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Systematics of Evaluated Double-Beta Decay Half-Life Times

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A new evaluation of 2β-decay half lives and their systematics is presented. These data extend the previous evaluation and include the analysis of all recent measurements. The nuclear matrix elements for 2β-decay transitions in 12 nuclei have been extracted. The recommended values are compared with the large-scale shell-model, QRPA calculations and experimental works. $T^{2\nu}_{1/2} \sim 1/E^8$ systematic trend has been observed for ^{128,130}Te recommended values. Such trend indicates similarities for nuclear matrix elements in Te nuclei and was predicted for $2\beta(2\nu)$-decay mode. The complete list of results is available online at *http://www.nndc.bnl.gov/bbdecay/*.

I. INTRODUCTION

Double-beta decay was originally proposed by M. Goeppert-Mayer in 1935 [1] as a nuclear disintegration with simultaneous emission of two electrons and two neutrinos

$$(Z, A) \to (Z + 2, A) + 2e^- + 2\bar{\nu}_e \qquad (1)$$

There are several double-beta decay processes: $2\beta^-$, $2\beta^+$, $\epsilon\ \beta^+$, 2ϵ and decay modes: two-neutrino (2ν), neutrinoless (0ν) and Majoron emission (χ^0)

$$(Z, A) \to (Z \pm 2, A) + (2e^{\pm}) + (2\bar{\nu}_e,\ 2\nu_e\ or\ \chi^0) \qquad (2)$$

2ν-mode is not prohibited by any conservation law and definitely occurs as a second-order process compared to the regular β-decay [2]. 0ν-mode differs from the 2ν-mode by the fact that only electrons are emitted during the decay. This normally requires that lepton number is not conserved and neutrino should contain a small fraction of massive particles that equals to its anti-particles (Majorana neutrino). Obviously, observation of $2\beta(0\nu)$-decay will have enormous implications on particle physics and fundamental symmetries. While observation of $2\beta(2\nu)$-decay will provide information on nuclear structure physics that can be used in 0ν-mode calculations.

Historically, search for double-beta decay has been a very hot topic in nuclear physics [3, 4]. Nuclear physicists and chemists employed a variety of direct (nuclear radiation detection) and geochemical methods. In the recent years claims have been made for observation of 0ν-decay mode in ^{76}Ge [5]. These, somewhat controversial, results were widely scrutinized and often rejected by the nuclear physics community [6, 7]. At the same time 2ν-decay mode has been definitely observed in the dozen of isotopes. Table I provides a brief review of 2β-decay observations. Due to extremely low probability for double beta decay it was detected first by analyzing chemical composition of rock samples and later verified by more accurate direct detection methods.

Experimental evidence and theoretical calculations indicate that probability for 2ν-mode is much higher than for 0ν-mode. In fact, ^{76}Ge 2β-decay measurements have demonstrated that decay rate for $2\beta(2\nu)$-decay is at least four orders of magnitude higher than $2\beta(0\nu)$. Therefore, I will concentrate on the experimentally observed 2ν-mode only.

II. COMPILATION AND EVALUATION OF EXPERIMENTAL DATA

Double-beta decay is an important nuclear physics process and experimental results, in this field, have been compiled by several groups [4, 8, 9]. Fig. 1 shows the online compilation and evaluation conducted at the National Nuclear Data Center [8, 10] since 2006. The 2β-decay observation data for isotopes of interest are shown in Table I. Due to space limitations, Table I lists only a single paper per nuclide for direct and geochemical discovery methods. A complete compilation is available from the NNDC website *http://www.nndc.bnl.gov/bbdecay/*. This compilation of experimental results includes results of previous [4] and recent works using the Nuclear Science References database [11, 12] searches. It was used to produce evaluated or recommended values.

Table II shows the latest recommended values which were deduced in the accordance with the U.S. Nuclear

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TABLE I. Brief history of experimental observations of 2β-decay and reported $T_{1/2}(2\beta)$ values. Results are shown for direct detection and geochemical methods.

