}$Zr, $^{100}$Mo, $^{100}$Mo - $^{100}$Ru ($0^+_1$), $^{116}$Cd, $^{150}$Nd and $^{238}$U were obtained. Existing geochemical data were analyzed and recommended values for half-lives of $^{128}$Te and $^{130}$Te are proposed. We recommend to use these results as most precise and reliable values for half-lives at this moment.

1 Introduction

At present two neutrino double beta decay process ($2\nu\beta\beta$) has been detected in 10 nuclei. In $^{100}$Mo this type of decay was detected for the transition to $0^+$ excited state of daughter nucleus too. All these results were obtained in a few tens of geochemical experiments, more then two tens of direct (counting) experiments and in one radiochemical experiment. In direct experiments for some nuclei there are up to 5 independent positive results ($^{76}$Ge, $^{100}$Mo). In some experiments, statistical error does not play the main role. Thus in Heidelberg-Moscow experiment with $^{76}$Ge more then 64000 useful events were detected [1, 2] and in NEMO experiment with $^{100}$Mo 1423 events were detected [3]. This results in values for the statistical error of 0.5% and
4%, respectively. At the same time systematic error in the experiments on 2$\nu$ββ decay remain quite high ($\sim 10 - 30\%$) and, in addition, very often it can’t be determined reliably enough. For example, in Geidelberg-Moscow experiment the measured half-life value recently was changed by 15% with an indicated systematic error $\sim 7\%$ (see [1] and [2]). This demonstrates that the real systematic error in this experiment [1] was higher than the indicated one. And now authors estimate the systematic error as $\sim 10 - 12\%$ [3].

In the present work critical analysis of all ”positive” experimental results are made and averaged, and recommended values for all isotopes are obtained.

2 Present experimental data

Experimental results on 2$\nu$ββ decay in different nuclei are presented in Table 1. For direct experiments number of useful events and signal/background ratio are presented.

3 Data analysis

To obtain an average of the data a standard weighted least-squares procedure recommended by Particle Data Group [31] was used. Weighted average and error were calculated as:

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

(1)

where $w_i = 1/(\delta x_i)^2$.

Here $x_i$ and $\delta x_i$ are the value and error reported by the i-th experiment, and the sums run over the N experiments. We then calculate $\chi^2 = \frac{\sum w_i (\bar{x} - x_i)^2}{\sum w_i}$ 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 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, but then make an educated guess of the error, a conservative estimate designed to take into account known problems with the data.
Table 1: Present ”positive” $2
\nu\beta\beta$ decay results. N is the number of useful events, S/B is the signal/background ratio.

