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Title: ββ decay of 104Ru and multipole giant resonances in ββ-Decaying nuclei

Year: 2024

Version: Accepted version (Final draft)

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Please cite the original version:

Kauppinen, E., Kotila, J., & Suhonen, J. (2024). ββ decay of 104Ru and multipole giant resonances in ββ-Decaying nuclei. In O. Civitarese, R. Hodak, J. Suhonen, & I. Stekl (Eds.), Workshop on the Calculation of Double-Beta-Decay Matrix Elements : MEDEX'23 (Article 020023). American Institute of Physics. AIP Conference Proceedings, 3138. https://doi.org/10.1063/5.0213597

$\beta\beta$ decay of ^{104}Ru and multipole giant resonances in $\beta\beta$-decaying nuclei

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Abstract. This work presents results of quasiparticle random-phase approximation (QRPA) calculations of multipole giant resonances and microscopic interacting boson model (IBM-2) calculations of the double-beta ($\beta\beta$) decay of ^{104}Ru. The QRPA calculations were done to study spin-multipole giant resonances in $\beta\beta$-decay parent and daughter nuclei, and multipole resonances (without the spin contribution) in zirconium and molybdenum isotopes. The other task of this study was to calculate nuclear matrix elements and phase-space factors for the double-beta decay of ^{104}Ru. Preliminary estimates were also provided for the half-lives of two-neutrino and neutrinoless $\beta\beta$ decay.

MOTIVATION

Double-beta ($\beta\beta$) decay, especially neutrinoless $\beta\beta$ decay, is among the most interesting subjects in nuclear physics. If it were detected, it would mean existence of new physics beyond the standard model. By studying $\beta\beta$ decay, new information, for example, about neutrino mass and lepton-number violation, would be possible to gain. From the theory point of view the problem are the involved nuclear matrix elements (NME) which are hard to calculate and have large uncertainties, thus impeding the interpretation of experimental results, potentially gained in the future. Concerning the NME problem, by studying the (spin-)multipole giant resonances in parent and daughter $\beta\beta$-decay nuclei, one could obtain more information about the wave functions of the virtual states of the $\beta\beta$ intermediate nuclei at high energies and test basic assumptions of quasiparticle-based nuclear models, like the adopted two-body interactions and the size and energies of the single-particle mean field.

GIANT RESONANCES

Introduction

The spin-multipole giant resonances have been studied in $\beta\beta$-decay parent and daughter nuclei in [1]. The studied parent-daughter-nuclei pairs are (^{76}Ge, ^{76}Se), (^{82}Se, ^{82}Kr), (^{96}Zr, ^{96}Mo), (^{100}Mo, ^{100}Ru), (^{116}Cd, ^{116}Sn), (^{128}Te, ^{128}Xe), (^{130}Te, ^{130}Xe), and (^{136}Xe, ^{136}Ba). The strength functions of isovector and isoscalar spin-multipole giant resonances were studied. For this, transitions from the ground state of the parent nucleus to the excited states of the daughter were calculated. These transitions included the spin-dipole ($L = 1$, $J^\pi = 0^-, 1^-, 2^-$) and spin-quadrupole ($L = 2$, $J^\pi = 1^+, 2^+, 3^+$) excitations. The used theory was quasiparticle random-phase approximation (QRPA). The theory's thorough derivation can be read, for example, in [2]. The QRPA is based on a quasiparticle mean field obtained from the particle mean field by a BCS transformation, resulting in BCS quasiparticles. The basic excitations of QRPA are "bosonized" by introducing collective combinations of quasiparticle pairs in the form

$$Q^\dagger = \sum_{a\leq b} [X^\omega_{ab} A^\dagger_{ab}(JM) - Y^\omega_{ab} \tilde{A}_{ab}(JM)] \,, \tag{1}$$

where the X and Y are the forward-going and backward-going amplitudes, representing the probability amplitudes for a quasiparticle-pair creation ($A^\dagger$) or annihilation ($\tilde{A}$) to happen. Transition operators for isovector and isoscalar excitations are needed to calculate the transition nuclear matrix elements (NMEs). The transition operators are of the form