Parent Nuclide	Process	Transition	Discovery Year		Originally Reported $T_{1/2}(\beta\beta)$, (y)		
			Direct	Geochemical	2ν, Direct	$(2+0)\nu$, Direct	$(2+0)\nu$, Geochemical
^{48}Ca	$2\beta^-$	$0^+ \to 0^+$	1996		4.3x10^{19} [13]		
^{76}Ge	$2\beta^-$	$0^+ \to 0^+$	1990		9.0x10^{20} [14]		
^{82}Se	$2\beta^-$	$0^+ \to 0^+$	1992	1969	1.08x10^{20} [16]		1.4x10^{20} [15]
^{96}Zr	$2\beta^-$	$0^+ \to 0^+$	1999	1993	2.1x10^{19} [18]		3.9x10^{19} [17]
^{100}Mo	$2\beta^-$	$0^+ \to 0^+$	1990		3.3x10^{18} [19]		
^{100}Mo	$2\beta^-$	$0^+ \to 0^+_1$	1995		9.5x10^{18} [20]		
^{100}Mo	$2\beta^-$	$0^+ \to 0^+_1$	1995			6.1x10^{20} [21]	
^{116}Cd	$2\beta^-$	$0^+ \to 0^+$	1995		2.7x10^{19} [22]		
^{128}Te	$2\beta^-$	$0^+ \to 0^+$		1975			1.5x10^{24} [23]
^{130}Te	$2\beta^-$	$0^+ \to 0^+$	2003	1966	6.1x10^{20} [25]		8.2x10^{20} [24]
^{136}Xe	$2\beta^-$	$0^+ \to 0^+$	2011		5.5x10^{21} [26]		
^{130}Ba	2ϵ	$0^+ \to 0^+$		2001			2.2x10^{21} [27]
^{150}Nd	$2\beta^-$	$0^+ \to 0^+$	1993		1.7x10^{19} [28]		
^{150}Nd	$2\beta^-$	$0^+ \to 0^+_1$	2004			1.4x10^{20} [29]	
^{238}U	$2\beta^-$	$0^+ \to 0^+$		1991			2.0x10^{21} [30]

TABLE II. The recommended $T_{1/2}(2\beta)$ and complimentary parameter values.

Parent Nuclide	Process	Transition	Q-value (keV)	β_2	$T^{2\nu}_{1/2}$(y)	$T^{2\nu+0\nu}_{1/2}$(y)
^{48}Ca	$2\beta^-$	$0^+ \to 0^+$	4267.0	0.2575(56)	(4.39±0.58)x10^{19}	
^{76}Ge	$2\beta^-$	$0^+ \to 0^+$	2039.06	0.3133(+55-20)	(1.43±0.53)x10^{21}	
^{82}Se	$2\beta^-$	$0^+ \to 0^+$	2996.4	0.2031(+30-28)	(9.19±0.76)x10^{19}	
^{96}Zr	$2\beta^-$	$0^+ \to 0^+$	3349.0	0.1525(27)	(2.16±0.26)x10^{19}	
^{100}Mo	$2\beta^-$	$0^+ \to 0^+$	3034.37	0.21539(90)	(6.98±0.44)x10^{18}	
^{100}Mo	$2\beta^-$	$0^+ \to 0^+_1$	2339.3		(5.70±1.36)x10^{20}	
^{100}Mo	$2\beta^-$	$0^+ \to 0^+_1$	2339.3			(6.12±0.20)x10^{20}
^{116}Cd	$2\beta^-$	$0^+ \to 0^+$	2813.44	0.1083(18)	(2.89±0.25)x10^{19}	
^{128}Te	$2\beta^-$	$0^+ \to 0^+$	866.5	0.1862(37)		(3.49±1.99)x10^{24}
^{130}Te	$2\beta^-$	$0^+ \to 0^+$	2527.51	0.1630(+38-28)	(7.14±1.04)x10^{20}	
^{136}Xe	$2\beta^-$	$0^+ \to 0^+$	2457.99	0.1262(17)	(2.34±0.13)x10^{21}	
^{130}Ba	2ϵ	$0^+ \to 0^+$	2620.1	0.1630(+38-28)		(2.20±0.5)x10^{21}
^{150}Nd	$2\beta^-$	$0^+ \to 0^+$	3371.38		(8.37±0.45)x10^{18}	
^{150}Nd	$2\beta^-$	$0^+ \to 0^+_1$	2696.0			(1.33±0.40)x10^{20}
^{238}U	$2\beta^-$	$0^+ \to 0^+$	1144.2			(2.00±0.60)x10^{21}

Data Program guidelines [31, 32]. In present work all final results from independent observations were included in the evaluation process. These evaluated half lives represent the best currently-available values, further measurements will result in the addition of new and improvements to existing evaluated values. Table II also includes recent data on decay Q-values [33, 34] and quadrupole deformation parameters that would be used in the analysis section.

