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Double-beta decay of ^{104}Ru

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Summary. — In this study we have carried out the calculations concerning the double-beta decay of ^{104}Ru to ^{104}Pd. The calculations utilize the microscopic interacting boson model (IBM-2) for the nuclear matrix elements, and exact Dirac wave functions with finite nuclear size and electron screening for phase space factors. From these results, the half-life estimates for two-neutrino and neutrinoless double beta decay can be obtained.

1. – Introduction

While single-beta decay has been observed in many different nuclei, the study of double-beta decay is still, in many parts, a mystery. Two-neutrino double-beta decay has been observed in several nuclei that cannot undergo single beta decay. The experimental study of this rare process has begun to flourish as advanced technology allows more precise measurements and the detection of such rare events. However, there is an even more unique decay process that has not yet been detected: neutrinoless double-beta decay. Observing this type of decay would represent a huge leap in the knowledge of nuclear and particle physics today.

According to the standard model, the neutrino is described as a massless particle, which, in fact, it is not. Observations of neutrino oscillations have proven that the neutrino indeed must have, a small but non-zero, mass. The neutrinoless double-beta decay half-life is proportional to the effective neutrino mass making it intriguing and unique probe that could provide information about the mass of the neutrino. Therefore, observing the neutrinoless double-beta decay would provide an estimate of the mass if the nuclear model calculations are accurate enough.

In this study, we have carried out calculations on the phase-space factors and the nuclear matrix elements (NMEs) of the double beta decay of ^{104}Ru. The calculation of the phase-space factors can be done very accurately using the double-beta decay energy, the Q-value, as an input. This Q-value has been determined with great precision by

IGISOL (Ion Guide Isotope Separator On-Line), an experimental group at the University of Jyväskylä. The calculation of the NME involves more uncertainty and there are several nuclear models that can be used to calculate the NMEs [1]. However, there are large differences between the NME values provided by different methods. Once neutrinoless double-beta decay is observed, the NME must also be reliably calculated in order to extract the neutrino mass. Therefore the study of both two-neutrino and neutrinoless double-beta decay is crucial, both theoretically and experimentally.

2. – Theoretical aspects and calculations

The experiments [2] aim to measure the decay half-life. The inverse of the half-life for the two-neutrino double-beta decay can be written as

$$[t^{2\nu}_{1/2}]^{-1} = g_A^4 G_{2\nu} |M_{2\nu}|^2, \tag{1}$$

and the inverse of the neutrinoless double-beta decay half-life can be written as

$$[t^{0\nu}_{1/2}]^{-1} = g_A^4 G_{0\nu} |M_{0\nu}|^2 \frac{m_{\beta\beta}^2}{m_e^2}. \tag{2}$$

In eqs. (1) and (2) the M is the NME, G is the phase-space factor and g_A is the axial vector coupling. The NMEs and the phase-space factors are obtained for both the two-neutrino decay and neutrinoless decay individually. In this work, we have used three different values for the g_A: i) the bare value 1.269, ii) the renormalized value 1.00, and iii) the maximally quenched value, which for the IBM-2 model can be parametrized to depend on the mass number $1.269A^{-0.18}$. Also, in eq. (2) the $m_{\beta\beta}$ is the effective neutrino mass and m_e is the electron mass.

2·1. *Nuclear matrix elements.* – The calculation of the NMEs makes use of the microscopic interacting boson model (IBM-2), which was introduced in the 1970s. In this nuclear model, the main idea is to map nucleons into the bosonic space. The nucleons (protons, neutrons) form pairs and these pairs are considered as bosons. The number of bosons depends on the nucleus in consideration, in particular, which is the nearest closed shell. In this case the number of neutron bosons is $N_\nu = 3$ and the number of proton bosons is $N_\pi = 5$ for ^{104}Ru. Likewise for ^{104}Pd daughter nucleus $N_\nu = 2$ and $N_\pi = 4$. A very comprehensive background on IBM-2 can be found in ref. [3].

