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Calculation of the nuclear matrix elements and phase-space factors for the double-beta decay of ^{104}Ru

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Outline of the speech

- Motivation and introduction
- Theory
- Experimental measurements
- Results
- Conclusions

Motivation and introduction

- Neutrinoless double-beta decay remains one of the most talked topics in nuclear and particle physics.
- Observing this kind of decay would mean physics beyond the standard model.
  - -> Neutrino is a Majorana particle.

Motivation and introduction

- We have studied the double-beta decay of ^{104}Ru —> ^{104}Pd
  - From ground state to ground state
  - Both two-neutrino and neutrinoless decay
  - The used nuclear model is the microscopic interacting boson model (IBM-2)
  - In the phase-space factor calculations, we use newly measured *Q*-value for double-beta decay of ^{104}Ru
- This kind of study was previously made, for example [Eur. Phys. J. A (2022) 58:44]

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High-precision Q-value measurement and nuclear matrix element calculations for the double-β decay of ^{98}Mo

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Motivation and introduction

- Studies made before with IBM-2:
  - Ruthenium
    - $\beta^-\beta^-$: ^{100}Mo —> ^{100}Ru, $2\nu\beta\beta$ ja $0\nu\beta\beta$ (light and heavy neutrino) [PRC 91 (2015) 034304], Majoron emitting [PRC 103 (2021) 044302]
    - $\beta^+\beta^+$: ^{96}Ru —> ^{96}Mo (light and heavy) [PRC 91 (2015) 034304]
  - Palladium
    - $\beta^-\beta^-$: ^{110}Pd —> ^{110}Cd, $2\nu\beta\beta + 0\nu\beta\beta$ (light and heavy) [PRC 91 (2015) 034304], Majoron emitting [PRC 103 (2021) 044302]
    - $\beta^+\beta^+$: ^{106}Cd —> ^{106}Pd, $2\nu\beta\beta + 0\nu\beta\beta$ (light and heavy) [PRC 91 (2015) 034304]

Theory

- Microscopic interacting boson model (IBM-2)
  - Protons and neutrons pair up and are considered bosons with a total angular momentum of 0 or 2
  - The number of bosons depends on the active nucleon or hole pairs outside the active shell
    - For ^{104}Ru: $N_P = 3$ and $N_N = 5$
    - For ^{104}Pd: $N_P = 2$ and $N_N = 4$
  - Bosons create the excitation states

Measurements

- This study is done in collaboration with an experimental group from the University of Jyväskylä
- The measurements were done at IGISOL (*Ion Guide Isotope Separator On-Line*)
- They have used a mass spectrometer, which is a penning trap
- Q -value has been determined very precisely
  - The mass difference between ^{104}Ru and ^{104}Pd was measured
  - From the mass difference, the Q -value was calculated ($E = mc^2$)
- The measured Q -value for the double beta decay of ^{104}Ru is fully compatible with the previously measured value 1299(3)keV (AME2020) but is much more precise
  - Analyzation of the Q -value is still in progress

Nuclear matrix elements

- Two-neutrino double-beta decay matrix element consists of the Gamow-Teller (GT) and Fermi (F) parts

$$M^{2\nu} = M_{GT}^{2\nu} + \left(\frac{g_V}{g_A}\right)^2 M_F^{2\nu}$$

- We use the isospin restoration formalism, which leads to a very small Fermi matrix element for $2\nu\beta\beta$.
- Neutrinoless double-beta decay matrix element can be written as
- $$M^{0\nu} = M_{GT}^{0\nu} - \left(\frac{g_V}{g_A}\right)^2 M_F^{0\nu} + M_T^{0\nu}$$
- Where the Tensor (T) part is also included
- We use closure approximation in the calculation of both neutrinoless and two-neutrino nuclear matrix elements. The neutrinoless NME is not very sensitive to the choice of closure energy but the two-neutrino NME strongly depends on the closure energy. The calculation without closure approximation is a work in progress.

