Acta Physica Polonica B Proceedings Supplement **18**, 2-A22 (2025)

NEW LIFETIME MEASUREMENTS IN THE RUTHENIUM CHAIN: INVESTIGATING THE EVOLUTION OF TRIAXIALITY*

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Received 9 December 2024, accepted 19 December 2024, published online 10 April 2025

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* Presented at the 57$^{\text{th}}$ Zakopane Conference on Nuclear Physics, *Extremes of the Nuclear Landscape*, Zakopane, Poland, 25 August–1 September, 2024.

We have used the recoil distance Doppler-shift method to measure lifetimes of excited states in ^{108}Ru, ^{110}Ru, and ^{112}Ru. Excited states in these nuclei were populated by fusion–fission reactions between a ^{238}U beam and a ^{9}Be target in an experiment at GANIL. Fission fragments were identified event by event in the VAMOS++ spectrometer, while γ-rays were detected by the Advanced Gamma Tracking Array (AGATA). The lifetimes in the ground state band are consistent with rotational structures and constant B(E2) values indicate that the deformation does not change significantly across the chain of studied ruthenium nuclei. Preliminary results for lifetimes of states in the γ-band indicate a well deformed triaxial shape with a γ parameter close to 30° in ^{110}Ru, with a slight change towards oblate deformation in ^{112}Ru.

DOI:10.5506/APhysPolBSupp.18.2-A22

1. Introduction

Nuclei in the neutron-rich region around $A \approx 100$ exhibit several different nuclear shapes which in some cases change drastically as a function of proton and neutron number. These shape transitions make this an especially interesting region for testing theoretical predictions. Some nuclear chains, such as zirconium and strontium, present abrupt shape transitions and coexistence between near spherical and axially symmetric prolate shapes [1, 2]. The transition from spherical to deformed shapes is much more gradual for the ruthenium isotopes, and is predicted to pass through well-deformed triaxial shapes (see *e.g.* [3, 4]). The energy of the first 2^+ state drops gradually from ^{96}Ru to ^{110}Ru, indicating a smooth shape transition. Coulomb excitation measurements of ^{110}Ru [5] found evidence for triaxial deformation with γ close to 30°. Further evidence for pronounced triaxial shapes and a gradual transition from predominantly prolate to oblate near ^{112}Ru was provided by studies of rotational properties, which found the band crossing caused by the alignment of $g_{9/2}$ protons to be sensitive to the degree of triaxiality [6].

To understand the role of triaxiality in the neutron rich ruthenium isotopes, we need a complete set of transition probabilities including both the ground state band and γ band. Lifetimes of the 2_1^+ states are known from β-decay studies [7–9]. Lifetimes at higher angular momentum have been measured with the Doppler-shift attenuation method [10] and point to changes in deformation with angular momentum. Experimental B(E2) values for the low-spin states are sparse, except for the aforementioned Coulomb excitation study of ^{110}Ru. The present study aimed at measuring lifetimes for states in both the ground-state band and the γ band in the angular momentum range $I = 4\hbar$–$6\hbar$ for ^{108,110,112}Ru.

2. Experimental setup and data analysis

An experiment was conducted at the GANIL facility in Caen, France, with the aim of measuring lifetimes in the $A \sim 100$ region with the recoil distance Doppler-shift method (RDDS) [11]. The experimental setup used the variable mode spectrometer (VAMOS++) [12–14] to identify nuclei of interest on an event-by-event basis, correlating them with γ-ray events detected in AGATA [15, 16]. A $1.85\,\mathrm{mg\,cm^{-2}}$ ^{9}Be target and $4.5\,\mathrm{mg\,cm^{-2}}$ $^{\mathrm{nat}}$Mg degrader were mounted on the Orsay universal plunger system (OUPS) [17] for micrometre control over the distance between them. A ^{238}U beam was accelerated onto the target at 6.2 MeV$/u$, inducing a fusion–fission reaction. The target chamber and VAMOS++ were rotated by 19° with respect to the incoming beam to maximize acceptance of the lighter fission fragments. The 41 high-purity germanium crystals of AGATA were placed at backwards angles covering a solid angle of about 1π. The experiment was run with ten target–degrader distances from $43\,\mu$m to $2664\,\mu$m, for around 18 h per distance. More detail is given by Pasqualato *et al.* [18], who report the results of the experiment for the zirconium chain.

