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Abstract. As part of a systematic study of the nuclear structure of the Ru isotopes, ^{98}Ru was investigated via the β-decay of ^{98}Rh at iThemba LABS, and the ^{100}Ru(p,t) reaction at the Maier-Leibnitz Laboratory. The combined data results in significant revision of the previous spin assignments and clarification of the nature of levels in ^{98}Ru, as well as providing insights into the evolution of the structures across the Ru isotopic chain.

1. Introduction

The Ru isotopes lie in a region where the structure of the ground states can undergo a very rapid change as a function of neutron number. The Sr and Zr isotopes undergo the most rapid transition known across the nuclear landscape; those with $N < 60$ have very weakly-deformed or spherical shapes, and those with $N \geq 60$ have rather well-deformed ground states [1, 2]. The appearance of low-lying excited 0^+ states at $N = 60$ in Sr and Zr has been associated with shape coexistence, and consistent with this is the observation of enhanced $\rho^2(E0)$ values observed for the $0_2^+ \to 0_1^+$ transitions [3]. The spectroscopic quadrupole moment, Q_s, of the 2_1^+ state in ^{96}Sr is consistent with zero, as expected for a spherical shape, and a moderate $B(E2; 2_1^+ \to 0_1^+)$ value of $17.3^{+4.0}_{-3.2}$ W.u. [4, 5]. A low-lying rotational band is also observed, but it remains unclear if it should be associated with the 0_2^+ or 0_3^+ state. In ^{98}Sr, matrix elements extracted from a Coulomb excitation study [4, 5] were sufficient to determine the invariant $\langle Q^2 \rangle$ values for both the ground state and the 0_2^+ state, along with the Q_s values for the 2_1^+ and 2_2^+ levels. For the ground state, the extracted β deformation parameter indicates a large deformation with $\beta_2 = 0.5(1)$. For the 2_2^+ state, the Q_s value is consistent with zero, and the $\langle Q^2(0_2^+) \rangle$ value is dramatically smaller (0.33(3) e^2b^2) than that for the ground state (1.30(4) e^2b^2), suggestive of a crossing of the 0_1^+ and 0_2^+ configurations between ^{96}Sr and ^{98}Sr [4, 5]. In the Zr isotopes, rotational bands with enhanced in-band $B(E2; 2^+ \rightarrow 0^+)$ values have been observed in ^{94}Zr [6] and ^{96}Zr [7], and a rotational band has been suggested in ^{98}Zr (see, e.g. Ref. [8]). The prevailing view is that the strongly deformed excited configuration for $N < 60$ becomes the ground state at $N = 60$, while the spherical or weakly-deformed ground states for $N < 60$ becomes excited states at $N = 60$.

Progressing to higher Z, the Mo isotopes also have well established shape coexistence. In ^{96}Mo, the 0_2^+ state has a much smaller value of $\langle Q^2 \rangle$ than the ground state [9]. In ^{98}Mo, these become nearly equal [10], but the $\langle \cos 3\delta \rangle$ values indicate that the ground state is triaxial while the 0_2^+ state is prolate [10]. For ^{100}Mo, the $\langle Q^2 \rangle$ values for the 0_1^+ and 0_2^+ states increase substantially, with that for the 0_2^+ exceeding the ground state value and the $\langle \cos 3\delta \rangle$ values mirror those of ^{98}Mo [11]. Associated with this evolution, the $\rho^2(E0; 0_2^+ \rightarrow 0_1^+)$ values also increase substantially with increasing neutron number [3].

The Ru isotopes show a much smoother evolution in their structure. Indeed, crossing $N = 60$, there does not appear to be dramatic change in the nature of the ground state. The Ru isotopes with neutron number $N \geq 60$ have a definite deformed structure. The Coulomb excitation study of ^{104}Ru performed by Srebrny *et al.* [12] provided a precise set of the invariant quantities $\langle Q^2 \rangle$ and $\langle Q^3 \cos 3\delta \rangle$. For the ground-state band, the values are approximately constant up to the 8_1^+ level and correspond to $\beta_2 \approx 0.28$ and a triaxial shape with $\gamma \approx 25^\circ$ [12]. For the 0_2^+ level the $\langle Q^2 \rangle$ corresponds to $\beta_2 \approx 0.21$, indicating substantially smaller deformation, and $\langle \cos 3\delta \rangle$ corresponding to $\gamma = 28(6)^\circ$ [12].

