# Precise half-life values for two neutrino double beta decay

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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 <sup>48</sup>Ca, <sup>76</sup>Ge, <sup>82</sup>Se, <sup>96</sup>Zr, <sup>100</sup>Mo, <sup>100</sup>Mo - <sup>100</sup>Ru (0<sub>1</sub><sup>+</sup>), <sup>116</sup>Cd, <sup>130</sup>Te, <sup>150</sup>Nd, <sup>150</sup>Nd - <sup>150</sup>Sm (0<sub>1</sub><sup>+</sup>) and <sup>238</sup>U were obtained. Existing geochemical data were analyzed and recommended values for half-lives of <sup>128</sup>Te, <sup>130</sup>Te and <sup>130</sup>Ba are proposed. Given the measured half-life values, nuclear matrix elements were calculated. I recommend the use of these results as the most currently reliable values for the half-lives and nuclear matrix elements.

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### I. 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 and more than thirty direct (counting) experiments as well as 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 has currently detected more than 219,000  $2\nu\beta\beta$  events [1], which results in a value for the statistical error of  $\sim 0.2\%$ . At the same time, the systematic error for many experiments on  $2\nu\beta\beta$  decay remains quite high ( $\sim 10-30\%$ ) and very often cannot be determined reliably. As a consequence, it is frequently difficult for the "user" to select the "best" half-life value among the results. Using an averaging procedure, one can produce the most reliable and accurate half-life values for each isotope.

Why are accurate half-life periods necessary? The most important motivations are the following:

- 1) Nuclear spectroscopy. Now we know that some isotopes which were earlier considered to be stable are not, and decay via the double beta decay processes with a half-life period of  $\sim 10^{18}-10^{21}$  yr are observed. The values which are presented here should be introduced into the isotope table.
- 2) Nuclear matrix elements (NME). First, it gives the possibility to improve the quality of NME calculations for two neutrino double beta decay, so one can directly compare experimental and calculated values. Second, it gives the possibility to improve the quality of NME calculations for neutrinoless double beta decay. The accurate half-life values for  $2\nu\beta\beta$  decay are used to adjust the most relevant parameter of the quasiparticle random-phase approximation (QRPA) model, the strength of the particle-particle interaction  $g_{pp}$  [2–5].
- 3) Research on the single state dominance (SSD) mechanism [6, 7] and a check of the "bosonic" component of the neutrino hypothesis [8, 9] is possible.

In this article, an analysis of all "positive" experimental results has been performed, and

averaged or recommended values for isotopes are presented.

The first time that this work was done was in 2001, and the results were presented at the International Workshop on the Calculation of Double Beta Decay Nuclear Matrix Elements (MEDEX'01) [10]. Then revised half-life values were presented at MEDEX'05 and published in Ref. [11]. In this article, new positive results obtained since 2005 have been added and analyzed.

#### II. 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 events and the signal-to-background ratio are presented.

### III. DATA ANALYSIS

To obtain an average of the ensemble of available data, a standard weighted least-squares procedure, as recommended by the Particle Data Group [12], was used. The weighted average and the corresponding error were calculated, as follows:

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

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 summations run over the N experiments.

The next 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 no known problems with the data, then one accepts the results to be sound. If  $\chi^2/(N-1)$  is very large (>> 1), one chooses not to use the average. Alternatively, one 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, it is still best to use the average data, but to increase the quoted error,  $\delta \bar{x}$  in Equation 1, by a factor of S defined by

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

For averages, the statistical and systematic errors are treated in quadrature and used as a

combined error  $\delta x_i$ . In some cases only the results obtained with high enough signal-to-background ratio were used.

In certain cases, the experimental results have asymmetrical errors. In most cases, asymmetry is small and is practically absent in the final result. For  $^{48}$ Ca,  $^{100}$ Mo -  $^{100}$ Ru ( $^{+}$ ) and  $^{130}$ Te the average value has the "top" error slightly larger than the "bottom" error, as shown in the current presentation. The case of  $^{82}$ Se is discussed in Sec. III C.

# **A.** 48**Ca**

There are three independent experiments in which  $2\nu\beta\beta$  decay of <sup>48</sup>Ca was observed [13–15]. The results are in good agreement. The weighted average value is:

$$T_{1/2} = 4.4^{+0.6}_{-0.5} \cdot 10^{19} \text{yr}.$$

## B. <sup>76</sup>Ge

Considering the results of five experiments, a few additional comments are necessary, as follows:

