

SHAPE COEXISTENCE IN THE Ru ISOTOPES;
MULTI-SPECTROSCOPIC STUDY OF ^{98}Ru
AND BEYOND-MEAN-FIELD CALCULATIONS*

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The level structure of ^{98}Ru was investigated via γ -ray spectroscopy following the β^+ /electron capture decay of ^{98}Rh and with the $^{100}\text{Ru}(p, t)^{98}\text{Ru}$ reaction. Additional γ -ray transitions from low-lying levels were observed and spin-parity assignments of some key states were clarified, permitting the assignment of the 0_2^+ band and the γ band. The energies of the states in these bands fit well into the systematic trends observed in the heavier isotopes. The results are interpreted with the aid of beyond-mean-field calculations performed within the self-consistent configuration mixing method.

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1. Introduction

The even–even Ru isotopes, especially those with neutron numbers between 54 and 60, have low-lying level schemes reminiscent of those expected for quadrupole harmonic vibrators. In a survey conducted by Kern *et al.* [1], that primarily used the level excitation energies as indicators, a number of nuclei in the $Z = 50$ region were selected as excellent candidates for spherical vibrational motion, or in the language of the Interacting Boson Model (IBM), possessing U(5) symmetry [1]. While the Cd isotopes, especially $^{110,112}\text{Cd}$, stood out as perhaps the best examples, the survey also highlighted the Ru isotopes, albeit with some discrepancies noted. In a recent update of that survey [2], it was shown that the existing data rule out such an interpretation for the Ru isotopes with $A \geq 102$; there is evidence that shape coexistence occurs in these nuclei (see, *e.g.*, Refs. [2–4]). For $^{98,100}\text{Ru}$, however, the current state of spectroscopic data, despite recent experimental studies [5–9], cannot exclude a vibrational interpretation, at least up to the two-phonon level. We have thus initiated a programme, utilising both β^+ and electron capture (EC) decay, and the selective (p, t) reaction, to study the excited states of ^{98}Ru and ^{100}Ru . Since the results on ^{98}Ru have been the most extensively analysed to date, we concentrate on those results here.

2. Experimental details and results

A very sensitive spectroscopic tool to study excited nuclear states is via γ -ray spectroscopy following β decay. However, the parents of the neutron-deficient Ru isotopes are Rh, a refractory element that is difficult to produce as beams at ISOL facilities. We have thus used fusion–evaporation reactions, $^{12}\text{C}+^{89}\text{Y}$ and $^{14}\text{N}+^{89}\text{Y}$, at iThemba LABS to produce activities of ^{98}Rh and ^{100}Rh , respectively, at the newly-commissioned iThemba Tape Station. Beams of up to 8 μnA of ^{12}C or ^{14}N bombarded the ^{89}Y foil that was approximately 250 μm thick and mounted on a wagon attached to the tape. For the study of the ^{98}Rh decay, the cycle consisted of a bombardment of approximately 18 minutes (approximately 2 half-lives of the ^{98}Rh parent ground state), after which the beam was turned off and the source transported (transit time ≈ 2 minutes) to the counting station that consisted of 3 unsegmented and 1 segmented, BGO-suppressed, HPGe clover detectors for γ -ray detection, a plastic scintillator for β -particle detection, and a Si(Li) detector for conversion electron measurements. The decay of the ^{98}Rh activity was measured for 18 minutes and then the target was transported back to the irradiation position and the cycle repeated. The data were sorted into γ -ray singles histograms as well as $4k \times 4k$ γ - γ coincidence matrices. The background-subtracted γ - γ coincidence matrix of 25×10^6 events enabled the observation of many additional γ -ray transitions, filling in the necessary details of the low-lying level scheme required to ascertain the structure. Figure 1 displays results of γ - γ coincidences that confirm the