The structures of the Ru isotopes with $N < 58$ have often been discussed in terms of spherical vibrational motion. A recent survey [13] of previously claimed [14] multi-phonon spherical vibrational nuclei, that cited many examples in the $Z = 40 - 50$ region including some Ru isotopes, found that few viable candidates remained. In fact, it was only ^{98,100}Ru where a spherical vibrational nature could not be excluded. The 0_2^+, 2_2^+, and 4_1^+ levels lie in close proximity to each other at approximately twice the energy of the 2_1^+ state and would indeed appear to be good candidates for the two-phonon states. The structure of ^{98}Ru was investigated by Cakirli *et al.* [15], who concluded that the three-phonon (or higher) states could not be assigned in ^{98}Ru, and thus if ^{98}Ru were vibrational, the pattern appeared to terminate at the two-phonon level. The most recent experimental study by Giannatiempo *et al.* [16] concluded that the IBM-1 description was inadequate and that a large number of states were of mixed-symmetry character requiring an IBM-2 description [17].

Urban *et al.* [18] studied ^{102}Ru and established the higher-spin members of the 0_2^+ band. It was suggested [18] that there are two relatively unperturbed configurations for the 0^+ states at $N = 52$ which evolve differently with N (see Fig. 5 of Ref. [18]). The first configuration forms the ground state in ^{96}Ru that has a nearly spherical shape. The deformation of this configuration remains approximately constant with N and always small, and at $N = 60$ becomes the excited 0_2^+ band. The second configuration is the 0_2^+ state in ^{96}Ru, and also possesses low deformation that increases with N. These two configurations cross in the vicinity of ^{100,102}Ru such that the deformed second configuration becomes the ground state band in ^{104}Ru. As a result of the mixing near the crossing, both 0^+ states take on deformed characteristics.

We have initiated studies of the Ru isotopes to understand their evolving structure, and the evolution of deformation with increasing Z between the $Z = 40$ subshell closure and the $Z = 50$ shell closure. To date, this has involved: a) γ-ray spectroscopy following the β-decay of ^{98,100}Rh at the iThemba LABS facility, b) γ-ray spectroscopy following ^{99,101}Ru(n_{th}, γ) capture reactions using the FIPPS facility of the Institute Laue-Langevin, Grenoble, c) the Coulomb excitation of ^{102}Ru by ^{12}C and ^{16}O beams performed using the Q3D magnetic spectrograph of the Maier-Leibnitz Laboratory at Garching, d) the Coulomb excitation of ^{100}Ru with a ^{32}S beam performed at the Heavy Ion Laboratory, Warsaw, and e) a series of measurements with direct reactions that included the ^{100,102}Ru(p,t) two-neutron-transfer reactions, and the ^{103}Rh(p,α) and ^{103}Rh$(d,^{3}$He$)$ proton transfer reactions. Herein, we report results on experiments on which we have initially focused: the β decay of ^{98}Rh to ^{98}Ru and the ^{100}Ru(p,t) reaction.