III. ANALYSIS OF RECOMMENDED VALUES

To separate nuclear structure effects from the kinematics, I will extract nuclear matrix element for $\beta\beta(2\nu)$-decay from the present evaluation of half lives. $T^{2\nu}_{1/2}$ values are often described as follows [2]

$$\frac{1}{T^{2\nu}_{1/2}(0^+ \to 0^+)} = G^{2\nu}(E,Z)|M^{2\nu}_{GT} - \frac{g_V^2}{g_A^2} M^{2\nu}_F|^2, \quad (3)$$

where the function $G^{2\nu}(E,Z)$ results from lepton phase space integration and contains all relevant constants. Table III shows effective nuclear matrix elements ($M^{2\nu}_{eff}$) for $\beta\beta(2\nu)$-decay based on the latest phase factors calculation from the Yale group [35].

Present results could be compared with the Yale University re-evaluation of the ITEP [38] data. The list of major differences between present and ITEP works includes ^{128}Te and ^{136}Xe evaluated half lives and general evaluation philosophy:

- ^{128}Te: ITEP evaluation rejects one geochemical result [36] as a possible indication of changing weak interaction constants over the last billion years and

TABLE III. Effective nuclear matrix elements ($M^{2\nu}_{eff}$) for $2\beta(2\nu)$-decay from the present work, ITEP evaluation, large-scale shell-model and QRPA calculations.

Parent Nuclide	Process	Transition	Present work	Yale & ITEP [35, 38]	Shell Model [42]	QRPA [43]
^{48}Ca	$2\beta^-$	$0^+ \to 0^+$	0.0383±0.0025	0.038±0.003	0.0389,0.0397,0.0538	0.0373
^{76}Ge	$2\beta^-$	$0^+ \to 0^+$	0.120±0.021	0.118±0.005	0.0961	0.147
^{82}Se	$2\beta^-$	$0^+ \to 0^+$	0.0826±0.0034	0.083±0.004	0.104	0.0687
^{96}Zr	$2\beta^-$	$0^+ \to 0^+$	0.0824±0.0050	0.080±0.004		0.0952
^{100}Mo	$2\beta^-$	$0^+ \to 0^+$	0.208±0.007	0.206±0.007		0.183
^{100}Mo	$2\beta^-$	$0^+ \to 0^+_1$	0.170±0.020	0.167±0.011		
^{116}Cd	$2\beta^-$	$0^+ \to 0^+$	0.112±0.005	0.114±0.005		0.132
^{128}Te	$2\beta^-$	$0^+ \to 0^+$	0.0326±0.0093	0.044±0.006	0.0489,0.0306	0.0464
^{130}Te	$2\beta^-$	$0^+ \to 0^+$	0.0303±0.0022	0.031±0.004	0.0356,0.0224	0.019
^{136}Xe	$2\beta^-$	$0^+ \to 0^+$	0.0173±0.0005		0.0207	
^{130}Ba	2ϵ	$0^+ \to 0^+$	0.0268±0.0305	0.0268±0.031		
^{150}Nd	$2\beta^-$	$0^+ \to 0^+$	0.0572±0.0015	0.058±0.004		0.0348
^{150}Nd	$2\beta^-$	$0^+ \to 0^+_1$	0.0417±0.0063	0.042±0.006		
^{238}U	$2\beta^-$	$0^+ \to 0^+$	0.185±0.028	0.19±0.04		

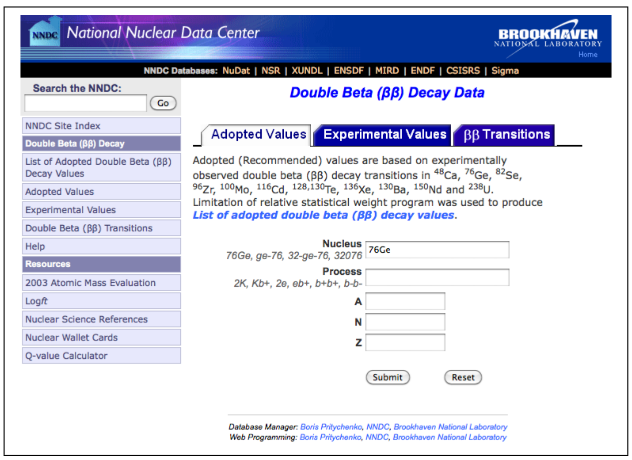

FIG. 1. The NNDC 2β-decay data website *http://www.nndc.bnl.gov/bbdecay/* [8, 10].

adopts the second one [37] with the corrections [38]. The present evaluation is based on the final published results of five measurements without any corrections.