| Nucleus | N       | $T_{1/2}$, y | S/B | Ref., year |
|---------|---------|--------------|-----|------------|
| $^{48}$Ca | $\sim$ 100 | $[4.3^{+2.4}_{-1.1}(\text{stat}) \pm 1.4(\text{syst})] \cdot 10^{19}$ | 1/5 | [1], 1996 |
|         | 5       | $4.2^{+3.3}_{-1.3} \cdot 10^{19}$ | 5/0 | [4], 2000 |
|         |         | **Average value: $4.2^{+2.1}_{-1.0} \cdot 10^{19}$** |     |            |
| $^{76}$Ge | $\sim$ 4000 | $(0.9 \pm 0.1) \cdot 10^{21}$ | $\sim$ 1/8 | [8], 1990 |
|         | 758     | $1.1^{+0.6}_{-0.3} \cdot 10^{21}$ | $\sim$ 1/6 | [9], 1991 |
|         | 132     | $0.93^{+0.5}_{-0.1} \cdot 10^{21}$ | $\sim$ 4  | [10], 1991 |
|         | 132     | $1.2^{+0.2}_{-0.1} \cdot 10^{21}$ | $\sim$ 4  | [11], 1994 |
|         | $\sim$ 3000 | $(1.45 \pm 0.15) \cdot 10^{21}$ | $\sim$ 1.5 | [12], 1999 |
|         | 64553   | $[1.55 \pm 0.01(\text{stat})^{+0.19}_{-0.15}(\text{syst})] \cdot 10^{21}$ | $\sim$ 1.5 | [13], 2001 |
|         |         | **Average value: $1.42^{+0.09}_{-0.07} \cdot 10^{21}$** |     |            |
| $^{82}$Se | 149.1   | $[0.83 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})] \cdot 10^{20}$ | 2.3 | [14], 1998 |
|         | 89.6    | $1.08^{+0.26}_{-0.06} \cdot 10^{20}$ | $\sim$ 8 | [15], 1992 |
|         |         | $(1.3 \pm 0.05) \cdot 10^{20}$ (geochem.) |     | [16], 1986 |
|         |         | **Average value: $(0.9 \pm 0.1) \cdot 10^{20}$** |     |            |
| $^{90}$Zr | 26.7    | $[2.1^{+0.8}_{-0.5}(\text{stat}) \pm 0.2(\text{syst})] \cdot 10^{19}$ | 1.9 | [17], 1999 |
|         |         | $(3.9 \pm 0.9) \cdot 10^{19}$ (geochem.) |     | [18], 1993 |
|         |         | **Recommended value: $2.1^{+0.8}_{-0.4} \cdot 10^{19}$** |     |            |
| $^{100}$Mo | $\sim$ 500 | $11.5^{+3.0}_{-2.0} \cdot 10^{18}$ | 1/7 | [19], 1991 |
|         | 67      | $11.6^{+3.4}_{-0.8} \cdot 10^{18}$ | 1    | [20], 1991 |
|         | 1433    | $[9.5 \pm 0.4(\text{stat}) \pm 0.9(\text{syst})] \cdot 10^{18}$ | 3    | [21], 1995 |
|         | 175     | $7.6^{+2.2}_{-1.3} \cdot 10^{18}$ | 1/2  | [22], 1997 |
|         | 377     | $[6.75^{+0.37}_{-0.42}(\text{stat}) \pm 0.68(\text{syst})] \cdot 10^{18}$ | 10   | [23], 1997 |
|         | 800     | $[7.2 \pm 1.1(\text{stat}) \pm 1.8(\text{syst})] \cdot 10^{18}$ | 1/9  | [24], 2001 |
|         |         | **Average value: $(8.0 \pm 0.7) \cdot 10^{18}$** |     |            |
| $^{100}$Mo - $^{100}$Ru (0$^+_1$) | 66       | $6.1^{+1.8}_{-1.1} \cdot 10^{20}$ | 1/7  | [25], 1995 |
|         | $\sim$ 80 | $[9.3^{+2.8}_{-1.7}(\text{stat}) \pm 1.4(\text{syst})] \cdot 10^{20}$ | 1/4  | [26], 1999 |
|         | 19.5    | $[5.9^{+1.7}_{-1.1}(\text{stat}) \pm 0.6(\text{syst})] \cdot 10^{20}$ | $\sim$ 8 | [27], 2001 |
|         |         | **Average value: $(6.8 \pm 1.2) \cdot 10^{20}$** |     |            |
| $^{116}$Cd | $\sim$ 180 | $2.6^{+0.9}_{-0.5} \cdot 10^{19}$ | $\sim$ 1/4 | [28], 1995 |
|         | 3600    | $[2.6 \pm 0.1(\text{stat})^{+0.7}_{-0.4}(\text{syst})] \cdot 10^{19}$ | $\sim$ 2 | [29], 2000 |
|         | 174.6   | $[3.75 \pm 0.35(\text{stat}) \pm 0.21(\text{syst})] \cdot 10^{19}$ | 3    | [30], 1996 |
|         |         | **Average value: $3.3^{+0.4}_{-0.3} \cdot 10^{19}$** |     |            |
Table 1: continued.

| $^{128}$Te       | $2.2 \cdot 10^{24}$ (geochem.) \( (7.7 \pm 0.4) \cdot 10^{24} \) (geochem.) | [27], 1991 \[28], 1993 |
|------------------|----------------------------------------------------------------------------------|-----------------------|
|                   | **Recommended value:** \((2.5 \pm 0.4) \cdot 10^{24}\)**                          |                       |
| $^{130}$Te        | $0.8 \cdot 10^{21}$ (geochem.) \( (2.7 \pm 0.1) \cdot 10^{21} \) (geochem.)     | [27], 1991 \[28], 1993 |
|                   | **Recommended value:** \((0.9 \pm 0.15) \cdot 10^{21}\)**                        |                       |
| $^{150}$Nd        | 23 \[414] \[1.88^{+0.09}_{-0.39}(stat) \pm 0.19(syst)] \cdot 10^{19} \[6.75^{+0.37}_{-0.22}(stat) \pm 0.68(syst)] \cdot 10^{18} | 1.8 \+0.01^{−0.01}_{−0.01}(stat) \+0.19^{−0.19}_{−0.19}(syst)] \cdot 10^{19} \[19], 1997 |
|                   | **Average value:** \((7.0 \pm 1.7) \cdot 10^{18}\)**                              |                       |
| $^{238}$U         | \((2.0 \pm 0.6) \cdot 10^{21}\)                                                 | [30], 1991 |