- 1) The result of the Heidelberg-Moscow group has been corrected. Instead of the previously published value of  $T_{1/2} = [1.55 \pm 0.01(stat)^{+0.19}_{-0.15}(syst)] \cdot 10^{21} \text{ yr } [54]$ , a new value  $T_{1/2} = [1.74 \pm 0.01(stat)^{+0.18}_{-0.16}(syst)] \cdot 10^{21} \text{ yr } [21]$  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. [21], namely  $T_{1/2} = [1.78 \pm 0.01(stat)^{+0.08}_{-0.10}(syst)] \cdot 10^{21} \text{ yr } [55]$ .
- 2) In Ref. [18], the value  $T_{1/2} = 0.92^{+0.07}_{-0.04} \cdot 10^{21}$  yr was presented. However, after a more careful analysis, this result has been changed to a value of  $T_{1/2} = 1.2^{+0.2}_{-0.1} \cdot 10^{21}$  yr [19], which was used in the analysis.
- 3) The results presented in Ref. [16] do not agree with the more recent experiments [20, 21]. Furthermore, the error presented in [16] appears to be too small, especially taking into account that the signal-to-background ratio in this experiment is equal to  $\sim 1/8$ . It has been mentioned before [56] 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 (and this is the case!), 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. [19–21]). The weighted average value is:

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

# C. 82Se

There are three independent counting experiments and many geochemical measurements ( $\sim 20$ ) for <sup>82</sup>Se. The geochemical data are neither in good agreement with each other nor in good agreement with the data from the direct measurements. Typically, the accuracy of geochemical measurements is at the level of 10% and sometimes even better. Nevertheless, the possibility of existing large systematic errors cannot be excluded (see discussion in Ref. [57]). It is mentioned in Ref. [58] 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 <sup>82</sup>Se, only the results of the direct measurements [1, 22, 23] were used. The result of Ref. [59] is the preliminary result of [22]; hence it has not been used in our analysis. The result of work [22] is presented with very asymmetrical errors. To be more conservative only "the top" error in this case is used. As a result, the weighted average value is:

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

# $\mathbf{D}$ . $^{96}\mathbf{Zr}$

There are two "positive" geochemical results [26, 27] and two results from the direct experiments of NEMO-2 [25] and NEMO-3 [15]. Taking into account the comment in Sec. III C, I use the values from Refs. [15, 25] to obtain a "present" weighted half-life value for <sup>96</sup>Zr of:

$$T_{1/2} = (2.3 \pm 0.2) \cdot 10^{19} \text{yr}.$$

# **E.** $^{100}$ **Mo**

Formally, there are seven positive results from direct experiments and one recent result from a geochemical experiment. We do not consider the result of Ref. [60] because of a potentially high background contribution that was not excluded in this experiment. In addition, we do not consider the preliminary result of Elliott et al. [29] and instead use their final result [32], plus I do not use the geochemical result (again, see comment in Sec. III C). 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. [1, 30, 32]). In addition, I have used the corrected half-life value from Ref. [30]. Thus, the original result was decreased by 15% because the calculated efficiency, in the MC, was overestimated (see Ref. [61]). In addition, the half-life value was decreased by 10% taking into account that for <sup>100</sup>Mo we have the SSD mechanism (see discussion in [62, 63]). The following weighted average value for this half-life is then obtained:

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

In the framework of the high state dominance (HSD) mechanism (see [6, 7]) the following average value was obtained,  $T_{1/2} = (7.6 \pm 0.4) \cdot 10^{18} \text{ yr.}$ 

# F. $^{100}{ m Mo}$ - $^{100}{ m Ru}$ $(0^+_1;\, 1130.29 \,\,{ m keV})$

The transition to the  $0^+$  excited state of  $^{100}$ Ru was detected in five independent experiments. The results are in good agreement, and the weighted average for the half-life using the results from [35, 36, 38, 39] is:

$$T_{1/2} = 5.9^{+0.8}_{-0.6} \cdot 10^{20} \text{yr.}$$

The result from [37] was not used here because I considered the result from [38] as the final result of the TUNL-ITEP experiment.

## G. 116Cd

There are four independent "positive" results [15, 40–42] that are in good agreement with each other when taking into account the corresponding error bars. Again, I use here

the corrected result for the half-life value from Ref. [42]. The original half-life value was decreased by  $\sim 25\%$  (see remark in Sec. III E). The weighted average value for the SSD mechanism is:

$$T_{1/2} = (2.8 \pm 0.2) \cdot 10^{19} \text{yr}.$$

If the HSD mechanism is realized, then the adjusted half-life value is  $T_{1/2} = (3.0 \pm 0.2) \cdot 10^{19}$  yr. This is because of different single electron energy spectra for different mechanisms. And experimental threshold in two most accurate experiments [15, 42] ( $\sim 200 \text{ keV}$ ) leads to different efficiency to detect  $2\nu\beta\beta$  events.

