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Spectroscopy of ^{96,97,98}Ru: Possible Emergence of Collectivity at N ≥ 52

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ABSTRACT

Detailed experimental information on high-spin states (up to ~ 20 ħ) in the N ≥ 52 nuclei ^{96,97,98}Ru has been obtained from gamma-ray spectroscopic studies following ^{65}Cu(^{36}S,pxn) reactions. The level schemes exhibit sequences of presumably negative-parity states linked by E2 transitions with monotonously increasing energies. These sequences coexist with the positive-parity yrast states where the transition energies are rather irregular. The negative-parity structures are suggestive of the emergence of rotational collectivity. The data are compared with TRS calculations for deformed $h_{11/2}$ neutron configurations.

The nuclei just outside the Z = 50 closed shell have been observed to exhibit a range of collective phenomena, such as coexistence of band structures corresponding to different shapes and the presence of deformed intruder states even at Z = 51 [1]. The obvious question is whether a similar interplay of single-particle and collective behavior occurs also near the N = 50 closed shell. The transitional nuclei in the A = 100 mass region (Z < 50, N > 50) have so far not been subject of extensive high-spin studies comparable to those performed in other regions (*e.g.* the A = 80 and the A=130 regions). Outside the N = 50 closed shell, about 8 valence neutrons are needed before deformation starts becoming dominant; for example, in ^{102}Ru and other neutron-rich A > 100 nuclei very strong rotational bands based on $\nu h_{11/2}$ intruder states have been identified [2]. Although the decay scheme of ^{100}Ru looks quite different [3], this nucleus also appears to be weakly deformed and, in particular, a side-band based on the the 9^- state has been observed and interpreted in terms of collective degrees of freedom [3].

We have studied the nuclei ^{96,97,98}Ru (N ≥ 52) up to high spins with the specific purpose of searching for the onset of deformation above N = 50. For these nuclei, softness (along the β and γ axes) and shape coexistence is expected from TRS calculations [4]. The Ru nuclei are particulary suitable for this type of investigation since they are located in the middle of the Z = 38 subshell and the Z = 50 closed shell, and an abrupt change from a spherical to a deformed shape, as in the isotopic chain of Sr nuclei [5, 6], is unlikely. In fact, a rather smooth, transitional behavior as a function of neutron number is expected. Furthermore, in the Z > 40 systems $\pi g_{9/2}$

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configurations become available to form states with large angular momenta and to induce small deformations to the nuclear shape[6].

Previous studies of ^{96,98}Ru by Lederer *et al.* [7] and ^{97}Ru by Chowdhury *et al.* [8] had used (charged particle,xn)-reactions with relative light projectiles ranging from alpha particles to ^{7}Li. In the present work, ^{36}S beams have been employed in order to produce compound systems with significantly higher angular momenta than obtained in previous measurements, enhancing, in the process, the population of higher spin states in the final ^{96,97,98}Ru nuclei.

The three nuclei were studied using ^{65}Cu(^{36}S,pxn)$^{96-98}$Ru reactions with 135 and 142 MeV beams from the Argonne Tandem Linac Accelerator System. At these energies, the final nuclei were populated, for the p4n product, at an angular momentum of about 44 $\hbar$ and an excitation energy of about 33 MeV. A 0.9 mg/cm^2 thick ^{65}Cu target with a gold backing of 15.5 mg/cm^2 thickness was used in order to stop the recoiling nuclei. Gamma rays were detected with the Argonne-Notre Dame BGO gamma-ray facility which is comprised of 12 Compton-suppressed Ge-detectors located at 34°, 90° and 146° with respect to the beam direction, and a 50 element BGO array for multiplicity selection. Approximately 135 million events with a prompt array multiplicity $K \geq 4$ were recorded.

The compound nucleus formed in this reaction (^{101}Rh) evaporates protons, neutrons and alpha particles with comparable probabilities. Gates on high multiplicities ($K \geq 8$ and $K \geq 15$) were selected in the off-line analysis in order to enhance the intensities of high-spin transitions in ^{96}Ru, ^{97}Ru and ^{98}Ru in comparison with the strong transitions between low-spin states of the various other evaporation residues. Representative spectra from the gamma-gamma coincidence analysis are shown in Figure 1 and the level schemes of the three nuclei constructed on the basis of these coincidence data are shown in Figures 2, 3, and 4, respectively. Spin assignments of the new levels are proposed on the basis of the measured DCO ratios following the definition given in reference [9]. The parities, where not previously known, have been tentatively assigned on the basis of comparison with systematics of higher-mass Ru nuclei. Preliminary results of this work have been reported recently [10].

