Precise half-life values for two-neutrino double-β decay

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(Received 23 December 2009; published 3 March 2010)

All existing positive results on two-neutrino double-β 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, ^{130}Te, ^{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. 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.

DOI: 10.1103/PhysRevC.81.035501 PACS number(s): 23.40.−s, 14.60.Pq, 21.10.Tg, 27.50.+e

I. INTRODUCTION

At present, the two-neutrino double-β ($2\nu\beta\beta$) 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 these results were obtained in a few tens of geochemical experiments and more than 30 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 Neutrino Ettore Majorana Observatory (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:

(i) Regarding nuclear spectroscopy, now we know that some isotopes that were earlier considered to be stable are not, and decay via the double-β decay processes with a half-life period of $\sim 10^{18}$–10^{21} years is observed. The values presented here should be introduced into the isotope table.

(ii) First it gives the possibility to improve the quality of nuclear matrix element (NME) calculations for two-neutrino double-β decay so that one can directly compare experimental and calculated values. Second, it gives the possibility to improve the quality of NME calculations for neutrinoless double-β 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].

(iii) 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 this work was done was in 2001, and the results were presented at the International Workshop on the Calculation of Double-β 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 I. 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 (Ref. [12]), was used. The weighted average and the corresponding error were calculated as follows:

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

where $w_i = 1/(\delta x_i)^2$. Here x_i and δx_i are the value and error reported by the ith experiment, and the summations run over 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 χ^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 ($\gg$1), one chooses not to use the average. Alternatively, one may quote the calculated

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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.

