Systematics of Evaluated Half-Lives of Double-Beta Decay

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A new evaluation of $2\beta$-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 $2\beta$-decay transitions in 12 nuclei have been extracted. The recommended values are compared with the large-scale shell-model, QRPA calculations, and experimental data. A $T_{1/2}^{128,130}$-Te value. This 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 Goeppert-Mayer in 1935 [1] as a nuclear disintegration with simultaneous emission of two electrons and two neutrinos

\[
(Z, A) \rightarrow (Z + 2, A) + 2\epsilon^- + 2\nu_e.
\] (1)

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

\[
(Z, A) \rightarrow (Z \pm 2, A) + (2\epsilon^\pm) + (2\bar{\nu}_e, 2\nu_e \text{ or } \chi^0).
\] (2)

The $2\nu$-mode is not prohibited by any conservation law and definitely occurs as a second-order process compared with regular $\beta$-decay [2]. The $0\nu$-mode differs from the $2\nu$-mode in that only electrons are emitted during the decay. This normally requires that the lepton number is not conserved and the neutrino should contain a small fraction of massive particles equal to its antiparticles (Majorana neutrino). Obviously, observation of $2\beta(0\nu)$-decay will have significant implications for 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 $0\nu$-mode calculations.

Historically, the 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 recent years claims have been made for the observation of the $0\nu$-decay mode in $^{76}$Ge [5]. These rather controversial results were widely scrutinized and often rejected by the nuclear physics community [6] [7]. However, the $2\nu$-decay mode has definitely been observed in many isotopes. Table I provides a brief review of $2\beta$-decay observations. Because of the extremely low probability for double beta decay it was first detected by analyzing the chemical composition of rock samples and later verified by more accurate direct detection methods.

Experimental evidence and theoretical calculations indicate that the probability for the $2\nu$-mode is much higher than that for the $0\nu$-mode. In fact, $^{76}$Ge $2\beta$-decay measurements have demonstrated that the decay rate for $2\beta(2\nu)$-decay is at least four orders of magnitude higher than that of $2\beta(0\nu)$. Therefore, we will concentrate on the experimentally observed $2\nu$-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] [9]. Fig. 1 shows the online compilation and evaluation conducted at the National Nuclear Data Center since 2006 [8] [10]. Observed $2\beta$-decay data for isotopes of interest are shown in Table I. While 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 work obtained by searching the Nuclear Science References database [11] [12]. It was used to produce evaluated or recommended values.

Table II shows the latest recommended values which were deduced in the accordance with the US Nuclear Data Program guidelines [31] [32]. All final results from

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TABLE I. Brief history of experimental observations of $3\beta$-decay and reported $T_{1/2}(3\beta)$ values. Results are shown for direct detection and geochemical methods.

| Parent nuclide | Process | Transition | Discovery year | Originally reported $T_{1/2}(3\beta)$, (y) |
|----------------|---------|------------|----------------|---------------------------------------------|
|                |         |            |                | Direct | Geoch | $2\nu$, direct | $(2+0)\nu$, direct | $(2+0)\nu$, geochemical |
| $^{48}\text{Ca}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 1996 | 4.3x$10^{10}$ | 13 |
| $^{76}\text{Ge}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 1990 | 9.0x$10^{20}$ | 14 |
| $^{82}\text{Se}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 1987 | 1.1x$10^{19}$ | 16 |
| $^{90}\text{Zr}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 1999 | 2.1x$10^{19}$ | 18 |
| $^{100}\text{Mo}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 1990 | 3.3x$10^{18}$ | 19 |
| $^{100}\text{Mo}$ | $2\beta$ | $0^+ \rightarrow 0^+_1$ | 1995 | 9.5x$10^{18}$ | 20 |
| $^{100}\text{Mo}$ | $2\beta$ | $0^+ \rightarrow 0^+_1$ | 1995 | 6.1x$10^{20}$ | 21 |
| $^{116}\text{Cd}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 1995 | 2.7x$10^{20}$ | 22 |
| $^{128}\text{Te}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 1975 | 1.5x$10^{24}$ | 23 |
| $^{130}\text{Te}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 1966 | 6.1x$10^{20}$ | 24 |
| $^{136}\text{Xe}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 2011 | 5.5x$10^{21}$ | 26 |
| $^{136}\text{Ba}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 2011 | 2.2x$10^{21}$ | 27 |
| $^{150}\text{Nd}$ | $2\beta$ | $0^+ \rightarrow 0^+_1$ | 1993 | 1.4x$10^{20}$ | 29 |
| $^{150}\text{Nd}$ | $2\beta$ | $0^+ \rightarrow 0^+_1$ | 2004 | 2.0x$10^{21}$ | 30 |
| $^{238}\text{U}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 1991 |                | 31 |