The extraction of lifetimes from RDDS data is a two-step process: first, the peaks in the γ spectra must be fitted to create the decay curves, then the lifetime must be extracted from the latter. The decay curves are constructed from the ratio of the intensity of the γ rays emitted after the degrader to that of those emitted before. We hereafter refer to these two components of the decay as the slow and fast component, respectively. We Doppler correct the γ spectra to the slow component using the velocity measured in VAMOS++. This correction smooths out the γ spectra from the complementary fission fragments, which then form a large part of the observed background. Figure 1 shows spectra for γ rays correlated with the detection of ^{110}Ru in VAMOS++, at the shortest and longest target–degrader distance. The fast and slow components are clearly distinguishable in the spin range from $4\hbar$ to $8\hbar$ in both the ground-state band and γ band. The spectra sometimes contain transitions with similar energies where components partially overlap, which makes peak fitting challenging. To disentangle such peaks, we fit all ten spectra simultaneously, fitting a constant centroid and width to each peak component. This also ensures consistency between the fits which is crucial for the next step in the process.

Let I_{ij} denote the measured intensity of the decay from state i to state j. Let $R_{ij} = I_{ij}^{\mathrm{slow}}/(I_{ij}^{\mathrm{slow}} + I_{ij}^{\mathrm{fast}})$ denote the decay curve of the transition of interest, and R_{hi} denote those of transitions feeding into it from various states h. The lifetime τ_i is then given by the relation [11]

$$\tau_i \frac{\mathrm{d}}{\mathrm{d}t} R_{ij}(t) = \sum_h b_{ij}\alpha_{hi} R_{hi}(t) - R_{ij}(t)\,, \tag{1}$$

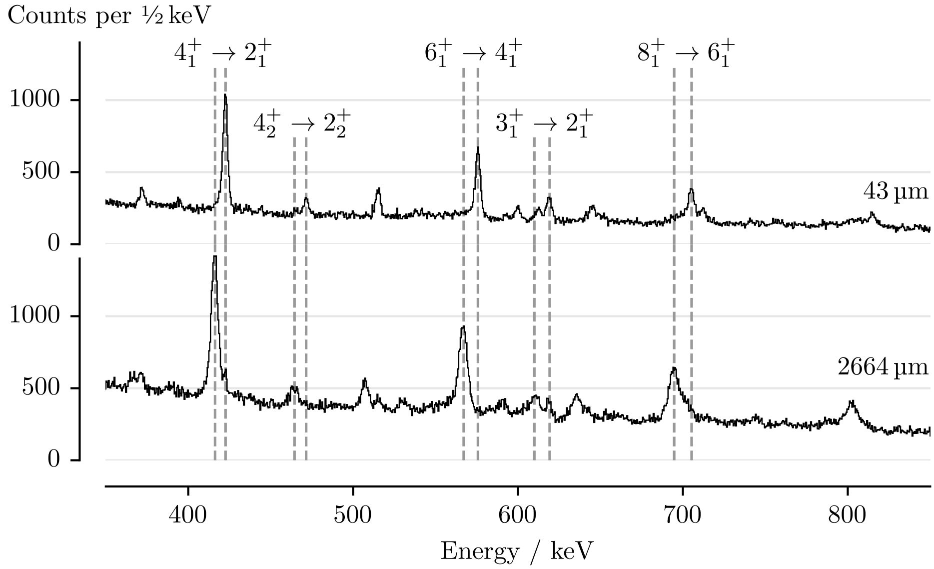

Fig. 1. Plot showing γ-spectra for ^{110}Ru at the shortest (top) and longest (bottom) target–degrader distance. The spectra are Doppler corrected using the velocity after the degrader measured in VAMOS++. Since the γ-rays are measured at backwards angles, γ-rays emitted before the degrader are shifted to lower energies.

where b_{ij} is the branching ratio corresponding to R_{ij} and α_{hi} is the fraction of observed feeding from higher-lying states adjusted for the efficiency of the detector. Direct population of the state of interest does not affect the lifetime measurement. In the studied cases, we only observe a single feeding transition, coming from within the rotational band. We assume any potential feeding from other states to be prompt.