Nucleus	N	$T_{1/2}$ (years)	S/B	Ref. (year)
^{48}Ca	∼100	$\left[4.3^{+2.4}_{-1.1}(\text{stat}) \pm 1.4(\text{syst})\right] \times 10^{19}$	1/5	Ref. [13] (1996)
	5	$4.2^{+3.3}_{-1.3} \times 10^{19}$	5/0	Ref. [14] (2000)
	116	$\left[4.4^{+0.5}_{-0.4}(\text{stat}) \pm 0.4(\text{syst})\right] \times 10^{19}$	6.8	Ref. [15] (2008)
		Average value: $4.4^{+0.6}_{-0.5} \times 10^{19}$		
^{76}Ge	∼4000	$(0.9 \pm 0.1) \times 10^{21}$	∼1/8	Ref. [16] (1990)
	758	$1.1^{+0.6}_{-0.3} \times 10^{21}$	∼1/6	Ref. [17] (1991)
	∼330	$0.92^{+0.07}_{-0.04} \times 10^{21}$	∼1.2	Ref. [18] (1991)
	132	$1.2^{+0.2}_{-0.1} \times 10^{21}$	∼1.4	Ref. [19] (1994)
	∼3000	$(1.45 \pm 0.15) \times 10^{21}$	∼1.5	Ref. [20] (1999)
	∼80,000	$\left[1.74 \pm 0.01(\text{stat})^{+0.18}_{-0.16}(\text{syst})\right] \times 10^{21}$	∼1.5	Ref. [21] (2003)
		Average value: $(1.5 \pm 0.1) \times 10^{21}$		
^{82}Se	89.6	$1.08^{+0.26}_{-0.06} \times 10^{20}$	∼8	Ref. [22] (1992)
	149.1	$\left[0.83 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})\right] \times 10^{20}$	2.3	Ref. [23] (1998)
	2750	$\left[0.96 \pm 0.03(\text{stat}) \pm 0.1(\text{syst})\right] \times 10^{20}$	4	Ref. [1] (2005)
		$(1.3 \pm 0.05) \times 10^{20}$ (geochem.)		Ref. [24] (1986)
		Average value: $(0.92 \pm 0.07) \times 10^{20}$		
^{96}Zr	26.7	$\left[2.1^{+0.8}_{-0.4}(\text{stat}) \pm 0.2(\text{syst})\right] \times 10^{19}$	1.9[a]	Ref. [25] (1999)
	453	$[2.35 \pm 0.14(\text{stat}) \pm 0.19(\text{syst})] \times 10^{19}$	1	Ref. [15] (2009)
		$(3.9 \pm 0.9) \times 10^{19}$ (geochem.)		Ref. [26] (1993)
		$(0.94 \pm 0.32) \times 10^{19}$ (geochem.)		Ref. [27] (2001)
		Average value: $(2.3 \pm 0.2) \times 10^{19}$		
^{100}Mo	∼500	$11.5^{+3.0}_{-2.0} \times 10^{18}$	1/7	Ref. [28] (1991)
	67	$11.6^{+3.4}_{-0.8} \times 10^{18}$	7	Ref. [29] (1991)
	1433	$[7.3 \pm 0.35(\text{stat}) \pm 0.8(\text{syst})] \times 10^{18}$[b]	3	Ref. [30] (1995)
	175	$7.6^{+2.2}_{-1.4} \times 10^{18}$	1/2	Ref. [31] (1997)
	377	$\left[6.75^{+0.37}_{-0.42}(\text{stat}) \pm 0.68(\text{syst})\right] \times 10^{18}$	10	Ref. [32] (1997)
	800	$[7.2 \pm 1.1(\text{stat}) \pm 1.8(\text{syst})] \times 10^{18}$	1/9	Ref. [33] (2001)
	219,000	$[7.11 \pm 0.02(\text{stat}) \pm 0.54(\text{syst})] \times 10^{18}$[c]	40	Ref. [1] (2005)
		$(2.1 \pm 0.3) \times 10^{18}$ (geochem.)		Ref. [34] (2004)
		Average value: $(7.1 \pm 0.4) \times 10^{18}$		
^{100}Mo-^{100}Ru (0^+_1)	133[d]	$6.1^{+1.8}_{-1.1} \times 10^{20}$	1/7	Ref. [35] (1995)
	153[d]	$\left[9.3^{+2.8}_{-1.7}(\text{stat}) \pm 1.4(\text{syst})\right] \times 10^{20}$	1/4	Ref. [36] (1999)
	19.5	$\left[5.9^{+1.7}_{-1.1}(\text{stat}) \pm 0.6(\text{syst})\right] \times 10^{20}$	∼8	Ref. [37] (2001)
	35.5	$\left[5.5^{+1.2}_{-0.8}(\text{stat}) \pm 0.3(\text{syst})\right] \times 10^{20}$	∼8	Ref. [38] (2009)
	37.5	$\left[5.7^{+1.3}_{-0.9}(\text{stat}) \pm 0.8(\text{syst})\right] \times 10^{20}$	∼3	Ref. [39] (2007)
		Average value: $5.9^{+0.8}_{-0.6} \times 10^{20}$		
^{116}Cd	∼180	$2.6^{+0.9}_{-0.5} \times 10^{19}$	∼1/4	Ref. [40] (1995)
	9850	$[2.9 \pm 0.06(\text{stat})^{+0.4}_{-0.3}(\text{syst})] \times 10^{19}$	∼3	Ref. [41] (2003)
	174.6	$[2.9 \pm 0.3(\text{stat}) \pm 0.2(\text{syst})] \times 10^{19}$[b]	3	Ref. [42] (1996)
	1370	$[2.8 \pm 0.1(\text{stat}) \pm 0.3(\text{syst})] \times 10^{19}$[c]	7.5	Ref. [15] (2008)
		Average value: $(2.8 \pm 0.2) \times 10^{19}$		