2. Study of ^{98}Ru

γ-ray spectroscopy following β decay is an excellent tool for the observation of weak decay branches from excited states since the backgrounds present in the spectra are much lower than typically observed for in-beam experiments. We sought to utilize the β-decay of Rh to study Ru, however Rh, being a refractory element, is not available from ISOL-style radioactive beam facilities. We thus used for this purpose the newly commissioned iThemba Tape Station which appeared ideal. Shown in Fig. 1 is a schematic of the facility. Originally designed to use the Recoil Shadow technique to capture fusion-evaporation residues on the tape, the reactions that we chose to employ, the ^{12}C+^{89}Y$\rightarrow$^{101}Rh* $\rightarrow$^{98}Rh+3n and ^{14}N+^{89}Y$\rightarrow$^{103}Pd* $\rightarrow$^{100}Ru+$p2n$ reactions would not lead to sufficient recoil energies and angular dispersion to result in a significant deposit on the tape. Taking advantage of the relatively long half lives of the β-decaying states involved, which in the case of ^{98}Rh are 8.72(12) min for the (2^{+}) ground state, and 3.6(2) min for the (5^{+}) isomer, we thus modified the infrastructure to be able to transport the Y target and its holder from the target chamber to the counting chamber. The tape, in essence, acted like a slow rabbit transport. The ^{89}Y target was bombarded with 47.5 MeV ^{12}C ions with a current up to 8 pnA for 18 minutes, and the transport to the counting station was approximately 2 minutes in duration after which the activity was counted for 18 minutes, and

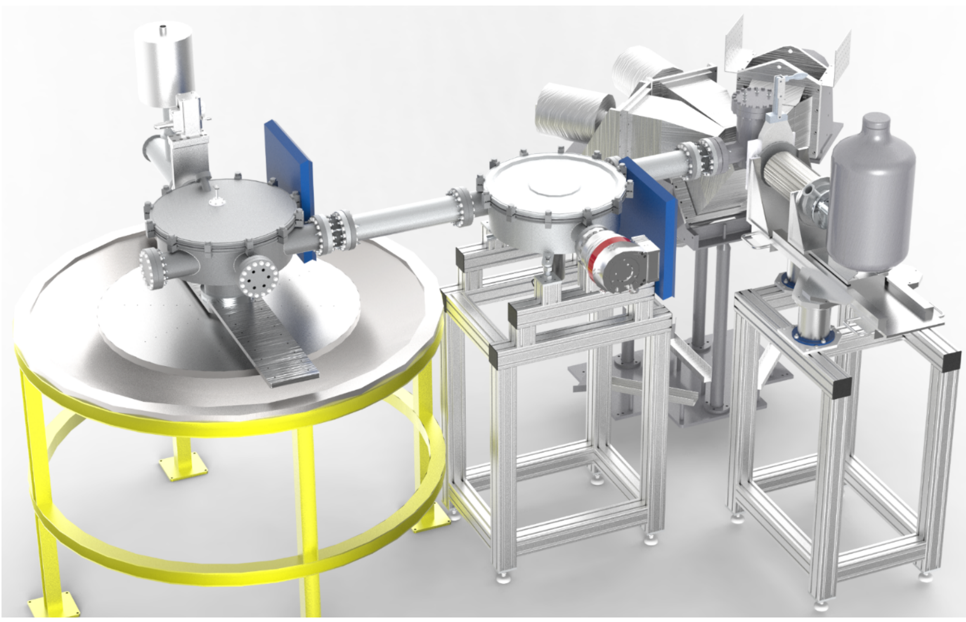

Figure 1. Schematic drawing of the iThemba Tape Station. The cylindrical chamber on the left is the target chamber where the irradiation takes place, the center chamber houses the spools and drive motors for the tape, and the rightmost chamber is the counting station housing the Si(Li) detector, the plastic scintillator, and is surrounded by the HPGe detectors.