It is well documented [*e.g.* 11, 18] that single-γ analysis of RDDS data risks being skewed by unseen feeding transitions. This problem can be eliminated by gating on the fast component of a specific feeding transition from a $\gamma\gamma$-coincidence measurement, with the added advantage of removing most contaminations from overlapping transitions. This does, however, require much higher statistics and generally results in a higher statistical uncertainty. Only the transitions in the ground-state band produce enough events for $\gamma\gamma$ analysis, and only in some cases. In ^{112}Ru, there were not enough statistics to perform a coincidence analysis. In ^{108}Ru, meanwhile, there were too many overlapping transitions to get reliable results in singles. In ^{110}Ru, we performed both analyses and if the two were in agreement, kept the measurement with lower uncertainty.

In both single-γ and $\gamma\gamma$-coincidences, we fit the decay curves by using a basis of smooth and monotonic B-splines [19]. We convert the plunger distances to flight times using the measured recoil velocities corrected for the energy loss in the degrader. For singles analysis, we perform a global fit of the feeding and decay curves to Eq. (1). This means that in addition to fitting the experimental data points, we also minimize the difference between the two sides of Eq. (1), treating the lifetime itself directly as a fit parameter. By doing this, we can propagate errors more accurately through the fitting process, and we avoid having to define a region of sensitivity which can affect the results. For the coincidence analysis, we use the proportionality between the gated decay curve and its derivative to determine the lifetime in a similar global fit of all distances. Figure 2 shows an example fit of the lifetime of the 6_1^+ state, with feeding from the 8_1^+ state, in ^{110}Ru.

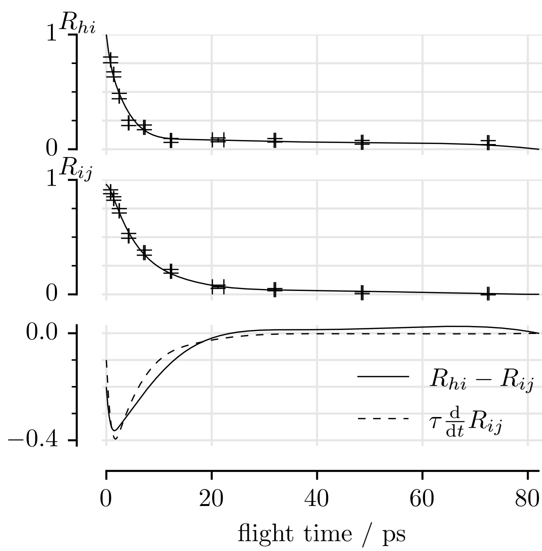

Fig. 2. Plot showing B-spline fits of the decay curves corresponding to the $8_1^+ \rightarrow 6_1^+$ (R_{hi}) and $6_1^+ \rightarrow 4_1^+$ (R_{ij}) transitions in ^{110}Ru, along with the two sides of Eq. (1). The data points show the error in the fit of the peaks and in the plunger position.

3. Results and discussion

For E2 transitions, the lifetime gives us the reduced transition probabilities B(E2) through the relation

$$B\left(\mathrm{E2}; i \rightarrow j\right) = \frac{b_{ij}}{\tau_i} \left[1.225 \times 10^9 E_\gamma^5\right]^{-1} . \tag{2}$$

Figure 3 shows the B(E2) values obtained from measured lifetimes in the ground-state bands of ^{108,110,112}Ru. The RDDS setup lets us measure lifetimes of the 4_1^+ and 6_1^+ states; the 2_1^+ states are too long lived, but have been measured previously by other methods [5, 7–9]. For ^{110}Ru, our results are consistent with those obtained by Coulomb excitation in [5], and have slightly improved uncertainties. The good agreement increases our confidence in our analysis and results for other nuclei.