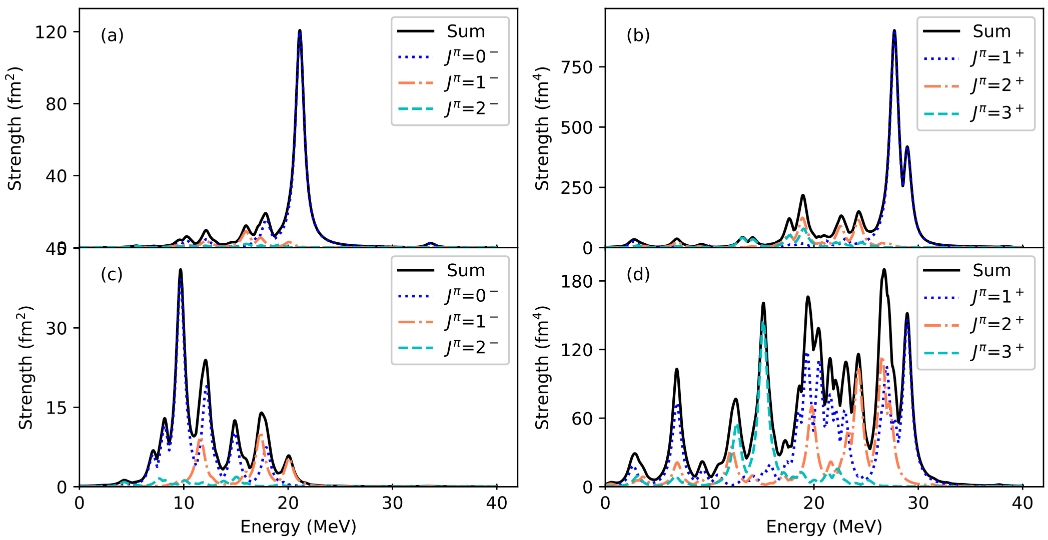

FIGURE 1. Strength functions for ^{100}Mo. Panels (a) and (b) represent isovector strengths, and panels (c) and (d) represent isoscalar strengths. Panels (a) and (c) are the spin-dipole ($L = 1$) strengths, and panels (b) and (d) are the spin-quadrupole strengths ($L = 2$).

$$\mathscr{O}^{0,v}_{L,JM} = i^L r^L [Y_L \sigma]_{JM} t_0 \,, \tag{2}$$

for an isovector excitation. The Y_L is a spherical harmonic, and σ is the spin operator. Operator t_0 represents the third component of the isospin operator. For the isoscalar excitations, the operator can be written similarly but without the t_0 component. With the use of transition and QRPA excitation operators, the transition strengths can be calculated as the square of the transition NMEs

$$S^L_{nJ^\pi} = |(nJ^\pi||\mathscr{O}^0_{L,J}||\mathrm{QRPA})|^2 \,. \tag{3}$$

Results and conclusions

Several conclusions can be drawn based on the obtained results. The width of the strength distribution depends on the type of excitation: Isoscalar strength is more widely spread in energy and contains a large number of separate peaks, in particular for the quadrupole strength. On the contrary, the isovector strength tends to be located in one or a few isolated strong peaks consisting of transitions to the 0^- dipole and 1^+ quadrupole states. Also for the isoscalar excitations these multipoles dominate but there are also strong contributions from other multipole states, like 3^+ at lower energies and 2^+ at higher energies. An example of the obtained results can be seen in Fig. 1.

Lately, we also have calculated some new results of multipole giant resonances in molybdenum and zirconium isotopes. In these calculations, the spin operator is not active. Transition operators are the same form as (2), but the spin operator is replaced with the unit operator, **1**. We have calculated the results for monopole ($L = 0$), dipole ($L = 1$), quadrupole ($L = 2$), and octupole ($L = 3$) resonances. These results can be compared with the corresponding measured ones and results computed by using Hartree-Fock and Skyrme based random-phase approximation, available in [3]. We have found a good correspondence of our QRPA results and the results of [3]. In this way we can "calibrate" our QRPA approach for the future applications to $\beta\beta$-decaying systems of nuclei. Finally, possible future experimental data of the (spin-)multipole giant resonances would potentially help us fine-tune the $\beta\beta$ NMEs and reduce their uncertainties.

DOUBLE-BETA DECAY OF ^{104}RU

Introduction

In the second part of this study, the $\beta\beta$ decay of ^{104}Ru $\rightarrow$ ^{104}Pd was studied. The nature of the ruthenium isotope ^{104}Ru does not allow it to decay by emitting only one beta since it is not energetically possible from the ground state of ^{104}Ru. That is why the decay of ^{104}Ru can only happen via two betas. The studied decay of ruthenium proceeds from the ground state to the palladium ground state. We have studied both the two-neutrino and neutrinoless $\beta\beta$ decay. The nuclear matrix elements (NMEs) and phase space factors are calculated, and the preliminary results for half-lives are estimated. The newly measured Q-value for the decay was used in the phase-space calculations. This kind of research has been done previously, for example, in [4].

The nuclear model used in this study is the microscopic interacting boson model (IBM-2). The IBM-2 has been used to study different ruthenium and palladium isotopes before. The studies made before are about the ^{96}Ru and ^{110}Pd as the parent nuclei in [5], and ^{100}Ru and ^{104}Pd as the daughter nuclei in [5, 6].