The data agree with the previously-known level schemes of ^{96,97,98}Ru [7,8] at low spins, with two exceptions. In ^{97}Ru, two weak sequences beginning with gamma rays of 947 keV and 1001 keV, respectively, are arranged in a different way than in reference [8]. In ^{98}Ru, the location of the 724-keV transition, proposed on the basis of the relative intensities, is different from that proposed in references [8] and [10]. The transition is also significantly admixed (most likely of the M1/E2 type) and a spin for this level and, consequently, the higher levels could not be deduced

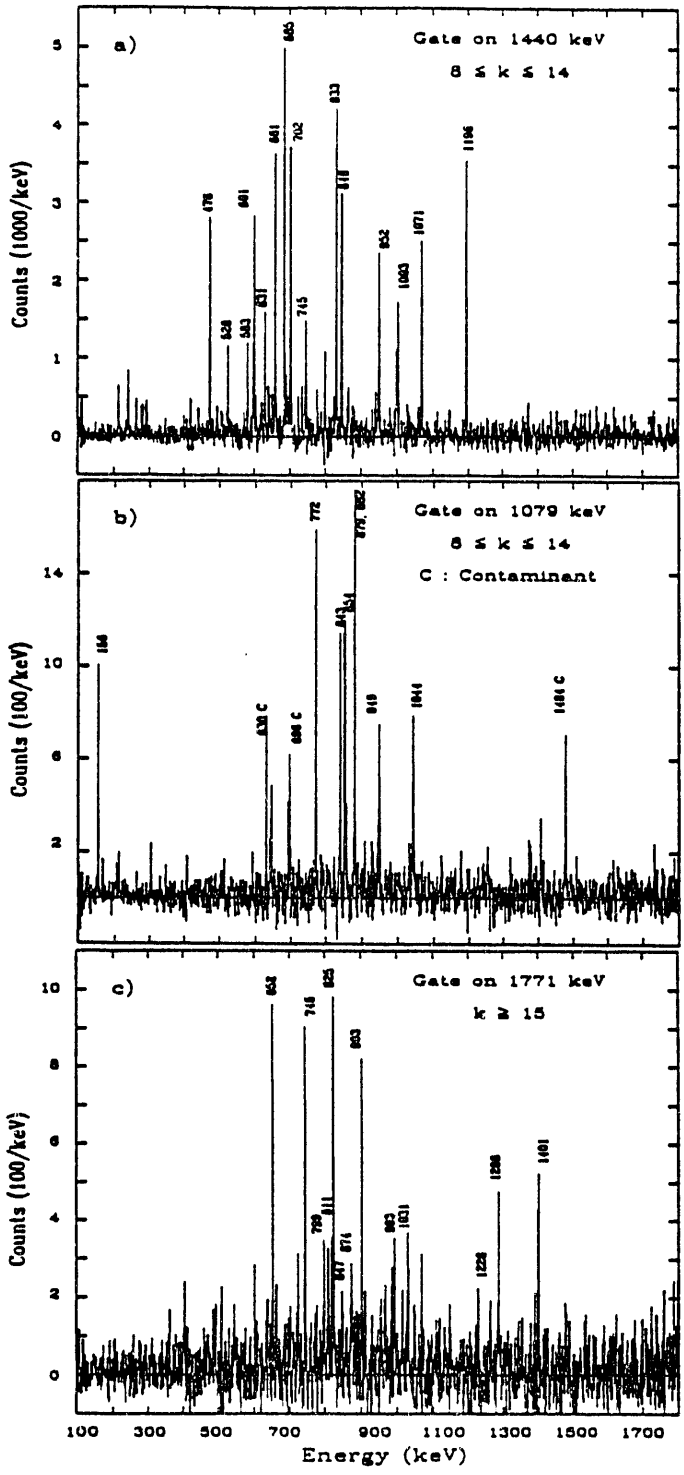

Figure 1. Efficiency corrected γ–γ coincidence spectra of (a) ^{96}Ru (gated on the 1440-keV transition), (b) ^{97}Ru (gated on the 1079-keV transition) and (c) ^{98}Ru (gated on the 1771-keV transition). The multiplicity requirements used in the analysis are indicated. Contaminants in spectrum (b) are from ^{96}Mo and/or ^{99}Rh.