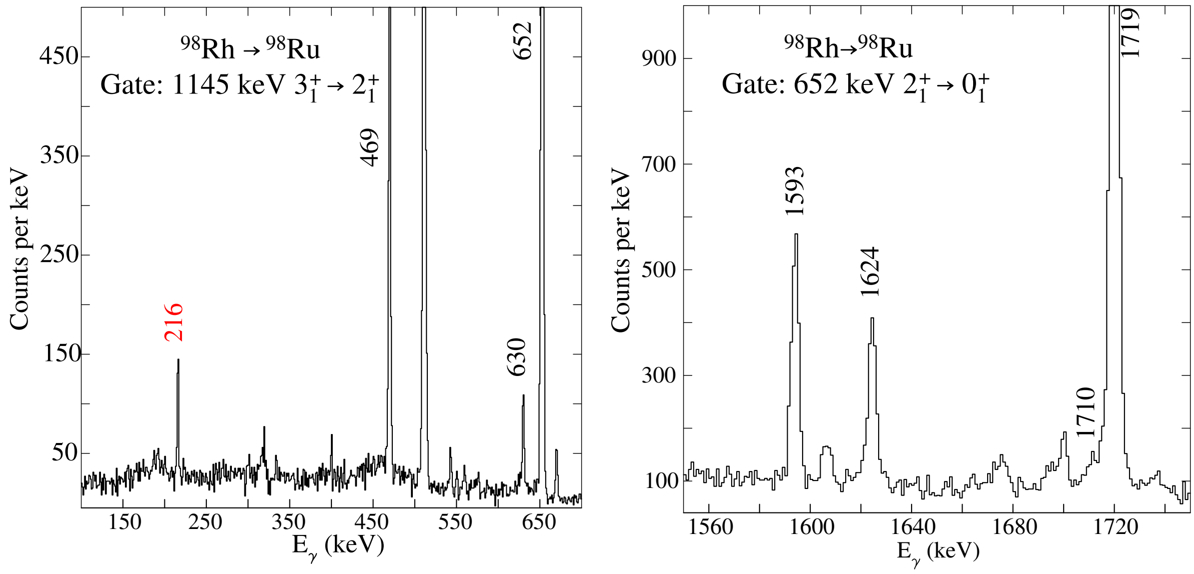

Figure 2. Partial γ-ray spectra obtained with a coincidence condition placed on the 1145-keV $2_2^+ \rightarrow 2_1^+$ γ ray, displaying the 216-keV γ ray assigned as the 2013-keV→1797-keV transition (left panel), and the 652-keV $2_1^+ \rightarrow 0_1^+$ γ ray showing the transitions decaying from the 2246-, 2277-, 2362-, and 2371-keV levels, as shown in Fig. 3.

the cycle repeated. Figure 2 displays a portion of the γ-ray spectrum in coincidence with the 1145-keV $3_1^+ \rightarrow 2_1^+$ transition. The 216-keV γ-ray was newly observed, and assigned as the transition from the 2013-keV level feeding the 3_1^+ state, as shown in Fig. 3. Also shown in Fig. 2 is a portion of the spectrum with a coincidence condition on the 652-keV $2_1^+ \rightarrow 0_1^+$ γ ray, displaying the region around 1.7 MeV. The transitions labelled with their energies are those

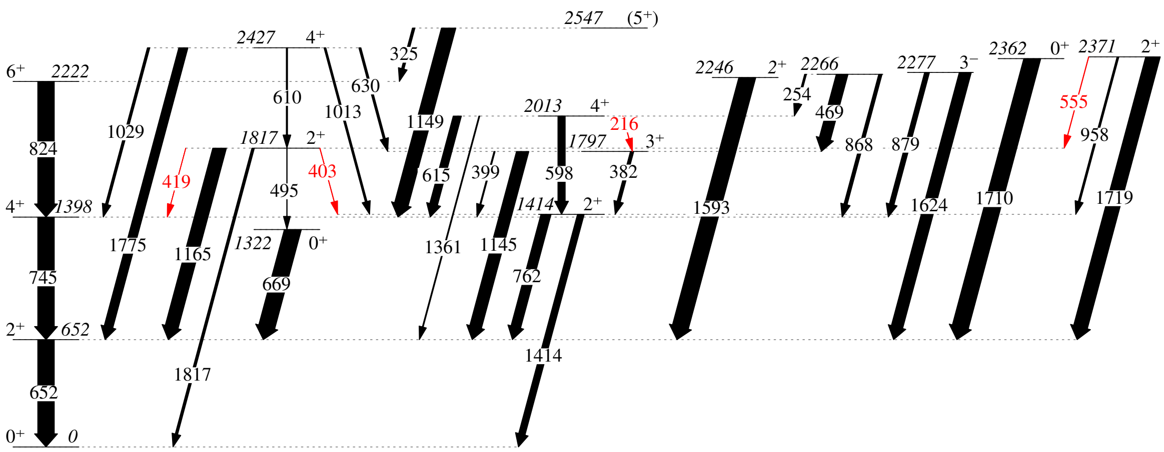

Figure 3. Partial ^{98}Ru decay scheme showing the ground state band, 0_2^+ band, and "γ"-band, as well as additional levels observed below 2.4 MeV in the decay of ^{98}Rh. The widths of the arrows are proportional to the γ-ray branching ratio for each level. Newly observed transitions are indicated by a red colour.