In this nuclear model, protons and neutrons pair up and are considered bosons with a total angular momentum of 0 or 2. The number of (proton or neutron) bosons depends on the active nucleon or hole pairs outside the closed shell. These bosons then create the excitation states. The model is explained in detail in [7].

Experimental measurements and theoretical basis

This study is done in collaboration with an experimental group, IGISOL (Ion Guide Isotope Separator On-Line), at the University of Jyväskylä. Using a mass spectrometer, they measured the Q-value for the $\beta\beta$ decay of ^{104}Ru very precisely. The measured Q-value is fully compatible with the former known Q-value 1299(3) keV [8] but is about 70 times more precise. The measured Q-value is used in the evaluation of the phase-space factors. The detailed publication about the precise value and analyzation about the measurement and calculations is about to be published soon.

The scattering electron wave functions play a significant role in evaluating the phase-space factors of the $\beta\beta$ decay of ^{104}Ru. In the calculations, the Dirac wave functions are used with finite nuclear size and electron screening. More about these calculations can be read from [9]. The preliminary results for the phase-space factors for the two-neutrino and neutrinoless $\beta\beta$ decay are $G_{2\nu} = 3.1 \times 10^{-21}$ yr^{-1} and $G_{0\nu} = 1.1 \times 10^{-15}$ yr^{-1}.

Also, the nuclear matrix elements for both two-neutrino $M_{2\nu}$ and neutrinoless $M_{0\nu}$ $\beta\beta$ decay are calculated using the IBM-2 [5]. The two-neutrino $\beta\beta$ decay matrix element consists of the Gamow-Teller and Fermi parts, and the neutrinoless decay also has the tensor part. In the calculations, the isospin restoration formalism [5] is used, which leads to a very small Fermi matrix element for the two-neutrino $\beta\beta$ decay. The closure approximation is assumed in both of the calculations. The two-neutrino $\beta\beta$ decay NME is strongly affected by the choice of the closure energy since the momentum of the virtual neutrino is within the same energy range as the closure energy. Fortunately, the neutrinoless $\beta\beta$ decay NME is not very much affected by the closure energy choice because the virtual neutrino's momentum in this decay mode is orders of magnitude higher than the closure energy.

With the use of the phase-space factors and NMEs, the estimates for the half-lives can be obtained. The formula for the inverse of the half-life of two-neutrino $\beta\beta$ decay is of the form

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

and for the neutrinoless $\beta\beta$ decay, it is

$$[t_{1/2}^{0\nu}]^{-1} = g_A^4 G_{0\nu} \left| M_{0\nu} \right|^2 \frac{m_{\beta\beta}^2}{m_e^2} . \tag{5}$$

In the neutrinoless $\beta\beta$ decay, the $m_{\beta\beta}$ is the effective neutrino mass for which we have used the interval 0.01 eV to 0.1 eV. The m_e is the mass of an electron. In both (4) and (5), the g_A is an effective axial vector coupling constant. We have used three different values for the g_A: the bare, which is 1.269; the renormalized value, 1.00; and one corresponding to maximal quenching, which depends on the mass number and can be parametrized for IBM-2 as $1.269 \times A^{-0.18}$.

Results and conclusions

A newly measured Q-value has been used to calculate the phase-space factors for the $\beta\beta$ decay of ruthenium. Also, the nuclear matrix elements were obtained using the IBM-2. Preliminary results for the half-lives for two neutrino and neutrinoless $\beta\beta$ decay were calculated. The estimates of the half-lives are $5.44 \times 10^{21} - 1.57 \times 10^{23}$ years for the two-neutrino $\beta\beta$ decay, and $4.64 \times 10^{26} - 142.07 \times 10^{28}$ years for the neutrinoless $\beta\beta$ decay. The longest directly measured half-life for the decay with two neutrinos decay is 1.8×10^{22} years for ^{124}Xe (2νECEC) [10], which is of the same order as some of the estimated half-lives, especially the half-life estimates for the two-neutrino $\beta\beta$ decay.

We plan on doing the same kind of measurement-calculations combination for other $\beta\beta$ decay candidates. For example, nuclei with mass numbers A = 120 and 122. The transitions to be considered will be ^{120}Te $\rightarrow$ ^{120}Sn, and ^{122}Sn $\rightarrow$ ^{122}Te. This way, valuable information about this rare decay process can be gained.

ACKNOWLEDGMENTS

We wish to acknowledge the support from Vilho, Yrjö and Kalle Väisälä Foundation, Academy of Finland (Grant Nos. 314733, 320062, 345869), and NEPTUN (Project no. CF 264/29.11.2022 of the EU call PNRR-III-C9-2022-I8).

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