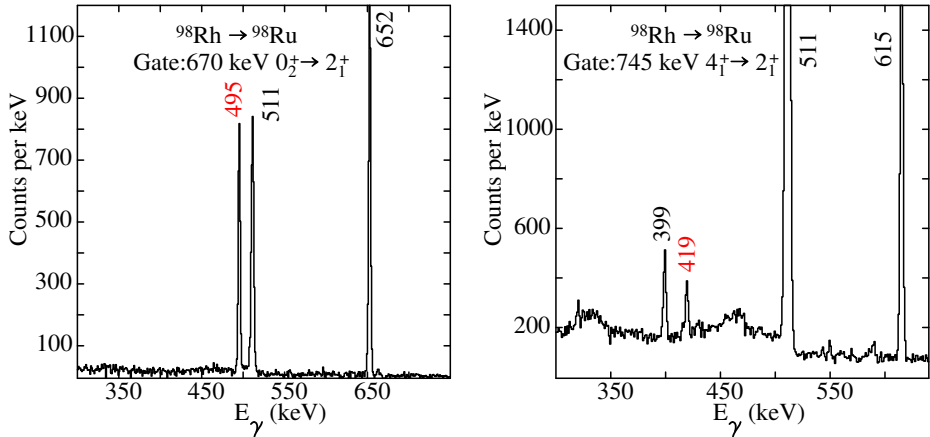


Fig. 1. Selected γ -ray spectra obtained in the present ^{98}Rh decay experiment, with coincidence conditions placed on the 670 keV γ -ray decay (left) from the 0_2^+ state, confirming the placement [9] of the 495 keV γ ray as the $2_3^+ \rightarrow 0_2^+$ transition, and on the 745 keV $4_1^+ \rightarrow 2_1^+$ γ -ray decay (right) showing the newly assigned 419 keV $2_3^+ \rightarrow 4_1^+$ γ -ray transition.

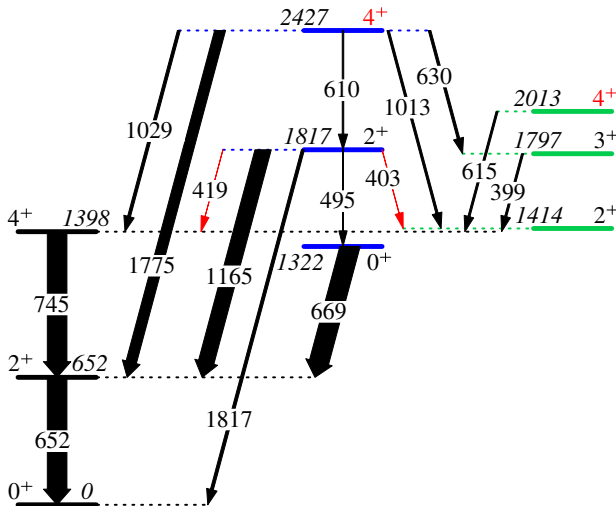


Fig. 2. Partial level scheme of ^{98}Ru observed in the decay of ^{98}Rh displaying the assigned 0_2^+ band with its transitions and the γ band. The previous placement [9] of the 495 keV and 610 keV transitions has been confirmed, and the 403 keV and 419 keV transitions are newly observed in the present study. The spin-parity assignments for the 2013 keV and 2427 keV levels as 4^+ are based on angular distributions of cross sections observed in the $^{100}\text{Ru}(p, t)$ reaction.

placement [9] of the 495 keV transition decaying from the 2_3^+ level feeding the 0_2^+ state, and also the newly observed 419 keV γ -ray decaying from the 2_3^+ level feeding the 4_1^+ state. The level scheme for the 0_2^+ band is shown in Fig. 2, where the new transitions are highlighted. Also highlighted are the new spin assignments for the 2013 keV and 2427 keV levels that are critical in the establishment of the rotational-like bands, discussed below.

