Half-lives of double β-decay with two neutrinos (Postprint)

Authors: REN Yue-Jiao, REN Zhong-Zhou

Date: 2023-06-18T00:00:00+00:00

Abstract

Nuclear double β-decay with two neutrinos is an important decay mode for some unstable nuclei. Based on the available experimental data of nuclear double β-decay, we propose that there is a law between the logarithm of double β-decay half-lives and the reciprocal of the decay energy. The physics behind the law is discussed and it is found that this is associated with the universal properties of the weak interaction. This double β-decay law is similar to the famous Geiger-Nuttall law of α-decay. The law is applied to predictions of the nuclear double β-decay half-lives for six even-even nuclei from Z=84 to Z=98 and we found that 232Th is very interesting for future experiments. The branching ratios between double β-decay and α-decay are also estimated for the six even-even nuclei and this is useful for future experimental search of new emitters of double β-decay.

Full Text

Preamble

Half-lives of double β^--decay with two neutrinos

REN Yue-Jiao (任月皎)[1] and REN Zhong-Zhou (任中洲)[1,2,†]

[1]Department of Physics, Nanjing University, Nanjing 210093, China
[2]Center of Theoretical Nuclear Physics, National Laboratory of Heavy-Ion Accelerator, Lanzhou 730000, China

(Received January 21, 2015; accepted in revised form February 9, 2015; published online April 20, 2015)

Abstract: Nuclear double β^--decay with two neutrinos is an important decay mode for certain unstable nuclei. Based on available experimental data for nuclear double β^--decay, we propose a systematic relationship between the logarithm of double β^--decay half-lives and the reciprocal of the decay energy. The underlying physics is discussed and found to be associated with universal properties of the weak interaction. This double β^--decay law is analogous to the famous Geiger-Nuttall law for α-decay. The law is applied to predict nuclear double β^--decay half-lives for six even-even nuclei from Z = 84 to Z = 98, revealing that ^{232}Th is particularly interesting for future experiments. Branching ratios between double β^--decay and α-decay are also estimated for these six even-even nuclei, which will be useful for future experimental searches for new double β^--decay emitters.

Keywords: Double β^--decay with two neutrinos, Systematic law, Half-lives of heavy nuclei, The nucleus ^{232}Th.

DOI: 10.13538/j.1001-8042/nst.26.S20510

INTRODUCTION

Research on nuclear β decay has led to important developments in both nuclear physics and particle physics. To explain the missing energy in β-decay, Pauli proposed in the 1930s that a new particle—the neutrino—carries away this energy. Fermi established the fundamental theory of nuclear β-decay, which incorporates the neutrino even before its experimental discovery in the 1930s. In the 1950s, Lee and Yang proposed that parity is not conserved in weak processes such as β-decay [1]. Wu and her collaborators subsequently performed β-decay experiments with polarized ^{60}Co nuclei, confirming that parity symmetry is violated in β-decay processes [2], which had a profound impact on the development of physics. Double β-decay was first predicted by Goeppert-Mayer in 1935 [3] and later observed through geochemical, radiochemical, and nuclear physics experiments [4–15]. Wu also provided valuable guidance on the direct observation of rare double β-decay, which was eventually achieved when Elliott, Hahn, and Moe directly observed the double β-decay of ^{82}Se [4].

To date, eleven nuclei have been observed to undergo double β^--decay [10–13]. Although substantial double β-decay data have been accumulated, no simple systematic law has been identified among them. This stands in stark contrast to research on other forms of radioactivity such as α-decay and cluster radioactivity, for which unified formulas relating half-lives to decay energies have been proposed [16]. A new Geiger-Nuttall law has been proposed recently that includes the influence of quantum numbers on α-decay half-lives [17, 18]. In contrast, most theoretical research on double β-decay half-lives involves complex calculations requiring lengthy computer codes and can only be performed by professional theoretical physicists. Furthermore, modern shell model calculations remain unavailable for heavy nuclei such as ^{238}U due to computational limitations.

Because of the computational complexity involved in calculating double β-decay half-lives, double β-decay processes are seldom discussed in standard textbooks for undergraduate and graduate students, despite having been clearly observed for many years. This differs markedly from α-decay and complex cluster radioactivity (such as ^{14}C), whose half-lives can be easily calculated using simple formulas with only three or four parameters. Therefore, a simple and accurate method for calculating double β-decay half-lives is needed—one that is also useful for experimental physicists to estimate decay half-lives before conducting double β-decay experiments and to analyze data afterward.

II. NUMERICAL RESULTS AND DISCUSSION

We recently performed a systematic analysis of double β^--decay data and proposed a new systematic law relating decay half-lives to decay energy [19]. This law is simple and accurate for ground-state transitions in double β^--decay between parent and daughter nuclei [19]. Without any additional adjustments, it also works well for double β^--decay from the ground state of parent nuclei to the first excited 0^+ state of daughter nuclei [19].