Finally, if $\chi^2/(N - 1)$ is greater than 1, but not greatly so, we still average the data, but we increase our quoted error, $\delta \bar{x}$ in Eq. (1), by a scale factor $S$ defined as

$$S = \left[\frac{\chi^2}{(N - 1)}\right]^{1/2}.$$  \hspace{1cm} (2)

For averages we add the statistical and systematic errors in quadrature and use this combined error as $\delta x_i$.

3.1. \textbf{$^{48}$Ca}. There are two independent experiments in which $2\nu\beta\beta$ decay of $^{48}$Ca was observed [4, 5]. Results are in good agreement, but 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. \textbf{$^{76}$Ge}. Let us consider the results of five experiments. But, first of all, a few additional comments are necessary:

1) Recently the result of the Heidelberg-Moscow group was corrected. Instead of the previously published value $T_{1/2} = [1.77 \pm 0.01(stat)^{+0.12}_{-0.11}(syst)] \cdot 10^{21} \text{y}$ [4], a new value $T_{1/2} = [1.55 \pm 0.01(stat)^{+0.19}_{-0.15}(syst)] \cdot 10^{21} \text{y}$ [4] has been presented. This last value has been used in our analysis.

2) In ref. [4] the value $T_{1/2} = 0.92^{+0.07}_{-0.04} \cdot 10^{21} \text{y}$ was presented. However, after more careful analysis, it was changed to a value of $T_{1/2} = 1.2^{+0.2}_{-0.1} \cdot 10^{21} \text{y}$ [4], which was used in our analysis.
3) The result of work [3] does not agree with more later and more precise experiments [4, 10]. Error presented in [3] looks too small, especially taking into account that signal/background ratio in this experiment is equal to $\sim 1/10$. Before it was mentioned [32], that half-life value in this work can be $\sim 1.5 - 2$ times higher because the thickness of dead layer in using Ge(Li) detectors can be different in crystals made of natural and enriched Ge. Under nonuniformity of external background it can have an appreciable influence on the final result.

Finally, in calculating the average, only result of experiments with signal/background ratio greater then 1 were used, i.e. the results of [2, 9, 10]. The weighted average value is:

$$T_{1/2} = 1.43^{+0.09}_{-0.07} \cdot 10^{21} y.$$ 

3.3. $^{82}$Se. There are two independent counting experiments and a lot of geochemical measurements ($\sim 20$). Geochemical data are not in good agreement with each other and with direct experiments data. Formally the accuracy of geochemical measurements can be on the level of a few percent and even better. Nevertheless, now the possibility of existing large systematic error cannot be excluded (see discussion in [33]). It is mentioned in ref. [34] that, if weak interaction constant $G_F$ depends of time, then half-life values obtained in geochemical experiments will depend of the age of the samples. This is why to obtain a "present" half-life value of $^{82}$Se, only results of direct measurements, [11] and [14], were used. Result of ref. [35] is the preliminary result of [12] and we do not use it in our analysis. Notice that "low" error in [12] looks too small. It is even smaller than the statistical error! This 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:

$$T_{1/2} = (0.9 \pm 0.1) \cdot 10^{20} y.$$ 

3.4. $^{96}$Zr. There are two "positive" results: geochemical result [15] and result of direct NEMO experiment [14]. Taking into account the comment in section 3.3 we take the value from [14] as "present" half-life value for $^{96}$Zr:

$$T_{1/2} = 2.1^{+0.8}_{-0.4} \cdot 10^{19} y.$$ 

3.5. $^{100}$Mo. Formally there are 6 positive results [1]. But we do not consider preliminary result of M.Moe et al. [17] and use their final result [19]. The