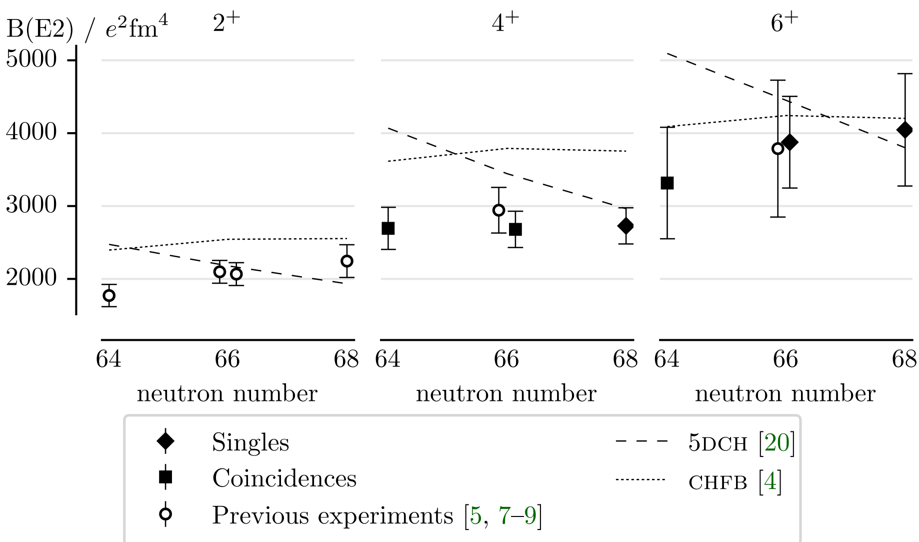

Fig. 3. Plot of the B(E2) values for the ground state bands in ^{108,110,112}Ru. We compare our values to previously measured values [5, 7–9] and to theoretical calculations [4, 20].

We compare the data with theoretical predictions from a calculation using a five-dimensional collective Hamiltonian and the Gogny D1S interaction [20], and with cranked Hartree–Fock–Bogoliubov calculations based on the Skyrme UNEDF0 interaction [4]. The former predicts a decrease in B(E2) values with neutron number from a maximum at ^{108}Ru. Our data is qualitatively more consistent with the approximately constant values predicted by the latter. This indicates that the overall deformation does not change significantly between ^{108}Ru and ^{112}Ru. However, the experimental data — especially for the 4^+ states — are lower than the prediction of the CHFB model.

While we here only show results for the ground-state bands, we have also obtained lifetimes for states in the γ band in ^{110,112}Ru. Preliminary lifetime results for these states, when interpreted through the triaxial rotor model, indicate substantial triaxiality in these nuclei: close to $\gamma = 30°$ for ^{110}Ru and a slight shift towards an oblate shape in ^{112}Ru. This is consistent with microscopic–macroscopic model calculations [3], which predict stable triaxial shapes for ^{108,110}Ru and a more γ-soft oblate shape for ^{112}Ru. A similar shape transition was used to interpret the lower band-crossing frequency for the proton $g_{9/2}$ alignment in ^{112}Ru [6]. We have also obtained lifetimes of states in the yrast band in ^{109,111}Ru. Lifetimes for states in the odd-mass nuclei provide not only B(E2) values, but also B(M1) values when combined with branching ratios, and hence information on the configuration of the odd neutron. Results for the γ bands and for the odd-mass ruthenium isotopes, and their interpretation, will be presented in an upcoming more comprehensive paper.

The experiment produced data for a large range of nuclei. Any systematic errors are expected to be the same for all of these, making this dataset particularly well suited for comparisons between nuclei. Results for the zirconium chain are published in [18]. Future work will establish B(E2) values for several other isotopic chains, forming a basis for systematic studies of collectivity and deformation within the neutron-rich $A \sim 100$ region.

The authors would like to thank the AGATA and VAMOS++ collaborations. We are grateful for the help from J. Goupil and the GANIL technical staff for their work in setting up the apparatuses and the good quality beam. The authors would also like to thank G. Fremont for preparing the target and degrader foils. J.S.H., V.M., and A.G. acknowledge support from the Norwegian Research Council projects 325714 and 341985. S.L. acknowledges support by project No. BG-RRP-2.004-0008-C01. P.A.S. acknowledges the support of the Institute of Atomic Physics, Măgurele, Romania, contract number ELI-RO/RDI/2024-002 (CIPHERS), and the Romanian Ministry of Research and Innovation under research contract PN 23 21 01 06.

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