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with any confidence. Many new transitions have been identified in each of these nuclei, allowing for extensions of the level schemes significantly (up to E_x > 10 MeV and I > 20 ħ).

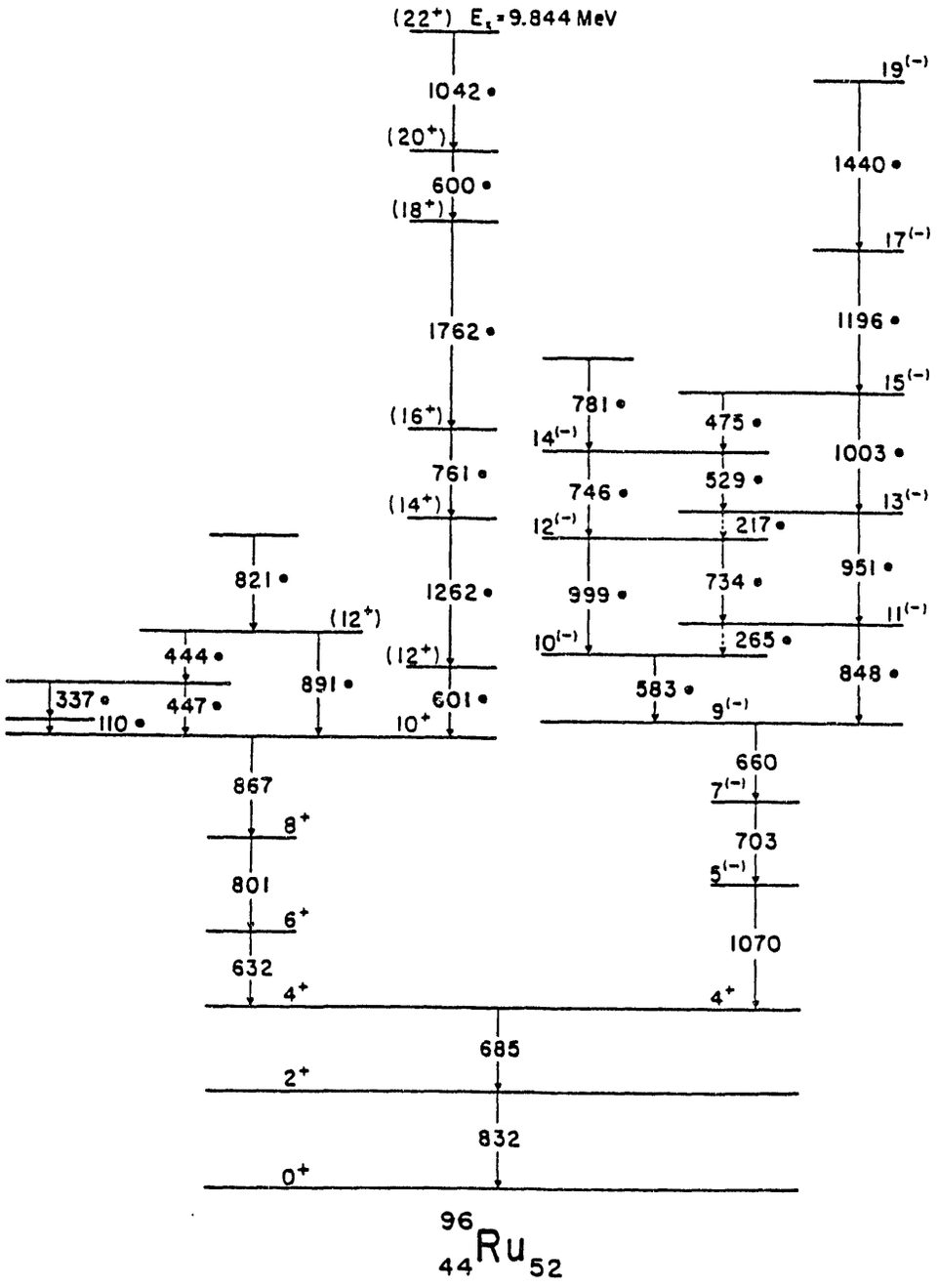

Figure 2. Partial level scheme of ^{96}Ru involving the strongest gamma transitions for K ≥ 8. Transition energies are given in keV. Newly-observed transitions are marked with a dot. The spin and parity assignments, given in parentheses, are tentative.