TABLE I. *(Continued.)*

Nucleus	N	$T_{1/2}$ (years)	S/B	Ref. (year)
^{128}Te		$\sim 2.2 \times 10^{24}$ (geochem.)		Ref. [43] (1991)
		$(7.7 \pm 0.4) \times 10^{24}$ (geochem.)		Ref. [44] (1993)
		$(2.41 \pm 0.39) \times 10^{24}$ (geochem.)		Ref. [45] (2008)
		$(2.3 \pm 0.3) \times 10^{24}$ (geochem.)		Ref. [46] (2008)
		Recommended value: $(1.9 \pm 0.4) \times 10^{24}$		
^{130}Te	260	$[6.1 \pm 1.4(\text{stat})^{+2.9}_{-3.5}(\text{syst})] \times 10^{20}$	1/8	Ref. [47] (2003)
	236	$\left[6.9 \pm 0.9(\text{stat})^{+1.0}_{-0.7}(\text{syst})\right] \times 10^{20}$	1/3	Ref. [48] (2009)
		$\sim 8 \times 10^{20}$ (geochem.)		Ref. [43] (1991)
		$(27 \pm 1) \times 10^{20}$ (geochem.)		Ref. [44] (1993)
		$(9.0 \pm 1.4) \times 10^{20}$ (geochem.)		Ref. [45] (2008)
		$(8.0 \pm 1.1) \times 10^{20}$ (geochem.)		Ref. [46] (2008)
		Recommended value: $\left(6.8^{+1.2}_{-1.1}\right) \times 10^{20}$		
^{150}Nd	23	$\left[18.8^{+6.9}_{-3.9}(\text{stat}) \pm 1.9(\text{syst})\right] \times 10^{18}$	1.8	Ref. [49] (1995)
	414	$\left[6.75^{+0.37}_{-0.42}(\text{stat}) \pm 0.68(\text{syst})\right] \times 10^{18}$	6	Ref. [32] (1997)
	2018	$\left[9.11^{+0.25}_{-0.22}(\text{stat}) \pm 0.63(\text{syst})\right] \times 10^{18}$	2.8	Ref. [50] (2009)
		Average value: $(8.2 \pm 0.9) \times 10^{18}$		
^{150}Nd-^{150}Sm (0^+_1)	177.5[d]	$\left[1.33^{+0.36}_{-0.23}(\text{stat})^{+0.27}_{-0.13}(\text{syst})\right] \times 10^{20}$	1/5	Ref. [51] (2009)
		Average value: $1.33^{+0.45}_{-0.26} \times 10^{20}$		
^{238}U		$(2.0 \pm 0.6) \times 10^{21}$ (radiochem.)		Ref. [52] (1991)
^{130}Ba; ECEC(2ν)		$(2.2 \pm 0.5) \times 10^{21}$ (geochem.)		Ref. [53] (2001)

[a]For $E_{2e} > 1.2$ MeV.
[b]After correction (see text).
[c]For the SSD mechanism.
[d]In both peaks.

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 Eq. (1), by a factor of S, defined by

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

For averages, the statistical and systematic errors are treated in quadrature and used as a combined error δx_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 (0^+_1), 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 ^{48}Ca was observed [13–15]. The results are in good agreement. The weighted average value is

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

B. ^{76}Ge

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

(i) The result of the Heidelberg-Moscow group has been corrected. Instead of the previously published value of $T_{1/2} = [1.55 \pm 0.01(\text{stat})^{+0.19}_{-0.15}(\text{syst})] \times 10^{21}$ years [54], a new value $T_{1/2} = [1.74 \pm 0.01(\text{stat})^{+0.18}_{-0.16}(\text{syst})] \times 10^{21}$ years [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, $T_{1/2} = [1.78 \pm 0.01(\text{stat})^{+0.08}_{-0.10}(\text{syst})] \times 10^{21}$ years [55].

(ii) In Ref. [18], the value $T_{1/2} = 0.92^{+0.07}_{-0.04} \times 10^{21}$ years was presented. However, after a more careful analysis, this result has been changed to a value of

$T_{1/2} = 1.2^{+0.2}_{-0.1} \times 10^{21}$ years [19], which was used in the analysis.

(iii) The results presented in Ref. [16] do not agree with the more recent experiments [20,21]. Furthermore, the error presented in Ref. [16] appears to be too small, especially taking into account that the signal-to-background ratio in this experiment is equal to ∼1/8. It has been mentioned before [56] that the half-life value in this work can be ∼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

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

C. ^{82}Se

There are three independent counting experiments and many geochemical measurements (∼20) for ^{82}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 ^{82}Se, only the results of the direct measurements [1,22,23] were used. The result of Ref. [59] is the preliminary result of Ref. [22]; hence it has not been used in our analysis. The result of Ref. [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

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

D. ^{96}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 ^{96}Zr of

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

E. ^{100}Mo

Formally, there are seven positive results from direct experiments and one recent result from a geochemical experiment. I do not consider the result of Ref. [60] because of a potentially high background contribution that was not excluded in this experiment. In addition, I do not consider the preliminary result of Elliot *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 Monte Carlo (MC) was overestimated (see Ref. [61]). In addition, the half-life value was decreased by 10%, taking into account that for ^{100}Mo, we have the SSD mechanism (see discussion in Refs. [62,63]). The following weighted average value for this half-life is then obtained:

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

In the framework of the high-state dominance (HSD) mechanism (see Refs. [6,7]), the following average value was obtained:

$$T_{1/2} = (7.6 \pm 0.4) \times 10^{18} \text{ years.}$$

F. ^{100}Mo-^{100}Ru (0^+_1; 1130.29 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 Refs. [35,36,38,39] is

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

The result from Ref. [37] was not used here because I considered the result from Ref. [38] as the final result of the Triangle Universities Nuclear Laboratory-Institute of Theoretical and Experimental Physics (TUNL-ITEP) experiment.