The β^+ /EC decay measurements were complemented by the two-neutron-transfer reaction, $^{100}\text{Ru}(p,t)^{98}\text{Ru}$, analysed with the Q3D magnetic spectrograph of the Maier–Leibnitz Laboratory in Garching, Germany. Beams of 22 MeV protons bombarded an enriched ^{100}Ru target and cross sections for population of individual levels were determined at spectrograph angles ranging from 6° to 50° . Shown in Fig. 3 is a portion of the triton spectrum obtained in the reaction with the spectrograph positioned at 10° . From examination of the spectrum, it is immediately clear that the previous spin assignment for the 2013 keV level, suggested [9] to have $I^\pi = 3^+$, cannot be supported. (In the two-neutron-transfer reaction, the pair of neutrons couple to spin $S = 0$, and thus the allowed spin and parity of the final states are $I^\pi = L^{(-1)^L}$. Unnatural parity states may be populated, but only very weakly through second-order effects.) The angular distribution for the 2013 keV state indicates that it has $I^\pi = 4^+$. Together with the 2^+ level at 1414 keV and the 3^+ state at 1797 keV, it is suggested that these levels form the low-spin members of the γ band. In addition, the angular distributions for the 2427 keV level indicate that it also is a $I^\pi = 4^+$ state, and with the 0_2^+ state at 1322 keV and the 2^+ state at 1817 keV, comprise the low-spin members of the 0_2^+ band. We thus suggest that ^{98}Ru possesses a low-lying 0^+ band and a γ band.

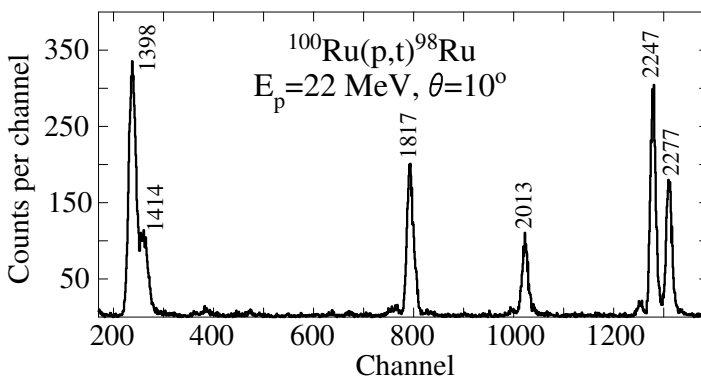


Fig. 3. Portion of the spectrum obtained with the $^{100}\text{Ru}(p,t)^{98}\text{Ru}$ reaction employing a 22 MeV proton beam, and a spectrograph angle of $\theta = 10^\circ$.

3. Interpretation and beyond-mean-field calculations

The newly assigned bands in ^{98}Ru fit very well the energy systematics of the corresponding structures established for the heavier Ru isotopes. Shown in Fig. 4 are the levels, to spin 6, assigned to the γ band in the Ru isotopic chain from $N = 54$ to $N = 62$. As can be seen, the structures have a rather smooth evolution as a function of neutron number, although there is a sudden increase in the staggering observed in the γ -band of ^{100}Ru .