## $\mathbf{H}$ . $^{128}\mathbf{Te}$ and $^{130}\mathbf{Te}$

For a long time, there were only geochemical data for these isotopes. Although the half-life ratio for these isotopes has been obtained with good accuracy ( $\sim 3\%$ ) [44], the absolute values for  $T_{1/2}$  of each nuclei are different from one experiment to the next. One group of authors [43, 64, 65] gives  $T_{1/2} \approx 0.8 \cdot 10^{21}$  yr for  $^{130}$ Te and  $T_{1/2} \approx 2 \cdot 10^{24}$  yr for  $^{128}$ Te, whereas the next groups [24, 44] claims  $T_{1/2} \approx (2.5 - 2.7) \cdot 10^{21}$  yr and  $T_{1/2} \approx 7.7 \cdot 10^{24}$  yr, respectively. Furthermore, as a rule, experiments with "young" samples ( $\sim 100$  million years) give results of the half-life value of  $^{130}$ Te in the range of  $\sim (0.7 - 0.9) \cdot 10^{21}$  yr, while "old" samples (> 1 billion years) have half-life values in the range of  $\sim (2.5 - 2.7) \cdot 10^{21}$  yr. It has even been assumed that the difference in half-life values could be connected to a variation of the weak interaction constant  $G_F$  with time [58].

One can estimate the absolute half-life values for  $^{130}$ Te and  $^{128}$ Te using only very well-known ratios from geochemical measurements and the "present" half-life value of  $^{82}$ Se (see Sec. III C). The first ratio [44] is given by  $T_{1/2}(^{130}\text{Te})/T_{1/2}(^{128}\text{Te}) = (3.52 \pm 0.11) \cdot 10^{-4}$ , while the second is  $T_{1/2}(^{130}\text{Te})/T_{1/2}(^{82}\text{Se}) = 9.9 \pm 1.5$ . This second value is the weighted average of three experiments with minerals containing the elements Te and Se yield:  $7.3\pm0.9$  [66],  $12.5\pm0.9$  [24] and  $10\pm2$  [67]. It is significant that the gas retention age problem has no effect on the half-life ratio in this case. Using the "present"  $^{82}$ Se half-life value of  $T_{1/2} = (0.92\pm0.07) \cdot 10^{20}$  y and the value  $9.9\pm1.5$  for the  $T_{1/2}(^{130}\text{Te})/T_{1/2}(^{82}\text{Se})$  ratio, one obtains the half-life value for  $^{130}$ Te:

$$T_{1/2} = (9.1 \pm 2.1) \cdot 10^{20} \text{yr}.$$

Using  $T_{1/2}(^{130}\text{Te})/T_{1/2}(^{128}\text{Te}) = (3.52 \pm 0.11) \cdot 10^{-4}$  [44], one obtains the half-life value for  $^{128}\text{Te}$  of

$$T_{1/2} = (2.6 \pm 0.6) \cdot 10^{24} \text{yr.}$$

Recently it was argued that "short "half-lives are more likely to be correct [45, 46]. Using different "young" mineral results the half-life values were estimated at  $(9.0 \pm 1.4) \cdot 10^{20}$  yr [45],  $(8.0 \pm 1.1) \cdot 10^{20}$  yr [46] for <sup>130</sup>Te and  $(2.41 \pm 0.39) \cdot 10^{24}$  yr [45],  $(2.3 \pm 0.3) \cdot 10^{24}$  yr [46] for <sup>128</sup>Te, corresponding to the observed  $T_{1/2}(^{130}\text{Te})/T_{1/2}(^{128}\text{Te})$  ratio.

The first sound indication of a positive result for <sup>130</sup>Te in a direct experiment was obtained in [47]. A result with greater accuracy was obtained recently in the NEMO-3 experiment [48]. These results are in good agreement, and the weighted average for the half-life is

$$T_{1/2} = (6.8^{+1.2}_{-1.1}) \cdot 10^{20} \text{yr}.$$

Now, using the  $T_{1/2}(^{130}\mathrm{Te})/T_{1/2}(^{128}\mathrm{Te})$  ratio, one can obtain a half-life value for  $^{128}\mathrm{Te}$ ,

$$T_{1/2} = (1.9 \pm 0.4) \cdot 10^{24} \text{yr.}$$

We recommend the use of these last two results as the best "present" half-life values for <sup>130</sup>Te and <sup>128</sup>Te, respectively.