G. ^{116}Cd

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 ∼25% (see remark in Sec. III E). The weighted average value for the SSD mechanism is

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

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

H. ^{128}Te and ^{130}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 (∼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 $T_{1/2} \approx 0.8 \times 10^{21}$ years for ^{130}Te and $T_{1/2} \approx 2 \times 10^{24}$ years for ^{128}Te, whereas the next group [24,44] claims

$T_{1/2} \approx (2.5\text{–}2.7) \times 10^{21}$ years and $T_{1/2} \approx 7.7 \times 10^{24}$ years, respectively. Furthermore, as a rule, experiments with young samples (∼100 million years) give results of the half-life value of ^{130}Te in the range of $\sim(0.7\text{–}0.9) \times 10^{21}$ years, while old samples (>1 billion years) have half-life values in the range of $\sim(2.5\text{–}2.7) \times 10^{21}$ years. 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 $T_{1/2}(^{130}\text{Te})/T_{1/2}(^{128}\text{Te}) = (3.52 \pm 0.11) \times 10^{-4}$, 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, yielding 7.3 ± 0.9 [66], 12.5 ± 0.9 [24], and 10 ± 2 [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 $T_{1/2} = (0.92 \pm 0.07) \times 10^{20}$ years and the value 9.9 ± 1.5 for the $T_{1/2}(^{130}\text{Te})/T_{1/2}(^{82}\text{Se})$ ratio, one obtains the half-life value for ^{130}Te:

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

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

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

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 $(9.0 \pm 1.4) \times 10^{20}$ years [45] and $(8.0 \pm 1.1) \times 10^{20}$ years [46] for ^{130}Te and $(2.41 \pm 0.39) \times 10^{24}$ years [45] and $(2.3 \pm 0.3) \times 10^{24}$ years [46] for ^{128}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 ^{130}Te in a direct experiment was obtained in Ref. [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

$$T_{1/2} = \left(6.8^{+1.2}_{-1.1}\right) \times 10^{20} \text{ years.}$$

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

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

I recommend the use of these last two results as the best present half-life values for ^{130}Te and ^{128}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] (∼3σ and ∼2σ differences, respectively). Using Eq. (1) and three existing values, one obtains $T_{1/2} = (8.2 \pm 0.5) \times 10^{18}$ years. Taking into account the fact that $\chi^2 > 1$ and $S = 1.89$ [see Eq. (2)], I then obtain

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

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

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

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

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

K. ^{238}U

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

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

L. ^{130}Ba (ECEC)

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

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

In geochemical experiments, it is not possible to recognize the different modes, but I believe this value is for the ECEC(2ν) process because other modes are strongly suppressed (see, e.g., estimations in Refs. [7,69]). In fact, the first indication of a positive result for ^{130}Ba was obtained in Ref. [70] ($T_{1/2} = 2.1^{+3.0}_{-0.8} \times 10^{21}$ years) but has not been seriously taken into account.

IV. NME VALUES FOR TWO-NEUTRINO DOUBLE-β DECAY

A summary of the half-life values are presented in Table II. Using the relation $T^{-1}_{1/2} = G \cdot (M^{2\nu})^2$, 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 previously mentioned isotopes. The results of these calculations are presented in Table II. To do the calculations, I used the G values from Ref. [71] for all

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

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

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 $G = 1.64 \times 10^{-19}$ yr^{-1} [73]. Recollect that G is in units of yr^{-1}, given for $g_A = 1.254$, and that $M^{2\nu}$ is scaled by the electron rest mass. One can see that we now have $M^{2\nu}$ with an accuracy of ∼3%–14%. Here it is easily noticed that the G value was calculated by different authors (see Refs. [71,72,74,75]). All these results are in good agreement for the majority of isotopes, with differences less than 1%, the exceptions being ^{96}Zr, with a difference of ∼6%; ^{100}Mo, with a difference of ∼6%; and ^{116}Cd, with a difference of ∼8%. One can consider these differences as systematic errors in the G value. This 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 ∼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 ^{128}Te and ^{130}Te, the so-called recommended values have been proposed. Using these half-life values, NMEs for two-neutrino double-β decay were obtained. A summary is collected in Table II. I strongly recommend the use of these values as the most reliable presently.