In the NME calculations, the closure approximation is assumed. In the closure approximation the completeness relation is used and the sum over all intermediate states can be replaced with an average energy of the intermediate states, which is called the closure energy. Without this approximation, the calculation of the nuclear matrix elements would include calculations concerning every possible (virtual) transition via the intermediate nucleus. Two-neutrino double-beta decay would undergo transitions via the 1^+ states but the neutrinoless double-beta decay would decay via all multipolarities, not just the 1^+ ones. The calculation of the two-neutrino double beta decay nuclear matrix element is rather sensitive to the choice of the closure energy, since the typical neutrino momentum is of the same order as the nuclear excitations, and thus, the closure energy.

TABLE I. – *Lowest estimates for the two-neutrino and neutrinoless double-beta decay half-lives of* ^{104}*Ru.*

g_A	$t_{1/2}^{2\nu}$ (yr)	$t_{1/2}^{0\nu}$ (yr)
$1.269A^{-0.18}$	1.54×10^{23}	1.31×10^{28}
1.00	1.41×10^{22}	1.20×10^{27}
1.269	5.44×10^{21}	4.64×10^{26}

Fortunately, the neutrinoless double-beta decay nuclear matrix element is not very sensitive to the value of the closure energy since the typical, large momentum of the virtual neutrino is much higher than the typical nuclear excitation energies.

To solve the problem of non-vanishing two-neutrino double-beta decay Fermi matrix elements arising from the mapping of the fermionic operators, we use the isospin restoration formalism, which also reduces the neutrinoless double-beta decay Fermi matrix elements. A detailed description of the calculation of the nuclear matrix elements in IBM-2 can be found in refs. [4, 5].

2˙2. *Phase space factors*. – We have calculated the phase-space factors using the experimentally measured Q-value of the double beta decay of the ^{104}Ru. The new Q-value has been measured by the IGISOL group at the University of Jyväskylä. The newly measured Q-value is with high precision and fully compatible with the previously measured one [6]. A detailed publication about the precise Q-value measurement and result is in preparation.

In order to calculate the phase space factors, one needs to obtain the electron scattering wave functions. The electron scattering wave functions are composed of radial functions, which can be solved when the potential is known. In our calculations, the finite nuclear size and screening effects are included. The screening effects are included by using the Thomas-Fermi approximation. A more detailed theoretical background can be read in ref. [7].

3. – Results and discussion

Two different parametrizations for the palladium isotope [8, 9] were used to calculate the nuclear matrix elements. The parameters obtained from the two papers had several diffrerences; for example, the parameters obtained in ref. [8] had separate energy parameters for protons and neutrons, and in ref. [9] only one parameter was used to describe both. Also, some of the parameters obtained in ref. [8] were missing from the earlier work [9]. Although the parameters were quite different, the nuclear matrix elements were essentially the same: $M_{2\nu} = 0.15$ and $M_{0\nu} = 4.3 - 4.5$, with the lower value corresponding to the Argonne short-range correlation and the upper value to the CD-Bonn short-range correlation.

With the obtained nuclear matrix elements and phase-space factors, the estimates for the two-neutrino and neutrinoless double beta decay half-lives can be calculated. The lowest estimates are given in table I. For the neutrino mass in these calculations, we have used the value $m_{\beta\beta} = 0.01$ eV.

As can be seen from table I, the lowest limit placed on the half-life of the two-neutrino double beta decay is 5.44×10^{21} years, which is, in fact, smaller than the longest directly measured half-life for double beta decay [10]. If the half-life of this process would be measured one day, the effective matrix elements including factor g_A^2 could be extracted offering new valuable information on both reliability of nuclear matrix elements and the effective value of the axial vector coupling constant.

We are also planning to continue the calculations of the nuclear matrix elements and phase-space factors in other double beta decay candidates. The collaboration with the IGISOL group helps us to obtain more precise results for the phase-space factors.

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