## I. $^{150}$ Nd

This half-life value was measured in three independent experiments [32, 49, 50]. The most accurate value was obtained in Ref. [50]. This value is higher than in Ref. [32] and lower than in Ref. [49] ( $\sim 3\sigma$  and  $\sim 2\sigma$  differences, respectively). Using Equation 1, and three existing values, one obtains  $T_{1/2} = (8.2 \pm 0.5) \cdot 10^{18}$  yr. Taking into account the fact that  $\chi^2 > 1$  and S = 1.89 (see Equation 2) we then obtain:

$$T_{1/2} = (8.2 \pm 0.9) \cdot 10^{18} \text{yr}.$$

# J. $^{150}$ Nd - $^{150}$ Sm ( $0_1^+; 740.4 \text{ keV}$ )

There is only one positive result from a direct (counting) experiment [51]:

$$T_{1/2} = [1.33^{+0.36}_{-0.23}(stat)^{+0.27}_{-0.13}(syst)] \cdot 10^{20} \text{yr.}$$

The preliminary result of this work was published in [68].

# **K.** $^{238}$ **U**

There is again only one positive result, but this time from a radiochemical experiment [52]:

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

# L. 130Ba (ECEC)

Here the only positive result is from a geochemical experiment [53]:

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

In geochemical experiments it is not possible to recognise the different modes. But I believe this value is for the  $ECEC(2\nu)$  process because other modes are strongly suppressed (see, for example, estimations in [7, 70]).

In fact, the first indication of a "positive" result for  $^{130}$ Ba was obtained in Ref. [69]  $(T_{1/2} = 2.1^{+3.0}_{-0.8} \cdot 10^{21} \text{ yr})$  but has not been seriously taken into account.

### IV. NME VALUES FOR TWO NEUTRINO DOUBLE BETA DECAY

A summary of the half-life values are presented in Table II. Using the relation  $T_{1/2}^{-1} = G \cdot (M^{2\nu})^2$ , where G is the phase space factor and  $M^{2\nu}$  is the nuclear matrix element, one can calculate  $M^{2\nu}$  values for all the above mentioned isotopes. The results of these calculations are presented in Table II (3-d column). To do the calculations, I used the G values from Ref. [71] for all isotopes with the exception of  $^{238}$ U, for which the G value from Ref. [72] was used. The transition of  $^{100}$ Mo to the  $0_1^+$  excited state of  $^{100}$ Ru used the value  $G = 1.64 \cdot 10^{-19} yr^{-1}$  [73]. Recollect that G is in units of  $yr^{-1}$  given for  $g_A = 1.254$  and  $M^{2\nu}$  is scaled by the electron rest mass. One can see that we now have  $M^{2\nu}$  with an accuracy of  $\sim 3-14\%$ . Here it is easily noticed that the G value was calculated by different authors (see Ref. [71], Ref. [74], Ref. [72] and Ref. [75]). All these results are in good agreement for the majority of isotopes with differences less than 1%. The exception being  $^{96}$ Zr with a difference of  $\sim 6\%$ ;  $^{100}$ Mo ( $\sim 6\%$ ); and  $^{116}$ Cd ( $\sim 8\%$ ). One can consider these differences as systematic errors in the G value. It means that the accuracy for  $M^{2\nu}$  for these three isotopes is limited to the

accuracy of G and is at present on the level of  $\sim 4-6\%$ . It is possible in the future that the G calculations for these three isotopes will be improved.

## V. 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 <sup>128</sup>Te and <sup>130</sup>Te, the so-called "recommended" values have been proposed. Using these half-life values, NMEs for two neutrino double beta decay were obtained. A summary is collected in Table II. I strongly recommend the use of these values as presently the most reliable.

Notice that the accurate half-life (or  $M^{2\nu}$ ) values for  $2\nu\beta\beta$  decay could be used to adjust the most relevant parameter of the quasiparticle random-phase approximation (QRPA) model, the strength of the particle-particle interaction  $g_{pp}$ . It will give the possibility to improve the quality of NME calculations for neutrinoless double beta decay and, finally, to improve the quality of neutrino mass  $\langle m_{\nu} \rangle$  estimations.

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<sup>[1]</sup> R. Arnold *et al.*, Phys. Rev. Lett. **95**, 182302 (2005).

<sup>[2]</sup> V.A. Rodin et al., Nucl. Phys. A 766, 107 (2006); A 793, 213 (2007).

<sup>[3]</sup> M. Kortelainen, and J. Suhonen, Phys. Rev. C **76**, 024315 (2007).

<sup>[4]</sup> M. Kortelainen, and J. Suhonen, Phys. Rev. C 75, 051303(R) (2007).

<sup>[5]</sup> F. Simkovic, A. Faessler, V. Rodin, P. Vogel and J. Engel, Phys. Rev. C 77, 045503 (2008).

<sup>[6]</sup> F. Simkovic, P. Domin, and S.V. Semenov, J. Phys. G 27, 2233 (2001).

<sup>[7]</sup> P. Domin et al., Nucl. Phys. A **753**, 337 (2005).

<sup>[8]</sup> A. Dolgov, and A. Smirnov, Phys. Lett. B **621**, 1 (2005).