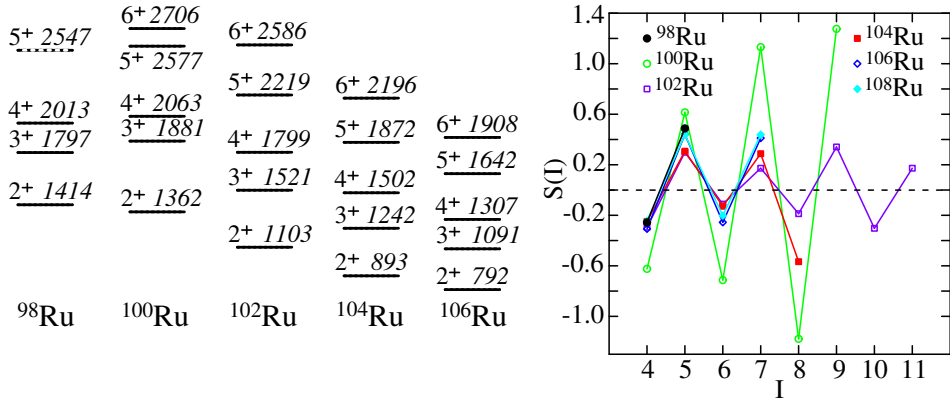


Fig. 4. Energy systematics (left) for the states assigned to the γ bands in $^{98-106}\text{Ru}$. The assignments are taken from the present work for ^{98}Ru , Ref. [14] for ^{100}Ru , Ref. [15] for ^{102}Ru , and Ref. [16] for $^{104,106,108}\text{Ru}$. The 5^+ state in ^{98}Ru is assigned based only on the systematics; no in-band γ -ray transition has yet been observed. Energy staggering (right), defined by Eq. (1), observed in the γ bands.

The staggering observed in bands is often used as an indicator of the dependence of the potential on the γ -shape degree of freedom (see, *e.g.*, Ref. [12]). For example, if the odd spin members are located closer to the higher-spin states (*e.g.*, the 3^+ state increases in energy towards the 4^+ state), this has been used as evidence for γ softness, whereas if they are located closer to the lower-spin members (*e.g.*, the 3^+ state lowers in energy approaching the 2^+ band head), it is taken as evidence for a rigid triaxial structure. Using a measure of the staggering defined by (see, *e.g.*, Ref. [13])

$$S(I) = [E(I) - 2E(I-1) + E(I-2)] / E(2_1^+), \quad (1)$$

the values of $S(I)$ vs. the spin I for the γ bands in $^{98-108}\text{Ru}$ are plotted in Fig. 4. All the Ru isotopes display a pattern characteristic for some degree of γ softness, although much smaller than the value expected for a completely γ -soft potential ($S(4) = -2.0$) [13]. The maximum staggering is observed for ^{100}Ru , which grows as a function of the angular momentum.

The structures of the Ru isotopes have been calculated in a beyond-mean-field (BMF) approach employing the Gogny D1S energy density functional, and the self-consistent configuration mixing (SCCM) method as described in Ref. [17]. The BMF effects are taken into account through the exact particle number projection before variation and angular-momentum restoration after variation, and include the possibility of axial and nonaxial shape mixing. The potential energy surfaces (PES) for $^{98-104}\text{Ru}$ resulting from the calculations are shown in Fig. 5. The position of the minimum occurs at larger deformation as the neutron number increases, consistent with the experimental trend of lowering of the $E(2_1^+)$ energies and increasing $B(E2; 2_1^+ \rightarrow 0_1^+)$ values. The surfaces also indicate that $^{98,100}\text{Ru}$ may be expected to be prolate in their ground state, with increasing γ softness maximizing at ^{104}Ru . The staggering pattern displayed in Fig. 4 would appear to favour that the maximum γ softness may be attained in ^{100}Ru , although no definitive statements can be made.