Nuclear matrix elements

- These were calculated with two different parameters for palladium. Parameters were taken from [Nucl. Phys. A 604, 163 (1996)] and [Nucl. Phys. A 348, 125 (1980)]

IBM-2 calculations of even–even Pd nuclei

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THE Ru AND Pd ISOTOPES IN THE PROTON-NEUTRON INTERACTING BOSON MODEL

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	^{104}Pd (1996)	^{104}Pd (1980)	^{104}Ru (1980)
ED	-	0.938	0.766
EDN	0.920	-	-
EDP	0.860	-	-
RKAP	-0.18	-0.25	-0.167
CHN	-0.48	-1.0	-1.118
CHP	-0.3	0.2	0.4
RMAJ1	0.2	0.0	0.0
RMAJ2	0.05	0.0	0.0
RMAJ3	0.0	0.0	0.0
C0N	-0.39	0.188	-0.188
C2N	-0.13	0.0	-1.125
C4N	0.0	0.0	0.0

Nuclear matrix elements

- Matrix elements calculated with two different parametrization
- Also, the NMEs are calculated with CD-Bonn and Argonne short-range correlations
- The two parametrizations give essentially the same NMEs

	$M^{2\nu}$ (CD-Bonn)	$M^{2\nu}$ (Argonne)	$M^{0\nu}$ (CD-Bonn)	$M^{0\nu}$ (Argonne)
(1996)	0.151	0.150	4.487	4.321
(1980)	0.151	0.149	4.482	4.316

Phase-space factors

- The key ingredients for the evaluation of phase-space factors in single- and double-β decay are the (scattering) electron wave functions.
- The calculation makes use of exact Dirac wave functions with finite nuclear size and electron screening.
- Phase-space factors were calculated using the measured Q -value for ^{104}Ru.
- These are also preliminary results because they rely on the Q -value
- The obtained results are
  - $2\nu\beta\beta$: $G_{2\nu} = 3.1 \times 10^{-21}$ yr^{-1}
  - $0\nu\beta\beta$: $G_{0\nu} = 1.1 \times 10^{-15}$ yr^{-1}

Estimates for the half-life

- The estimates for the half-life can be calculated using the nuclear matrix elements and phase space factors
- For the two-neutrino case, the inverse of the half-life can be calculated as
- $$\left[t_{1/2}^{2\nu}\right]^{-1} = g_A^4 G_{2\nu} \left| M_{2\nu} \right|^2$$
- And for the neutrinoless double-beta decay the inverse of the half-life is
- $$\left[t_{1/2}^{0\nu}\right]^{-1} = g_A^4 G_{0\nu} \left| M_{0\nu} \right|^2 \frac{m_{\beta\beta}^2}{m_e^2}$$
- Where the effective neutrino mass is $m_{\beta\beta} = \sum_i U_{ei} m_i$

Estimates for the half-life

- Preliminary results for the half-lives for two neutrino and neutrinoless double-beta decay were calculated
- The effective neutrino mass was estimated to be 0.01 keV - 0.1 keV

g_A^{eff}	$t_{1/2}^{2\nu\beta\beta}$(years)	$t_{1/2}^{0\nu\beta\beta}$(years)
$1.269A^{-0.18}$	1.55×10^{23}	$(1.42 - 142.06) \times 10^{28}$
1.269	5.47×10^{21}	$(5.01 - 501.43) \times 10^{26}$
1	1.42×10^{22}	$(1.30 - 130.03) \times 10^{27}$

Conclusions

- We have calculated the nuclear matrix elements for the double-beta decay of ^{104}Ru —> ^{104}Pd using the microscopic interacting boson model
  - Matrix elements were almost the same with the two different parameterizations
- The preliminary results for phase-space factors were also calculated
- The estimated half-lives were obtained
- The longest directly measured half-life for 2v decay is $t_{1/2} = 1.8 \times 10^{22}$ years for ^{124}Xe (2νECEC), which is of the same order as some of the estimated half-lives
- We are planning to do the same kind of measurement-calculations combination for other double-beta decay candidates in the future

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Thank you!