Because the systematic law was derived by analyzing experimental data for ground-state transitions in eleven even-even nuclei from ^{48}Ca to ^{238}U for double β^--decay, the law naturally incorporates the effects of the weak interaction, Coulomb interaction corrections, and the leading nuclear structure terms. The systematic law for double β-decay half-lives with two neutrinos is as follows [19]:

$$\lg T_{1/2}(E_y) = \frac{a - 2\lg(2\pi Z/137) + S}{Q_{2\beta}}$$

where $T_{1/2}$ is the double β^--decay half-life with units of E_y (10^{18} years), $Q_{2\beta}$ is the double β^--decay energy (MeV), Z is the charge number of the parent nucleus [19]. The first term in this equation represents the effect of the weak interaction, with constant $a = 5.843$ obtained by fitting experimental double β^--decay data for ground-state transitions in eleven even-even nuclei. The second term accounts for the effect of the Coulomb potential on double β^--decay. The third term is related to shell effects, where $S = 2$ when the neutron number of the parent nucleus is magic and $S = 0$ when it is not.

[Figure 1: see original paper] shows the variation of the logarithms of calculated and experimental double β-decay half-lives with decay energy for eleven even-even nuclei from ^{48}Ca ($Z = 20$) to ^{238}U ($Z = 92$). It is interesting to note that the half-lives also depend on the charge number according to Eq. (1). The half-lives are highly sensitive to decay energies. Although the decay energies vary within a narrow range of only a few MeV, the half-lives span an extremely wide range from E_y (10^{18} years) to 10^6 E_y, demonstrating the important effect of decay energy on half-lives. Higher decay energy generally leads to shorter half-lives for nuclei along an isotopic chain. The calculated results using Eq. (1) agree reasonably well with available data, and the number of adjustable parameters in Eq. (1) is minimal compared to other theoretical calculations. The average deviation for the eleven nuclei is a factor of three, which is satisfactory for such a simple formula.

Below, we predict the double β-decay half-lives of six radioactive nuclei from ^{216}Po ($Z = 84$) to ^{256}Cf ($Z = 98$) using Eq. (1). The calculated results for these six nuclei are listed in Table 1 and plotted in Fig. 2 [Figure 2: see original paper]. For these six nuclei, none have magic neutron numbers, so $S = 0$.

In Table 1, the first column indicates the parent nucleus, the second column gives the experimental double β-decay energy for the ground-state transition between parent and daughter nucleus ($Q_{2\beta} = M(A,Z) - M(A,Z-2)$ [12, 13]), and the third column presents the calculated double β-decay half-lives ($T_{1/2}^{(\text{theor.})}$) in units of E_y (10^{18} years). For comparison, the experimental α-decay half-lives ($T_{\alpha,1/2}^{(\text{expt.})}$) from references [12, 13] are listed in column 4. Column 5 shows the branching ratio between double β^--decay and α-decay ($T_{\alpha,1/2}^{(\text{expt.})}/T_{1/2}^{(\text{theor.})}$).

Table 1 reveals that the shortest double β-decay half-life is $8.36 \times 10^2 E_y$ for ^{256}Cf, while the longest is $3.64 \times 10^{13} E_y$ for ^{220}Rn, corresponding to the highest and lowest double β-decay energies, respectively. This demonstrates the strong dependence of half-life on decay energy. Although ^{256}Cf and ^{216}Po have relatively short double β-decay half-lives, they are unsuitable for future double β-decay experiments because their α-decay half-lives are too short. ^{220}Rn and ^{254}Cf are also unsuitable for future searches for new double β-decay emitters because their double β-decay half-lives are too long and their α-decay half-lives are too short. Only ^{226}Ra and ^{232}Th are promising for future double β-decay experiments due to their longer α-decay half-lives. ^{232}Th is particularly noteworthy, with a very long α-decay half-life (1.4×10^{10} years) and a relatively short double β-decay half-life ($3.19 \times 10^5 E_y$), resulting in the largest branching ratio between double β-decay and α-decay among the six nuclei. This makes ^{232}Th an excellent candidate for future double β-decay experiments. Additionally, ^{232}Th is abundant in nature, which makes experiments easier and more cost-effective compared to other isotopes.

[Figure 2: see original paper] shows the variation of the logarithms of calculated double β-decay half-lives with decay energy for six even-even nuclei from ^{216}Po ($Z = 84$) to ^{256}Cf ($Z = 98$). Again, the logarithms of double β-decay half-lives are inversely proportional to decay energies. Generally, higher decay energy corresponds to shorter double β-decay half-life, though there is also a dependence on the charge number of the parent nucleus.

Finally, it is worthwhile to briefly discuss the physics behind the double β-decay half-life law (equation (1)). In this systematic law, the first term depends on decay energy because the weak interaction is universal for natural decay processes, and the total effect from the weak interaction is not highly sensitive to changes in nucleon numbers such as the charge number. This differs from α-decay, where the total effect of the repulsive Coulomb potential is directly related to the charge number of the nucleus and α-decay occurs from ground states of medium and heavy nuclei [17, 18].