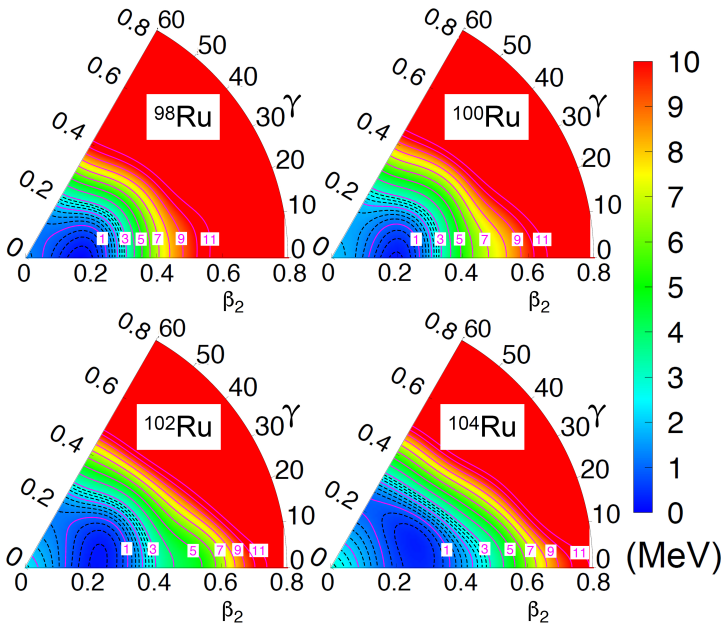


Fig. 5. Potential energy surfaces for $^{98,100}\text{Ru}$ (top) and $^{102,104}\text{Ru}$ (bottom) resulting from the BMF calculations described in the text.

Figure 6 displays the calculated probability distributions, plotted in the (β, γ) plane, for the 0_1^+ and 0_2^+ states in $^{98,100}\text{Ru}$. The calculations predict that shape coexistence occurs in these isotopes. For ^{98}Ru , the ground state is predicted to have a moderate deformation with a triaxial shape, with the 0_2^+ state weakly deformed and prolate. For ^{100}Ru , the ground state increases

in deformation, and the shape becomes axially symmetric, while the 0_2^+ state is predicted to have very large triaxiality. It should be noted that while the magnitude of the deformation extracted from the wave function distributions is in line with expectations based on the PES, the dynamics results in a wave function distribution not maximized at the location of the minimum in the PES for γ degree of freedom, resulting in a triaxial shape rather than prolate. Furthermore, the wave function distributions for the 0_2^+ states are inconsistent with those expected for vibrational excitations. The experimental results would favour the 0_2^+ band having a greater deformation than the ground state, whereas the calculations predict the opposite.

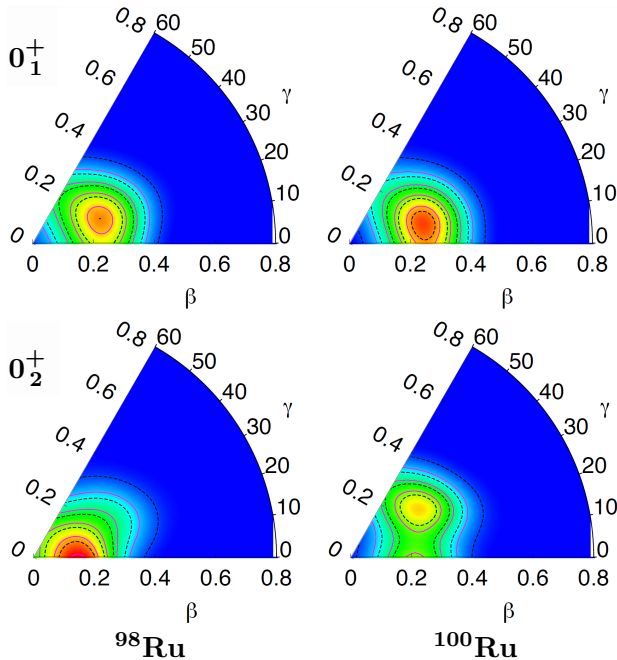


Fig. 6. Probability distributions of the wave functions for the 0_1^+ (top) and 0_2^+ (bottom) states in ^{98}Ru (left) and ^{100}Ru (right).

4. Conclusions

The level structure of ^{98}Ru was investigated via the β^+/EC decay of ^{98}Rh , and also with the $^{100}\text{Ru}(p,t)^{98}\text{Ru}$ reaction. From the observation of new γ -ray transitions, and spin assignments from the angular distributions obtained from the two-neutron-transfer data, rotational bands based on the 0_2^+ state and the γ band are suggested. The energies of the levels fit well the systematics observed in the heavier Ru isotopes for these excitations. The results of beyond-mean-field calculations indicate that shape coexistence occurs in ^{98}Ru .

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