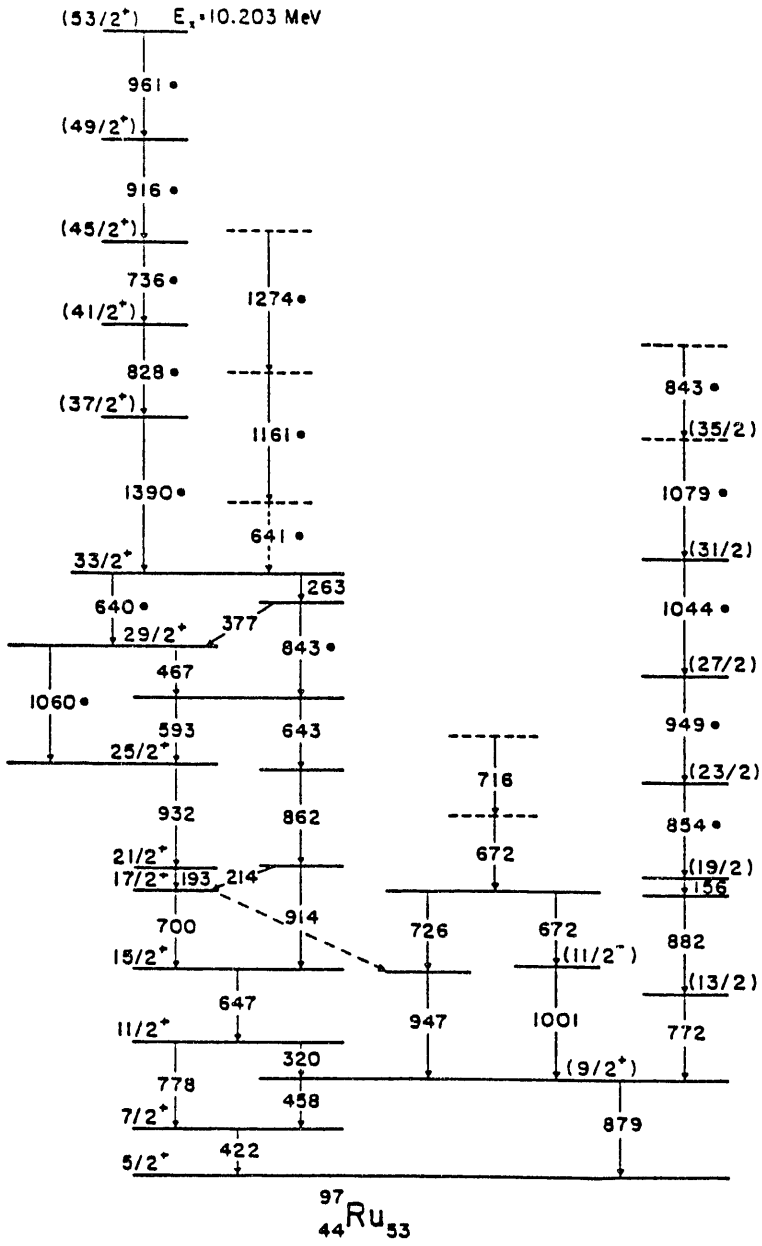

Figure 3. Partial level scheme of ^{97}Ru. Analysis for K ≥ 8. Symbols have the same meanings as in Figure 2.

Two indepent and distinct level structures have been established consistently in all three nuclei. Most of the intensity feeds through the level sequence shown on the left half of each scheme (Figures 2, 3 and 4). These structures, with rather irregular energy-spacings, appear to be continuations of the positive-parity yrast sequences and, in the case of the even nuclei, can be tentatively described as vibrational-like. Additionally, we observe the level structures, shown in the right halves of these schemes that have been placed on top of the known 9(-) state in ^{96}Ru [7] and the analogous I = 9 ħ state in ^{98}Ru, and on top of a I = 19/2 ħ state in ^{97}Ru. The transition energies are remarkably similar for states of the same (comparable) spins in the even-A (odd-A)