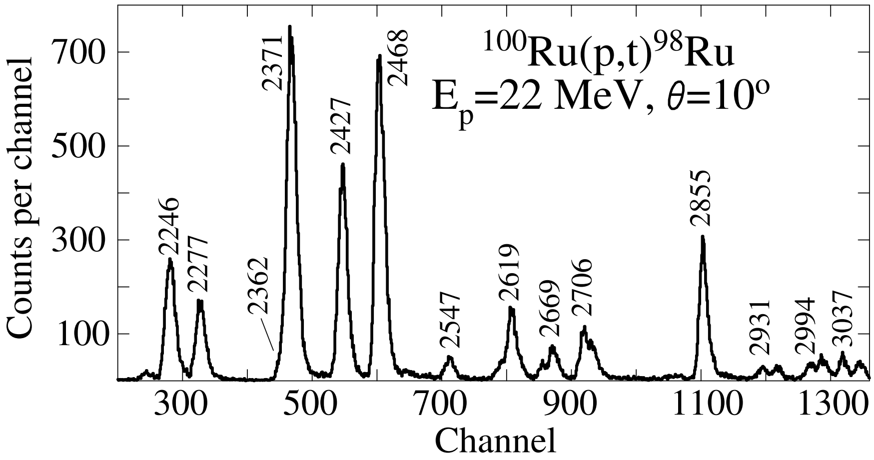

Figure 4. Portion of the triton spectrum observed at $\theta = 10°$ following the ^{100}Ru(p,t) reaction using a beam of 22 MeV protons. The prominent peaks are labelled with the corresponding excitation energies of ^{98}Ru in keV.

assigned as feeding the 2_1^+ state from, in order of their excitation energy, 2246-keV, 2277-keV, 2362-keV, and 2371-keV states. The remaining peaks in the spectrum are resulting from γ-rays feeding higher-lying states. These levels will be discussed in more detail below.

The statistics obtained in the experiment were insufficient to perform γ-γ angular correlations for the levels of interest, however, spin-parity values of states could be obtained from a complementary (p,t) reaction study. In an experiment performed using the Q3D spectrograph of the Maier-Leibnitz Laboratory, the ^{100}Ru$(p,t)^{98}$Ru reaction was performed using 22 MeV proton beams with currents up to 2 μA on a ^{100}Ru target 110 μg/cm^2 thick. Figure 4 displays a