- ^{136}Xe: These data became available one year later after the ITEP evaluation was published. The NNDC half life value is based on the results from three independent groups [26, 39, 40].
- ITEP evaluation treats all (2+0)ν observations as a pure 2ν-decay mode results and includes many other assumptions that allow to deduce the precise values of nuclear matrix elements based on very limited statistics. While, the present evaluation clearly indicates large uncertainties for nuclear matrix elements.
- Finally, this work is using the latest values of phase factors [35] while ITEP is based on somewhat outdated values [2, 41].

The evaluated nuclear matrix elements could be compared with recent theoretical calculations of $M^{2\nu}_{GT}$ [42, 43] using the following recipe [35]

$$|M^{2\nu}_{eff}| = g^2_A \times |(m_e c^2) M^{2\nu}_{GT}|, \quad (4)$$

where g^2_A=1.273^2 and $m_e c^2$=0.511 MeV. The analysis of the Table III data indicates a reasonably good agreement between theoretical and experimental values of nuclear matrix elements. Several deviations are due to problems with calculation of nuclear matrix elements for very weak decays [44] because accurate values of Gamow-Teller strength functions are often missing.

To gain a better understanding of decay half lives, I will analyze half-life values of ^{128,130}Te in more details. Both tellurium isotopes have the same charge, similar shell structure and deformation while $2\beta^-$-transition energies are different. It is natural to assume that difference between tellurium half-lives is due to transition energies [45]. In fact, present evaluation central values for $T^{2\nu}_{1/2}$ are consistent with the following ratio

$$\frac{T^{2\nu}_{1/2}(^{128}Te)}{T^{2\nu}_{1/2}(^{130}Te)} \approx 4.9 \times 10^3 \sim (\frac{E_{^{130}Te}}{E_{^{128}Te}})^{7.9}. \quad (5)$$

From here we deduce the following systematic trend

$$T^{2\nu}_{1/2}(0^+ \to 0^+) \sim \frac{1}{E^8}. \quad (6)$$

This conclusion agrees well with the theoretical calculation of Primakoff and Rosen [46] who predicted that for $2\beta(2\nu)$ decay, the phase space available to the (four) emitted leptons is roughly proportional to the eighth through 11^{th} power of energy release. It is worth noticing that in many direct detection experiments the discovery was based on the observation of the total energy deposition and authors often could not separate a two-electron event from the single-electron tracks [8]. Consequently, the observed dependence between experimental half lives and transition energies provides an additional observable quantity for double-beta decay processes.

Additional analysis of ^{96}Zr, ^{100}Mo, ^{130}Te and ^{136}Xe decay rates provides a complimentary experimental evidence that deformation strongly affects the half-life values. For example, it is easy to see that lower recommended value for ^{100}Mo vs. ^{96}Zr cannot be explained by transition energy or electric charge contributions; the similar situation is for case ^{130}Te vs. ^{136}Xe. These examples illustrate that well-known experimental values of quadrupole deformation parameters could help to understand the relations between recommended half lives when appropriate Gamow-Teller strength functions are not available from charge-exchange reactions [42] or notoriously difficult to measure [47].

IV. CONCLUSION

Double beta decay is very rare nuclear physics process that is often used to test theoretical model predictions for elementary particle and nuclear structure physics. The present work contains the latest evaluation of the experimental half lives and nuclear matrix elements. The nuclear matrix elements strongly rely on phase factors calculations that could vary [2, 35, 41]. This implies the importance of experimental $T^{2\nu}_{1/2}$ compilation and evaluation as a primary model-independent quantity.

The compilation and analysis of experimental papers [8] indicates strong interest in double-beta decay over the past 75 years. Several new measurements have been performed recently and many others are underway. This is why online compilation and 2β-decay data dissemination plays an essential role. Continuing research and observation of additional decay properties will help to clarify the situation by comparing the observables with theoretical predictions. The ^{128,130}Te half-lives and their systematic trend could play a crucial role in our understanding of interplay of phase factors and $2\beta(2\nu)$-decay nuclear matrix elements. That will eventually lead to overall improvements of theoretical models and better interpretation of experimental results.

Future work on the double beta decay horizontal evaluation and compilation will be conducted in collaboration with KINR, Ukrainian Academy of Sciences.

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