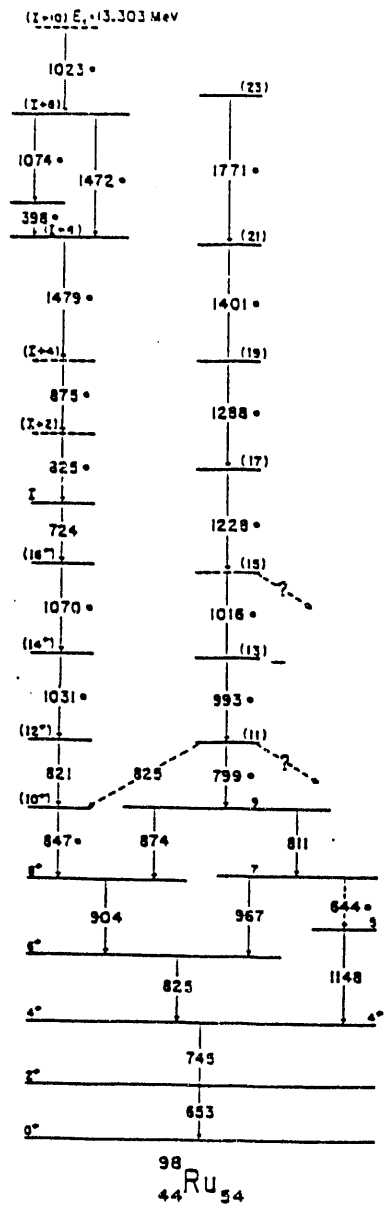

Figure 4. Partial level scheme of ^{98}Ru from the strongest gamma transitions for K ≥ 15. Dashed levels indicate ambiguities in the ordering of transitions. Intensity considerations indicate branching-out from some levels in the sequence on the right-hand side; these, as yet undetermined, transitions are indicated by (?).

isotopes. In the following sections we will concentrate on the latter level sequences, presented together in Figure 5, and on their systematic comparison, including the neighboring isotope ^{100}Ru.

The sequences emphasized here are characterized by: (i) level spacings which, although not following the I(I+1) rule strictly, do show a monotonous increase with the spin; (ii) "intraband" transitions with E2 multipolarity and relatively high intensities when compared with the competing dipole transitions observed in some cases; and, (iii) their consistent placement in the "collective quadrant" of the Mallman plots [11]. Another common feature in the even-A nuclei, including the aforemetioned ^{100}Ru[3], is the decay pattern of these E2 sequences: the $9^{(-)}$ states are linked with