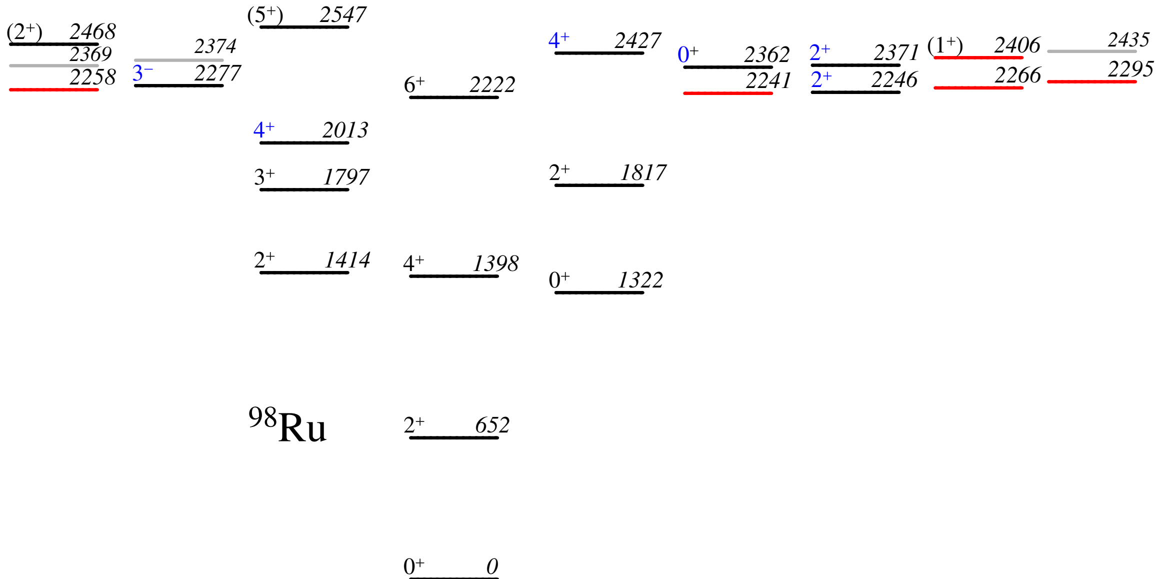

Figure 5. Revised level scheme for ^{98}Ru taking into account observations from the ^{100}Ru(p,t) reaction. The levels highlighted in red were not observed in the (p,t) reaction, and thus are candidates for unnatural parity states. The 2241-, 2258-, and 2295-keV levels, reported in Ref. [16] were not observed in our β-decay study. The 2369-, 2374-, and 2435-keV levels (light gray) are concluded not to exist. Spin assignments in blue are resulting from the present study.

portion of the triton spectrum observed at an angle of 10° corresponding to the ^{98}Ru excitation energy range from 2.2 - 3.1 MeV. Since the two-neutron-transfer reaction strongly favours the transfer of a di-neutron in a relative $S = 0$ state, when performed on a $J^\pi = 0^+$ target, the final states populated have $J^\pi = L^{(-1)^L}$, i.e., natural parity. Unnatural parity states may be populated, but extremely weakly and are usually unobservable in the spectra unless very high statistics are collected. Thus, all the peaks present in Fig. 4 are expected to correspond to natural parity states in the final nucleus, and their cross section angular distributions, examples of which are shown in Ref. [19] for the 2013- and 2427-keV levels that were consistent with an $L = 4$ transfer assignment, give the J^π value of the populated state. The analysis of the angular distributions indicates that the 2246-keV state has a definite 2^+ assignment, the 2277-keV state is a 3^- state, the 2361-keV level is a 0^+ state, the 2371-keV level has spin 2^+, and the 2468-keV level is populated with an angular distribution consistent with spin 2^+. There is no evidence from the (p, t) reaction data for levels at 2241, 2258, 2266, 2295, 2406, and 2435 keV. The results from Ref. [16] indicate two levels in the vicinity of 2370 keV; at 2362.5(3) keV and 2371.3(2) keV in good agreement with our observations, and no evidence for a level at 2435 keV. Furthermore, consistent with Ref. [16], we have no evidence for additional levels at 2369 keV or 2374 keV. The remaining levels listed above thus are candidates for unnatural parity. Interestingly, the 5^+ level at 2547 keV, which fits well into the systematics of the γ-band members, as shown in Ref. [19], was observed in the (p, t) reaction, albeit weakly and with an angular distribution that does not match those of other levels with known J^π values. The appearance of this peak in the spectra, however, indicates that the spin assignment may be incorrect.

Figure 5 gives the results of the present investigations of the levels below 2.5 MeV excitation energy. Further study is required to characterize the states not already assigned to band-like structures, especially the unnatural-parity state candidates.

3. Summary

The level scheme of ^{98}Ru has been studied by the β-decay of ^{98}Rh, as well as the ^{100}Ru(p, t) reaction. Substantial revision of the spin assignments of levels has resulted with a significant impact on the interpretation of the nuclear structure. ^{98}Ru is no longer a candidate for spherical vibrational motion. Additional measurements will be required to further clarify the level scheme, especially above 2 MeV. The present study is the first in a series of new experiments aimed at studying the evolution of structure in the Ru isotopic chain.

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