\footnote{We do not consider result of [36] because possible background contribution to the "effect" was not excluded in this experiment.}
following weighted average value for half-life is obtained:

\[ T_{1/2} = (8 \pm 0.7) \cdot 10^{18} \text{y}. \]

3.6. $^{100}\text{Mo}$ - $^{100}\text{Ru}$ ($0^+; 1130.29$ keV). Transition to $0^+$ excited state in $^{100}\text{Ru}$ was detected in three independent experiments. Results are in good agreement. Weighted average value for half-life is:

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

3.7. $^{116}\text{Cd}$. There are three independent ”positive” results which are in a good agreement with each other taking into account the error bars. The weighted average value is:

\[ T_{1/2} = 3.3^{+0.4}_{-0.3} \cdot 10^{19} \text{y}. \]

3.8. $^{128}\text{Te}$ and $^{130}\text{Te}$. There are only geochemical data for these isotopes. Though the half-life ratio for this isotopes is obtained with good accuracy (\(\sim 3\%\)) [28], absolute values for $T_{1/2}$ are different from one experiment to the next. One group of authors [27, 37, 38] gives $T_{1/2} \approx 0.8 \cdot 10^{21}$ y for $^{130}\text{Te}$ and $T_{1/2} \approx 2 \cdot 10^{24}$ y for $^{128}\text{Te}$ and another group [13, 28] - $T_{1/2} \approx (2.5 - 2.7) \cdot 10^{21}$ y and $T_{1/2} \approx 7.7 \cdot 10^{24}$ y, respectively. And besides, as a rule, experiments with ”young” samples (\(\sim 100\) million. years) give for half-life of $^{130}\text{Te}$ values $\sim (0.7 - 0.9) \cdot 10^{21}$ y and for ”old” samples (> 1 billion years) $\sim (2.5 - 2.7) \cdot 10^{21}$ y. It was even assumed that the difference in half-life values could be connected with a variation of the week interaction constant $G_F$ with time [34].

We will estimate the absolute values of $T_{1/2}$ for $^{130}\text{Te}$ and $^{128}\text{Te}$ using only very well known ratios from geochemical measurements and ”present” half-life value of $^{82}\text{Se}$ (see section 3.3). First ratio is $T_{1/2}(^{130}\text{Te})/T_{1/2}(^{128}\text{Te}) = (3.52 \pm 0.11) \cdot 10^{-4}$ [28]. Second ratio is $T_{1/2}(^{130}\text{Te})/T_{1/2}(^{82}\text{Se}) = 9.9 \pm 0.6$. This value is weighted average value from three experiments: 7.3 ± 0.9 [39], 12.5 ± 0.9 [13] and 10 ± 2 [10]. It is significant that the gas retention age problem has no effect on the half-life ratios. Now using ”present” $^{82}\text{Se}$ half-life value $T_{1/2} = (0.9 \pm 0.1) \cdot 10^{20}$ y. and value 9.9 ± 0.6 for $T_{1/2}(^{130}\text{Te})/T_{1/2}(^{82}\text{Se})$ ratio one can obtain the half-life value for $^{130}\text{Te}$:

\[ T_{1/2} = (0.9 \pm 0.15) \cdot 10^{21} \text{y}. \]
Using $T_{1/2}(^{130}\text{Te})/T_{1/2}(^{128}\text{Te}) = (3.52 \pm 0.11) \cdot 10^{-4}$ one can obtain the half-life value for $^{128}\text{Te}$:

$$T_{1/2} = (2.5 \pm 0.4) \cdot 10^{24} \text{y}.$$  

3.9. $^{150}\text{Nd}$. The half-life value was obtained in two independent experiments, [29] and [19]. But the two results are not in good agreement. Using the relation (1) one can obtain $T_{1/2} = (7.0 \pm 0.8) \cdot 10^{18} \text{ y}$. Taking into account that $\chi^2 > 1$ and $S = 2.2$ (see relation (2)) we finally obtain:

$$T_{1/2} = (7.0 \pm 1.7) \cdot 10^{18} \text{y}.$$  

3.10. $^{238}\text{U}$. There is only one positive result from radiochemical experiment [30]:

$$T_{1/2} = (2.0 \pm 0.6) \cdot 10^{21} \text{y}.$$  

4 Conclusion

Hence all ”positive” $2\nu\beta\beta$ results were analyzed and average values for half-lives were calculated. For $^{128}\text{Te}$ and $^{130}\text{Te}$ so-called ”recommended” values were proposed. We recommend the use of exactly these values as most precise and reliable by this moment.