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 QRPA model: the strength of the particle-particle interaction g_{pp}. This will make it possible to improve the quality of NME calculations for neutrinoless double-β decay and, finally, to improve the quality of neutrino mass $\langle m_\nu \rangle$ estimations.

ACKNOWLEDGMENTS

I am very thankful to S. Sutton for his useful remarks. A portion of this work was supported by grants from RFBR (Grant Nos. 06-02-72553 and 09-02-92676). This work was also supported by the Russian Federal Agency for Atomic Energy.

[1] R. Arnold *et al.*, Phys. Rev. Lett. **95**, 182302 (2005).
[2] V. A. Rodin *et al.*, Nucl. Phys. **A766**, 107 (2006); **A793**, 213 (2007).
[3] M. Kortelainen and J. Suhonen, Phys. Rev. C **76**, 024315 (2007).
[4] M. Kortelainen and J. Suhonen, Phys. Rev. C **75**, 051303(R) (2007).
[5] F. Simkovic, A. Faessler, V. Rodin, P. Vogel, and J. Engel, Phys. Rev. C **77**, 045503 (2008).
[6] F. Simkovic, P. Domin, and S. V. Semenov, J. Phys. G **27**, 2233 (2001).
[7] P. Domin *et al.*, Nucl. Phys. **A753**, 337 (2005).
[8] A. Dolgov and A. Smirnov, Phys. Lett. **B621**, 1 (2005).
[9] A. S. Barabash *et al.*, Nucl. Phys. **B783**, 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. **B495**, 63 (2000).
[15] R. L. Flack (NEMO-3 Collaboration), J. Phys. Conf. Ser. **136**, 022032 (2008); J. Argyriades *et al.*, arXiv:0906.2694[nucl-ex].
[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. **B256**, 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. Instrum. Methods 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. **A636**, 209 (1998).
[24] T. Kirsten *et al.*, in *Proceedings of the International Symposium "Nuclear Beta Decay and Neutrino (Osaka '86)"* (World Scientific, Singapore, 1986), p. 81.
[25] R. Arnold *et al.*, Nucl. Phys. **A658**, 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. **B258**, 17 (1991).
[29] S. R. Elliot, 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. **B345**, 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. **A821**, 251 (2009).
[39] R. Arnold *et al.*, Nucl. Phys. **A781**, 209 (2007).
[40] H. Ejiri *et al.*, J. Phys. Soc. Jpn. **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, J. Brannon, R. Brazzle, R. Cowsik, C. Hohenberg, and F. Podosek, Phys. Rev. C **47**, 806 (1993).
[45] A. P. Meshik *et al.*, Nucl. Phys. **A809**, 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. **B557**, 167 (2003).
[48] V. I. Tretyak (NEMO-3 Collaboration), AIP Conf. Proc. **1180**, 135 (2009).
[49] V. Artemiev *et al.*, Phys. Lett. **B345**, 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).
[56] A. S. Barabash and V. I. Umatov, ITEP note (1990).
[57] O. K. Manuel, in *Proceedings of the International Symposium "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); Astrophys. Space Sci. **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, Bordeaux University, 1997.
[62] R. Arnold *et al.*, JETP Lett. **80**, 377 (2004).
[63] Y. A. Shitov (NEMO Collaboration), Phys. At. Nucl. **69**, 2090 (2006).
[64] N. Takaoka and K. Ogata, Z. Naturforsch. A **21**, 84 (1966).
[65] N. Takaoka, Y. Motomura, and K. Nagao, Phys. Rev. C **53**, 1557 (1996).
[66] W. J. Lin *et al.*, Nucl. Phys. **A457**, 285 (1986).
[67] B. Srinivasan *et al.*, Econ. Geol. **68**, 252 (1973).
[68] A. S. Barabash *et al.*, JETP Lett. **79**, 10 (2004).
[69] S. Singh *et al.*, Eur. Phys. J. A **33**, 375 (2007).
[70] A. S. Barabash and R. R. Saakyan, Phys. At. Nucl. **59**, 179 (1996).
[71] J. Suhonen and O. Civitarese, Phys. Rep. **300**, 123 (1998).
[72] F. Boehm and P. Vogel, *Physics of Massive Neutrinos* (Cambridge Univ. 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).