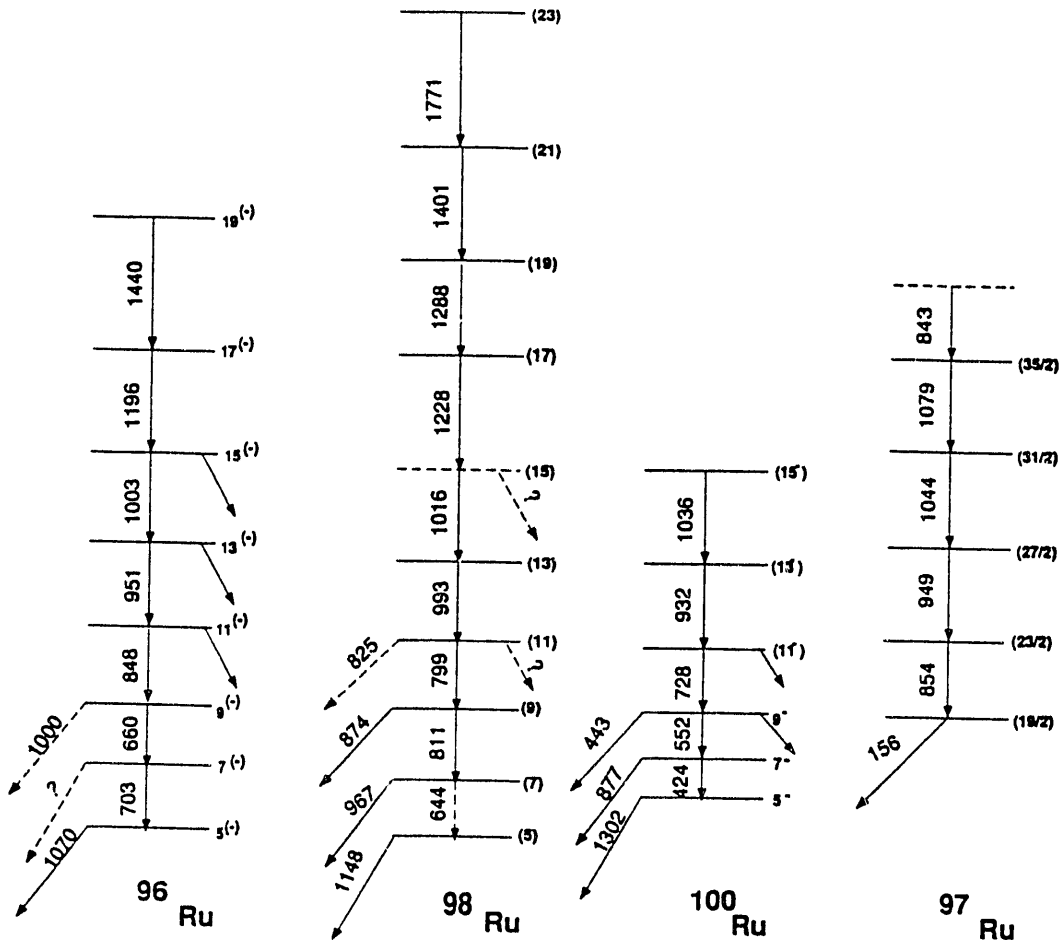

Figure 5. Systematics of negative-parity level structures in ^{96}Ru and ^{98}Ru (this work) and in ^{100}Ru [3]; the corresponding sequence in ^{97}Ru is also shown. All levels are displayed relative to the 9ħ (19/2 ħ) "bandhead" states (see text). The parity assignments for ^{100}Ru were firmly established on the basis of linear polarization measurements.

the positive-parity states in each nucleus and show an increasing preference for decay to the positive-parity states with increasing mass. For example, in ^{98}Ru, the 874-keV transition (to the known 8^+ state) is about 2 times stronger than the 811-keV transition (to the 7^- state). It is reasonable, then, to hypothesize that the $9^{(-)}$ states are indeed the "bandheads" of these level structures. We also note the trend that the excitation energies for states of the same spin decrease with increasing neutron number which would be the expected behavior for the increasing deformation associated with these structures.

These E2 sequences are, thus, quite suggestive of a "rotational-like" behavior. A lineshape analysis (DSAM) for these E2 transitions in ^{96,97,98}Ru shows that their decay proceeds on a time

scale (feeding + lifetime) which is longer than or comparable to the stopping time of the recoils in the gold backing (~ 1.2 ps). This provides a lower limit for the lifetimes which also is consistent with a weak deformation ($\beta_2 \leq 0.09$).

In earlier studies, the experimental data suggestive of collective behavior in the $^{96-100}$Ru nuclei have been compared with macroscopic calculations of quasi-rotational bands (VMI model) [7] and with IBA model predictions [3]. Recent TRS calculations by Wyss *et al.* [4] predict the existence of deformed neutron configurations with negative parity ($\nu h_{11/2}$) in ^{96,97,98}Ru at near-yrast energies. These configurations evidently involve the $\nu h_{11/2}$ orbital and tend to favor a deformed near-prolate shape ($\gamma \sim 0°$), but the expected deformations are small ($\beta_2 < 0.13$), with the local minima in the total routhian surfaces rather shallow. According to these calculations, the addition of a pair of aligned $g_{9/2}$ protons, which are not strong enough to drive the spherical configurations to a stable deformation on their own, does, nonetheless, contribute to the stabilization of an already deformed surface. The best case for a stable deformation among these nuclei appears to be ^{97}Ru where a relatively low-lying (*i.e.* less than 0.3 MeV above the yrast configuration) near-prolate minimum, based on the $[\nu h_{11/2} \otimes (\pi g_{9/2})^2]$ configuration, appears in the total routhian surface. Samples of the TRS calculations for this configuration, which corresponds to EA_pB_p in the standard CSM nomenclature, are shown in Fig. 6. The frequencies associated with this stable