TABLE II. Recommended $T_{1/2}(3\beta)$ and complimentary parameter values.

| Parent nuclide | Process | Transition | Q-value (keV) | $\beta_2$ | $T_{1/2}^{2\nu}(y)$ | $T_{1/2}^{(2+0)\nu}(y)$ |
|----------------|---------|------------|---------------|-----------|---------------------|---------------------|
| $^{48}\text{Ca}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 4267.0 | 0.2575(56) | (4.39+0.58)x$10^{19}$ | (6.12+0.20)x$10^{20}$ |
| $^{76}\text{Ge}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 2039.06 | 0.3133(55-20) | (1.43+0.53)x$10^{21}$ | (3.49+0.21)x$10^{23}$ |
| $^{82}\text{Se}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 2996.4 | 0.2031(+30-28) | (9.19+0.76)x$10^{19}$ | (1.7x10$^{19}$) |
| $^{90}\text{Zr}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 3349.0 | 0.1525(27) | (2.16+0.26)x$10^{19}$ | (6.50+0.13)x$10^{20}$ |
| $^{100}\text{Mo}$ | $2\beta$ | $0^+ \rightarrow 0^+_1$ | 3034.37 | 0.2153(90) | (6.98+0.44)x$10^{18}$ | (2.00+0.60)x$10^{21}$ |
| $^{100}\text{Mo}$ | $2\beta$ | $0^+ \rightarrow 0^+_1$ | 2339.3 | 0.2153(90) | (6.98+0.44)x$10^{18}$ | (2.00+0.60)x$10^{21}$ |
| $^{116}\text{Cd}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 2813.44 | 0.1083(18) | (2.89+0.25)x$10^{19}$ | (3.49+1.99)x$10^{24}$ |
| $^{128}\text{Te}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 866.5 | 0.1862(37) | (7.14+1.04)x$10^{20}$ | (1.40+0.80)x$10^{21}$ |
| $^{130}\text{Te}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 2527.51 | 0.1630(+38-28) | (2.34+0.13)x$10^{21}$ | (1.33+0.40)x$10^{20}$ |
| $^{136}\text{Xe}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 2457.99 | 0.1262(17) | (2.34+0.13)x$10^{21}$ | (1.33+0.40)x$10^{20}$ |
| $^{138}\text{Ba}$ | $2\beta$ | $0^+ \rightarrow 0^+$ | 2620.1 | 0.1630(+38-28) | (8.37+0.45)x$10^{18}$ | (2.00+0.60)x$10^{21}$ |

independent observations were included in the evaluation process. These evaluated half-lives represent the best values currently available; further measurements will result in the addition of new and improved values. Table II also includes recent data on decay Q-values [33, 34] and quadrupole deformation parameters which are used in the next section.

III. ANALYSIS OF RECOMMENDED VALUES

To separate nuclear structure effects from the kinematics, the nuclear matrix elements for $\beta\beta(2\nu)$-decay were extracted from the present evaluation of half-lives. $T_{1/2}^{2\nu}$ values are often described as follows [2]

$$\frac{1}{T_{1/2}^{2\nu}(0^+ \rightarrow 0^+)} = G^{2\nu}(E, Z)|M^{2\nu}_{GT} - \frac{g_A^2}{g_A^2} M^{2\nu}_{F}|^2,$$

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

The present results can be compared with the Yale University re-evaluation of the ITEP data [35]. The major differences between the present work and ITEP include $^{128}\text{Te}$ and $^{136}\text{Xe}$ evaluated half-lives and the general evaluation philosophy.