<sup>[9]</sup> A.S. Barabash et al., Nucl. Phys. B **783**, 90 (2007).

- [10] A.S. Barabash, Czech. J. Phys. **52**, 567 (2002).
- [11] A.S. Barabash, Czech. J. Phys. **56**, 437 (2006).
- [12] D.E. Groom et al., (Particle Data Group), Eur. Phys. J. C 15, 10 (2000).
- [13] A. Balysh et al., Phys. Rev. Lett. 77, 5186 (1996).
- [14] V.B. Brudanin et al., Phys. Lett. B 495, 63 (2000).
- [15] R.L. Flack, and the NEMO-3 Collaboration, J. Phys.: Conf. Ser. 136, 022032 (2008); J. Argyriades et al., nucl-ex/0906.2694.
- [16] A.A. Vasenko *et al.*, Mod. Phys. Lett. A **5**, 1299 (1990).
- [17] H.S. Miley, F.T. Avignone, R.L. Brodzinski, J.I. Collar and J.H. Reeves, Phys. Rev. Lett. 65, 3092 (1990).
- [18] F.T. Avignone et al., Phys. Lett. B 256, 559 (1991).
- [19] F.T. Avignone, Prog. Part. Nucl. Phys. **32**, 223 (1994).
- [20] A. Morales, Nucl. Phys. B (Proc. Suppl.) 77, 335 (1999).
- [21] C. Dorr, and H.V. Klapdor-Kleingrothaus, Nucl. Instr. Meth. A 513, 596 (2003).
- [22] S.R. Elliott, A.A. Hahn, M.K. Moe, M.A. Nelson and M.A. Vient, Phys. Rev. C 46, 1535 (1992).
- [23] R. Arnold et al., Nucl. Phys. A 636, 209 (1998).
- [24] T. Kirsten et al., in Proc. Int. Symp. "Nuclear Beta Decay and Neutrino (Osaka'86)", (World Scientific, Singapore, 1986), p.81.
- [25] R. Arnold et al., Nucl. Phys. A 658, 299 (1999).
- [26] A. Kawashima, K. Takahashi, and A. Masuda, Phys. Rev. C 47, R2452 (1993).
- [27] M.E. Wieser, and J.R. De Laeter, Phys. Rev. C 64, 024308 (2001).
- [28] H. Ejiri et al., Phys. Lett. B 258, 17 (1991).
- [29] S.R. Elliott, M.K. Moe, M.A. Nelson, and M.A. Vient, J. Phys. G 17, S145 (1991).
- [30] D. Dassie et al., Phys. Rev. D 51, 2090 (1995).
- [31] M. Alston-Garnjost et al., Phys. Rev. C 55, 474 (1997).
- [32] A. De Silva, M.K. Moe, M.A. Nelson, and M.A. Vient, Phys. Rev. C 56, 2451 (1997).
- [33] V.D. Ashitkov et al., JETP Lett. **74**, 529 (2001).
- [34] H. Hidaka, C.V. Ly, and K. Suzuki, Phys. Rev. C 70, 025501 (2004).
- [35] A.S. Barabash *et al.*, Phys. Lett. B **345**, 408 (1995).
- [36] A.S. Barabash et al., Phys. At. Nucl. 62, 2039 (1999).