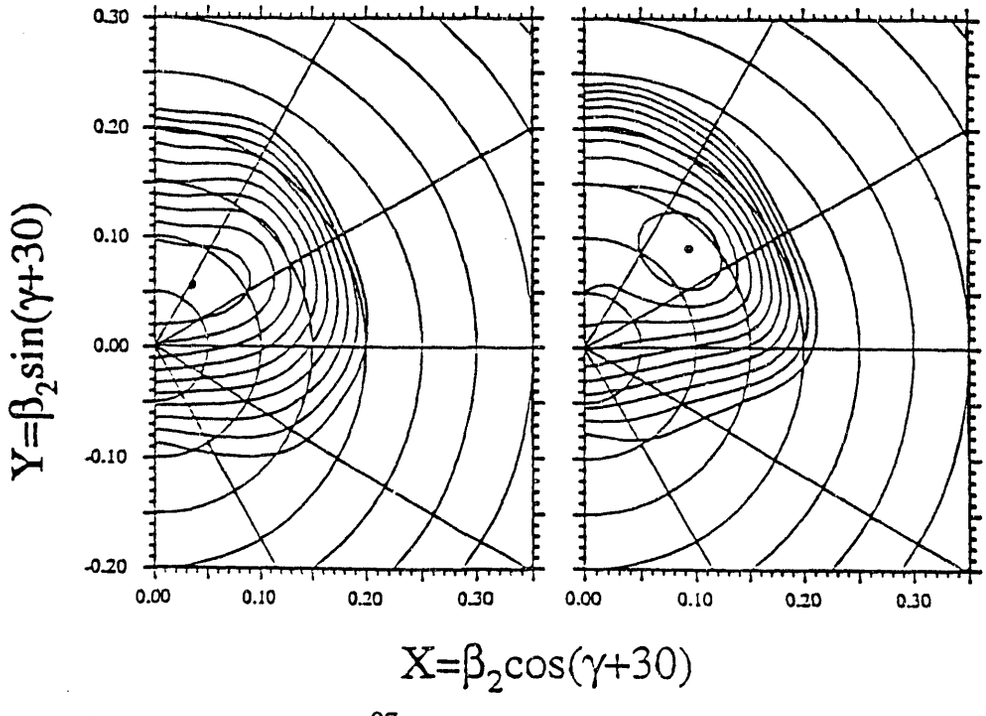

Figure 6. Total routhian surfaces of ^{97}Ru corresponding to $\hbar\omega = 0.375$ MeV (left) and $\hbar\omega = 0.438$ MeV (right) calculated for the $[\nu h_{11/2} \otimes (\pi g_{9/2})^2]$ configuration (EA_pB_p --see text).

shape ($\hbar\omega > 0.38$ MeV) and the predicted spin range ($I_n + I_p \geq 8.3\ \hbar$) are in fair agreement with the measured transition energies and spins in ^{97}Ru. The assumed proton alignment is also consistent with the previously proposed interpretation for the positive-parity branch of this nucleus [8] which identified $\pi g_{9/2}$ as one of the active orbitals in the range of spins under consideration, providing further confidence in the TRS results. For the even-A nuclei also, a similar shape, essentially driven by the $\nu h_{11/2}$ orbital, is likely with the negative-parity states at spins of interest based on the $[\nu h_{11/2} \otimes \nu g_{7/2}]$ or $[\nu h_{11/2} \otimes (\nu g_{7/2}, \nu d_{5/2}) \otimes (\pi g_{9/2})^2]$ configurations. The neutron configurations in the even-A cases appear to be less deformation-driving than the pure $\nu h_{11/2}$ configuration in the odd-A system. The calculations, however, are clearly indicative of a trend towards a near-prolate deformed shape, in contrast with the predicted spherical shape associated with the positive-parity states. Detailed CSM calculations for these nuclei, focussing on the energy spacings in the yrast and near-yrast level structures, and their relative excitation energies, are in progress to further elucidate the nature of collective behaviour in these nuclei.

To summarize, we have observed in ^{96}Ru, ^{97}Ru, and ^{98}Ru, E2 sequences with smooth increases in transition energies with spin, reminiscent of collective rotation. These sequences are associated with negative-parity states and coexist at $I > 8\ \hbar$ with the dominant non-rotational structures of the level schemes. A close similarity with the level scheme of ^{100}Ru has been observed. The data have been compared with TRS calculations which indicate the possibility of deformed configurations involving $\nu h_{11/2}$ orbitals in these nuclei. Emerging collectivity at high spins is suggested. However, lifetime measurements in the 1–1000 ps range (with the RDM technique) are imparative for the final verification of the collective nature of these E2 sequences.

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