- $^{128}\text{Te}$: The ITEP evaluation rejects one geochemical result [36] as a possible indication of changing weak interaction constants over the last billion years and adopts the second one with corrections [37, 38]. The present evaluation is based on the final published results of five measurements without any corrections.
TABLE III. Effective nuclear matrix elements (\(M_{\text{eff}}\)) 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 143 |
|---------------|---------|------------|--------------|----------------------|----------------|-----------|
| \(^{49}\)Ca | 2\(^-\) | 0\(^+\) → 0\(^+\) | 0.0383±0.0025 | 0.0383±0.0025 | 0.0389,0.0397,0.0538 | 0.0373 |
| \(^{76}\)Ge | 2\(^-\) | 0\(^+\) → 0\(^+\) | 0.120±0.021 | 0.118±0.005 | 0.0961 | 0.147 |
| \(^{82}\)Se | 2\(^-\) | 0\(^+\) → 0\(^+\) | 0.0826±0.0034 | 0.083±0.004 | 0.104 | 0.0687 |
| \(^{90}\)Zr | 2\(^-\) | 0\(^+\) → 0\(^+\) | 0.0824±0.0050 | 0.080±0.004 | 0.0952 | |
| \(^{100}\)Mo | 2\(^-\) | 0\(^+\) → 0\(^+\) | 0.170±0.020 | 0.167±0.011 | | 0.183 |
| \(^{116}\)Cd | 2\(^-\) | 0\(^+\) → 0\(^+\) | 0.112±0.005 | 0.114±0.005 | | 0.132 |
| \(^{128}\)Te | 2\(^-\) | 0\(^+\) → 0\(^+\) | 0.0326±0.0093 | 0.044±0.006 | 0.0480,0.0306 | 0.0464 |
| \(^{130}\)Te | 2\(^-\) | 0\(^+\) → 0\(^+\) | 0.0303±0.0022 | 0.031±0.004 | 0.0356,0.0224 | 0.019 |
| \(^{136}\)Xe | 2\(^-\) | 0\(^+\) → 0\(^+\) | 0.0173±0.0005 | | 0.0207 | |
| \(^{136}\)Ba | 2\(\nu\) | 0\(^+\) → 0\(^+\) | 0.218±0.062 | 0.174±0.017 | | 0.0348 |
| \(^{150}\)Nd | 2\(^-\) | 0\(^+\) → 0\(^+\) | 0.0572±0.0015 | 0.058±0.004 | | |
| \(^{150}\)Nd | 2\(^-\) | 0\(^+\) → 0\(^+\) | 0.0417±0.0063 | 0.042±0.006 | | |
| \(^{238}\)U | 2\(^-\) | 0\(^+\) → 0\(^+\) | 0.185±0.028 | 0.19±0.04 | | |

where \(g_A^2=1.273^2\) and \(m_e c^2=0.511\) MeV. Analysis of the data in Table III indicates reasonably good agreement between theoretical and experimental values of the nuclear matrix elements. Several deviations are due to problems with the calculation of nuclear matrix elements for very weak decays 44 because accurate values of the Gamow-Teller strength functions are often missing.

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

\[
\frac{T_{1/2}^{2\nu}(^{128}\text{Te})}{T_{1/2}^{2\nu}(^{130}\text{Te})} \approx 4.9 \times 10^3 \sim \frac{E_{130\text{Te}}}{E_{128\text{Te}}}^{7.9}. \tag{5}
\]

From this equation we deduce the following systematic trend

\[
T_{1/2}^{2\nu}(0^+ \rightarrow 0^+) \sim \frac{1}{E^{8/3}}. \tag{6}
\]

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 8th through 11th power of energy release. It is worth noting 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 relation 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 complimentary experimental evi-
dence that deformation strongly affects the half-life values. For example, it is easy to see that the lower recommended value for $^{100}$Mo vs. $^{96}$Zr cannot be explained by transition energy or electric charge contributions; a similar situation exists for $^{130}$Te vs. $^{136}$Xe. These examples show 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 [22] or are extremely difficult to measure [17].

IV. CONCLUSIONS

Double-beta decay is a 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 factor calculations that can vary [2, 35, 41]. This implies the importance of experimental $\frac{1}{2}$ compilation and evaluation as a primary model-independent quantity.

The compilation and analysis of experimental papers [8] indicates a strong interest in double-beta decay over the past 75 years. Several new measurements have been performed recently and many others are under way. This is why online compilation and $2\beta$-decay data dissemination play essential roles. 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 the interplay of phase factors and $2\beta(2\nu)$-decay nuclear matrix elements, which will eventually lead to an overall improvement 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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