- [37] L. De Braeckeleer, M. Hornish, A. Barabash and V. Umatov, Phys. Rev. Lett. 86, 3510 (2001).
- [38] M.F. Kidd *et al.*, Nucl. Phys. A **821**, 251 (2009).
- [39] R. Arnold et al., Nucl. Phys. A **781**, 209 (2007).
- [40] H. Ejiri et al., J. Phys. Soc. of Japan 64, 339 (1995).
- [41] F.A. Danevich et al., Phys. Rev. C 68, 035501 (2003).
- [42] R. Arnold et al., Z. Phys. C **72**, 239 (1996).
- [43] O.K. Manuel, J. Phys. G 17, 221 (1991).
- [44] T. Bernatowicz et al., Phys. Rev. C 47, 806 (1993).
- [45] A.P. Meshik et al., Nucl. Phys. A 809, 275 (2008).
- [46] H.V. Thomas, R.A.D. Pattrick, S.A. Crowther, D.J. Blagburn and J.D. Gilmour, Phys. Rev. C 78, 054606 (2008).
- [47] C. Arnaboldi et al., Phys. Lett. B **557**, 167 (2003).
- [48] V.I. Tretyak, and the NEMO-3 Collaboration, AIP Conf. Proc. 1180, 135 (2009).
- [49] V. Artemiev et al., Phys. Lett. B **345**, 564 (1995).
- [50] J. Argyriades et al., Phys. Rev. C 80, 032501(R) (2009).
- [51] A.S. Barabash, P. Hubert, A. Nachab and V.I. Umatov, Phys. Rev. C 79, 045501 (2009).
- [52] A.L. Turkevich, T.E. Economou, and G.A. Cowan, Phys. Rev. Lett. 67, 3211 (1991).
- [53] A.P. Meshik, C.M. Hohenberg, O.V. Pravdivtseva and Y.S. Kapusta, Phys. Rev. C 64, 035205 (2001) .
- [54] H.V. Klapdor-Kleingrothaus et. al., Eur. Phys. J. A 12, 147 (2001).
- [55] A.M. Bakalyarov et al., Phys. Part. Nucl. Lett. 2, 77 (2005); arXiv:hep-ex/0309016.
- [56] A.S. Barabash and V.I. Umatov, ITEP note, 1990 (unpublished).
- [57] O.K. Manuel, in Proc. Int. Symp. "Nuclear Beta Decay and Neutrino (Osaka'86)", (World Scientific, Singapore, 1986), p.71.
- [58] A.S. Barabash, JETP Lett. 68, 1 (1998); Eur. Phys. J. A 8, 137 (2000); Astrophysics and Space Science 283, 607 (2003).
- [59] S.R. Elliott, A.A. Hahn and M.K. Moe, Phys. Rev. Lett. **59**, 2020 (1987).
- [60] S.I. Vasil'ev et al., JETP Lett. **51**, 622 (1990).
- [61] A. Vareille, Ph.D. thesis of Bordeaux University, C.E.N.B.G. 97-03 (1997).
- [62] R. Arnold et al., JETP Lett. 80, 377 (2004).
- [63] Yu.A. Shitov, and NEMO Collaboration, Phys. At. Nucl. 69, 2090 (2006).

- [64] N. Takaoka and K. Ogata, Z. Naturforsch **21a**, 84 (1966).
- [65] N. Takaoka, Y. Motomura and K. Nagao, Phys. Rev. C 53, 1557 (1996).
- [66] W.J. Lin et al., Nucl. Phys. A 457, 285 (1986).
- [67] B. Srinivasan et al., Econ. Geol. 68, 252 (1973).
- [68] A.S. Barabash et al., JETP Lett. **79**, 10 (2004).
- [69] A.S. Barabash and R.R. Saakyan, Phys. At. Nucl. 59, 179 (1996).
- [70] S. Singh *et al.*, Eur. Phys. J. A **33**, 375 (2007).
- [71] J. Suhonen and O. Civitarese, Phys. Rep. **300**, 123 (1998).
- [72] F. Boehm and P. Vogel, *Physics of Massive Neutrinos*, Cambridge University Press, Cambridge, 1987.
- [73] J. Suhonen, private communication.
- [74] M. Doi, T. Kotani, and E. Takasugi, Prog. Theor. Phys. Suppl. 83, 1 (1985).
- [75] F. Simkovic, private communication (unpublished).

TABLE I: Present, "positive"  $2\nu\beta\beta$  decay results. Here, N is the number of useful events,  $T_{1/2}$  is a half-life, and S/B is the signal-to-background ratio.

<sup>a)</sup> For  $E_{2e} > 1.2$  MeV; <sup>b)</sup> after correction (see text); <sup>c)</sup> for the SSD mechanism; <sup>d)</sup> in both peaks.

Nucleus	N	$T_{1/2},  { m yr}$	S/B	Ref., year
<sup>48</sup> Ca	~ 100	$[4.3^{+2.4}_{-1.1}(stat) \pm 1.4(syst)] \cdot 10^{19}$	1/5	[13], 1996
	5	$4.2^{+3.3}_{-1.3} \cdot 10^{19}$	5/0	[14], 2000
	116	$[4.4^{+0.5}_{-0.4}(stat)\pm0.4(syst)\cdot10^{19}$	6.8	[15], 2008
		Average value: $4.4^{+0.6}_{-0.5} \cdot 10^{19}$		
$^{76}\mathrm{Ge}$	$\sim 4000$	$(0.9 \pm 0.1) \cdot 10^{21}$	$\sim 1/8$	[16], 1990
	758	$1.1^{+0.6}_{-0.3} \cdot 10^{21}$	$\sim 1/6$	[17], 1991
	$\sim 330$	$0.92^{+0.07}_{-0.04} \cdot 10^{21}$	$\sim 1.2$	[18], 1991
	132	$1.2^{+0.2}_{-0.1} \cdot 10^{21}$	$\sim 1.4$	[19], 1994
	$\sim 3000$	$(1.45 \pm 0.15) \cdot 10^{21}$	$\sim 1.5$	[20], 1999
	$\sim 80000$	$[1.74 \pm 0.01(stat)^{+0.18}_{-0.16}(syst)] \cdot 10^{21}$	$\sim 1.5$	[21], 2003
		Average value: $(1.5 \pm 0.1) \cdot 10^{21}$		
	89.6	$1.08^{+0.26}_{-0.06} \cdot 10^{20}$	~ 8	[22], 1992
$^{82}\mathrm{Se}$	149.1	$[0.83 \pm 0.10(stat) \pm 0.07(syst)] \cdot 10^{20}$	2.3	[23], 1998
	2750	$[0.96 \pm 0.03(stat) \pm 0.1(syst)] \cdot 10^{20}$	4	[1], 2005
		$(1.3 \pm 0.05) \cdot 10^{20}$ (geochem.)		[24], 1986
		Average value: $(0.92 \pm 0.07) \cdot 10^{20}$		
$^{96}\mathrm{Zr}$	26.7	$[2.1^{+0.8}_{-0.4}(stat) \pm 0.2(syst)] \cdot 10^{19}$	$1.9^{a)}$	[25], 1999
	453	$[2.35 \pm 0.14(stat) \pm 0.19(syst)] \cdot 10^{19}$	1	[15], 2009
		$(3.9 \pm 0.9) \cdot 10^{19}$ (geochem.)		[26], 1993
		$(0.94 \pm 0.32) \cdot 10^{19}$ (geochem.)		[27], 2001
		Average value: $(2.3\pm0.2)\cdot10^{19}$		