III. CONCLUSION

We have presented a law for calculating double β-decay half-lives that naturally incorporates the leading effects of the weak interaction, Coulomb potential, and strong interaction. This law provides an analytical formula for the half-lives of the complex double β-decay process with two neutrinos and can be easily introduced into textbooks due to its simplicity. The law reasonably reproduces experimental data for double β-decay half-lives of ground-state transitions in eleven even-even nuclei. We have also discussed the universal behavior of the weak interaction through this double β-decay half-life formula. The law for double β-decay half-lives is as simple as the new Geiger-Nuttall law for α-decay. We have predicted half-lives for six double β-decay candidates with charge numbers from $Z = 84$ to $Z = 98$ and identified ^{232}Th as particularly interesting for future experiments. Additionally, we have estimated branching ratios between double β-decay and α-decay for these six even-even nuclei, which will also be useful for future experimental efforts.

REFERENCES

[1] Lee T D and Yang C N. Question of parity conservation in weak interactions. Phys Rev, 1956, 104: 254-258. DOI: 10.1103/PhysRev.104.254
[2] Wu C S, Ambler E, Hayward R W, et al. Experimental test of parity conservation in beta decay. Phys Rev, 1957, 105: 1413-1415. DOI: 10.1103/PhysRev.105.1413
[3] Goeppert-Mayer M. Double beta-disintegration. Phys Rev, 1935, 48: 512-516. DOI: 10.1103/PhysRev.48.512
[4] Elliott S R, Hahn A A and Moe M K. Direct evidence for two-neutrino double-beta decay in 82Se. Phys Rev Lett, 1987, 59: 2020-2023. DOI: 10.1103/PhysRevLett.59.2020
[5] Haxton W C and Stephenson G J. Double beta decay. Prog Part Nucl Phys, 1984, 12: 409-479. DOI: 10.1016/0146-6410(84)90006-1
[6] Faessler A. Possible test of grand unification in the double beta decay. Prog Part Nucl Phys, 1988, 21: 183-205. DOI: 10.1016/0146-6410(88)90033-6
[7] Klapdor H V and Grotz K. Calculation of double beta decay of 76Ge, 82Se, 128,130Te. Phys Lett B, 1984, 142, 323-328. DOI: 10.1016/0370-2693(84)91332-7
[8] Simkovic F, Rodin V, Faessler A, et al. 0 $\beta\beta$ and 2 $\beta\beta$ nuclear matrix elements, quasiparticle random-phase approximation, and isospin symmetry restoration. Phys Rev C, 2013, 87: 045501. DOI: 10.1103/PhysRevC.87.045501
[9] Ejiri H. Nuclear spin isospin responses for low-energy neutrinos. Phys Rep, 2000, 338: 265-351. DOI: 10.1016/S0370-1573(00)00044-2
[10] Barabash A S. Precise half-life values for two-neutrino double-beta decay. Phys Rev C, 2010, 81: 035501. DOI: 10.1103/PhysRevC.81.035501
[11] Saakyan R. Two-neutrino double-beta decay. Annu Rev Nucl Part Sci, 2013, 63: 503-529. DOI:10.1146/annurev-nucl-102912-144022
[12] Audi G, Kondev F G, Wang M, et al. The NUBASE2012 evaluation of

nuclear properties. Chin Phys C, 2012, 36: 1157–1286. DOI: 10.1088/1674-1137/36/12/001

[13] Wang M, Audi G, Wapstra A H, et al. The AME2012 atomic mass evaluation (II). Tables, graphs and references. Chin Phys C, 2012, 36: 1603–2014. DOI: 10.1088/1674-1137/36/12/003

[14] Suhonen J. Analysis of double–beta transitions in 78Kr. Phys Rev C, 2013, 87: 034318. DOI: 10.1103/PhysRevC.87.034318

[15] Suhonen J and Civitarese O. Weak-interaction and nuclear-structure aspects of nuclear double beta decay. Phys Rep, 1998, 300: 123–214. DOI: 10.1016/S0370-1573(97)00087-2

[16] Ni D D, Ren Z Z, Dong T K, et al. Unified formula of half–lives for alpha decay and cluster radioactivity. Phys Rev C, 2008, 78: 044310. DOI: 10.1103/PhysRevC.78.044310

[17] Ren Y J and Ren Z Z. New Geiger-Nuttall law for alpha decay of heavy nuclei. Phys Rev C, 2012, 85: 044608. DOI: 10.1103/PhysRevC.85.044608

[18] Ren Y J and Ren Z Z. New Geiger-Nuttall law of odd-Z nuclei and long-lived island beyond the stable line. Nucl Sci Tech, 2013, 24: 050518.

[19] Ren Y J and Ren Z Z. Systematic law for half-lives of double beta-decay with two neutrinos. Phys Rev C, 2014, 89: 064603. DOI: 10.1103/PhysRevC.89.064603

Note: Figure translations are in progress. See original paper for figures.