References

[1] M. Gunther et al., Phys. Rev. D 55 (1997) 54.
[2] H.V. Klapdor-Kleingrothaus et. al., arXiv:hep-ph/0103062 6 Mar 2001.
[3] D. Dassie et al., Phys. Rev. D 51 (1995) 2090.
[4] A. Balysh et al., Phys. Rev. Lett. 77 (1996) 5186.
[5] V.B. Brudanin et al., Phys. Lett. B 495 (2000) 63.
[6] A.A. Vasenko et al., Mod. Phys. Lett. A5 (1990) 1299.
[7] H.S. Miley et al., Phys. Rev. Lett. 65 (1991) 3092.
[8] F.T. Avignone et al., Phys. Lett. B 256 (1991) 559.
[9] F.T. Avignone, Prog. Part. Nucl. Phys. 32 (1994) 223.
[10] A. Morales, Nucl. Phys. B (Proc. Suppl.) 77 (1999) 335.
[11] R. Arnold et al., Nucl. Phys. A 636 (1998) 209.
[12] S.R. Elliot et al., Phys. Rev. C 46 (1992) 1535.
[13] T. Kirsten et al., Proc. Int. Symp. "Nuclear Beta Decay and Neutrino (Osaka'86)", World Scientific, Singapore, 1986, p.81.
[14] R. Arnold et al., Nucl. Phys. A 658 (1999) 299.
[15] A. Kawashima, K. Takahashi, A. Masuda, Phyc. Rev. C 47 (1993) 2452.
[16] H. Ejiri et al., Phys. Lett. B 258 (1991) 17.
[17] S.R. Elliot, A.A. Halin, M.K. Moe, J. Phys. G 17 (1991) S145.
[18] M. Alston-Garnjost et al., Phys. Rev. C 55 (1997) 474.
[19] A. De Silva, M.K. Moe, M.A. Nelson, M.A. Vient, Phys. Rev. C 56 (1997) 2451.
[20] V.D. Ashitkov et al., JETP Lett. 74 (2001) 529.
[21] A.S. Barabash et al., Phys. Lett. B 345 (1995) 408.
[22] A.S. Barabash et al., Phys. At. Nucl., 62 (1999) 2039.
[23] L. De Braeckeleer et al., Phys. Rev. Lett., 86 (2001) 3510.
[24] H. Ejiri et al., J. Phys. Soc. of Japan 64 (1995) 339.
[25] F.A. Danevich et al., Phys. Rev. C 62 (2000) 045501.
[26] R. Arnold et al., Z. Phys. C 72 (1996) 239.
[27] O.K. Manuel, J. Phys. G 17 (1991) 221.
[28] T. Bernatowicz et al., Phys.Rev. C 47 (1993) 806.
[29] V. Artemiev et al., Phys. Lett. B 345 (1995) 564.
[30] A.L. Turkevich, T.E. Economou, G.A. Cowan, Phys. Rev. Lett. 67 (1991) 3211.

[31] Eur. Phys. J. C 15 (2000) 10.

[32] A.S. Barabash, V.I. Umatov, ITEP note, 1990.

[33] O.K. Manuel, Proc. Int. Symp. ”Nuclear Beta Decay and Neutrino (Osaka’86)”, World Scientific, Singapore, 1986, p.71.

[34] A.S. Barabash, Eur. Phys. J. A 8 (2000) 137.

[35] S.R. Elliot, A.A. Hahn, M.K. Moe, Phys. Rev. Lett. 59 (1987) 2020.

[36] S.I. Vasilyev et al., Pis’ma v ZhETP 51 (1990) 550.

[37] N. Takaoka, K. Ogata, Z. Naturforsch, 21a (1966) 84.

[38] N. Takaoka, Y. Motomura, K. Nagano, Phys. Rev. C 53 (1996) 1557.

[39] W.J. Lin et al., Nucl.Phys. A 457 (1986) 285.

[40] B. Srinivasan et al., Econ. Geol. 68 (1973) 252.