TABLE I: continued.

$^{100}\mathrm{Mo}$	$\sim 500$	$11.5^{+3.0}_{-2.0} \cdot 10^{18}$	1/7	[28], 1991
1,10	67	$11.6^{+3.4}_{-0.8} \cdot 10^{18}$	7	[29], 1991
	1433	$[7.3 \pm 0.35(stat) \pm 0.8(syst)] \cdot 10^{18b}$	3	[30], 1995
	175	$7.6^{+2.2}_{-1.4} \cdot 10^{18}$	1/2	[31], 1997
	377	1.1	10	
		$[6.75^{+0.37}_{-0.42}(stat) \pm 0.68(syst)] \cdot 10^{18}$		[32], 1997
	800	$[7.2 \pm 1.1(stat) \pm 1.8(syst)] \cdot 10^{18}$	1/9	[33], 2001
	219000	$[7.11 \pm 0.02(stat) \pm 0.54(syst)] \cdot 10^{18c}$	40	[1], 2005
		$(2.1 \pm 0.3) \cdot 10^{18}$ (geochem.)		[34], 2004
		Average value: $(7.1 \pm 0.4) \cdot 10^{18}$		
<sup>100</sup> Mo -	$133^{d)}$	$6.1^{+1.8}_{-1.1} \cdot 10^{20}$	1/7	[35], 1995
$^{100}$ Ru $(0_1^+)$	$153^{d)}$	$[9.3^{+2.8}_{-1.7}(stat) \pm 1.4(syst)] \cdot 10^{20}$	1/4	[36], 1999
	19.5	$[5.9^{+1.7}_{-1.1}(stat) \pm 0.6(syst)] \cdot 10^{20}$	$\sim 8$	[37], 2001
	35.5	$[5.5^{+1.2}_{-0.8}(stat) \pm 0.3(syst)] \cdot 10^{20}$	~ 8	[38], 2009
	37.5	$[5.7^{+1.3}_{-0.9}(stat) \pm 0.8(syst)] \cdot 10^{20}$	$\sim 3$	[39], 2007
		Average value: $5.9^{+0.8}_{-0.6} \cdot 10^{20}$		
<sup>116</sup> Cd	~ 180	$2.6^{+0.9}_{-0.5} \cdot 10^{19}$	$\sim 1/4$	[40], 1995
	9850	$[2.9 \pm 0.06(stat)^{+0.4}_{-0.3}(syst)] \cdot 10^{19}$	$\sim 3$	[41], 2003
	174.6	$[2.9 \pm 0.3(stat) \pm 0.2(syst)] \cdot 10^{19b}$	3	[42], 1996
	1370	$[2.8 \pm 0.1(stat) \pm 0.3(syst)] \cdot 10^{19c}$	7.5	[15], 2008
		Average value: $(2.8\pm0.2)\cdot10^{19}$		
<sup>128</sup> Te		$\sim 2.2 \cdot 10^{24} \text{ (geochem.)}$		[43], 1991
		$(7.7 \pm 0.4) \cdot 10^{24} \text{ (geochem.)}$		[44], 1993
		$(2.41 \pm 0.39) \cdot 10^{24} \text{ (geochem.)}$		[45], 2008
		$(2.3 \pm 0.3) \cdot 10^{24}$ (geochem.)		[46], 2008
		Recommended value: $(1.9 \pm 0.4) \cdot 10^{24}$		

TABLE I: continued 2.

$^{130}\mathrm{Te}$	260	$[6.1 \pm 1.4(stat)^{+2.9}_{-3.5}(syst)] \cdot 10^{20}$	1/8	[47], 2003
	236	$[6.9 \pm 0.9(stat)^{+1.0}_{-0.7}(syst)] \cdot 10^{20}$	1/3	[48], 2009
		$\sim 8 \cdot 10^{20}$ (geochem.)		[43], 1991
		$(27 \pm 1) \cdot 10^{20}$ (geochem.)		[44], 1993
		$(9.0 \pm 1.4) \cdot 10^{20}$ (geochem.)		[45], 2008
		$(8.0 \pm 1.1) \cdot 10^{20}$ (geochem.)		[46], 2008
		Recommended value: $(6.8^{+1.2}_{-1.1}) \cdot 10^{20}$		
$^{150}\mathrm{Nd}$	23	$[18.8^{+6.9}_{-3.9}(stat)\pm1.9(syst)]\cdot10^{18}$	1.8	[49], 1995
	414	$[6.75^{+0.37}_{-0.42}(stat)\pm0.68(syst)]\cdot10^{18}$	6	[32], 1997
	2018	$[9.11^{+0.25}_{-0.22}(stat) \pm 0.63(syst)] \cdot 10^{18}$	2.8	[50], 2009
		Average value: $(8.2 \pm 0.9) \cdot 10^{18}$		
<sup>150</sup> Nd -	$177.5^{d)}$	$[1.33^{+0.36}_{-0.23}(stat)^{+0.27}_{-0.13}(syst)] \cdot 10^{20}$	1/5	[51], 2009
$^{150}$ Sm $(0_1^+)$		Average value: $1.33^{+0.45}_{-0.26} \cdot 10^{20}$		
<sup>238</sup> U		$(2.0 \pm 0.6) \cdot \mathbf{10^{21}} \text{ (radiochem.)}$		[52], 1991
<sup>130</sup> Ba		$(\mathbf{2.2 \pm 0.5}) \cdot \mathbf{10^{21}} \; (\mathrm{geochem.})$		[53], 2001
$ECEC(2\nu)$				

TABLE II: Half-life and nuclear matrix element values for two neutrino double beta decay (see Sec. IV).

Isotope	$T_{1/2}(2\nu)$ , yr	$M^{2 u}$
$^{48}\mathrm{Ca}$	$4.4^{+0.6}_{-0.5} \cdot 10^{19}$	$0.0238^{+0.0015}_{-0.0017}$
$^{76}\mathrm{Ge}$	$(1.5 \pm 0.1) \cdot 10^{21}$	$0.0716^{+0.0025}_{-0.0023}$
$^{82}\mathrm{Se}$	$(0.92 \pm 0.07) \cdot 10^{20}$	$0.0503^{+0.0020}_{-0.0018}$
$^{96}{ m Zr}$	$(2.3 \pm 0.2) \cdot 10^{19}$	$0.0491^{+0.0023}_{-0.0020}$
$^{100}\mathrm{Mo}$	$(7.1 \pm 0.4) \cdot 10^{18}$	$0.1258^{+0.0037}_{-0.0034}$
$^{100}\mathrm{Mo}\text{-}^{100}\mathrm{Ru}(0_1^+)$	$5.9^{+0.8}_{-0.6} \cdot 10^{20}$	$0.1017^{+0.0056}_{-0.0063}$
$^{116}\mathrm{Cd}$	$(2.8 \pm 0.2) \cdot 10^{19}$	$0.0695^{+0.0025}_{-0.0024} \\$
$^{128}\mathrm{Te}$	$(1.9 \pm 0.4) \cdot 10^{24}$	$0.0249^{+0.0031}_{-0.0023}$
$^{130}\mathrm{Te}$	$(6.8^{+1.2}_{-1.1}) \cdot 10^{20}$	$0.0175^{+0.0016}_{-0.0014}$
$^{150}\mathrm{Nd}$	$(8.2 \pm 0.9) \cdot 10^{18}$	$0.0320^{+0.0018}_{-0.0017}$
$^{150}\mathrm{Nd}$ - $^{150}\mathrm{Sm}(0_1^+)$	$1.33^{+0.45}_{-0.26} \cdot 10^{20}$	$0.0250^{+0.0029}_{-0.0034}$
$^{238}\mathrm{U}$	$(2.0 \pm 0.6) \cdot 10^{21}$	$0.0271^{+0.0053}_{-0.0033}$
$^{130}$ Ba; ECEC $(2\nu)$	$(2.2 \pm 0.5) \cdot 10^{21}$	$0.105^{+0.014}_{-0.010}$