Structure of ^{108,110,112}Ru: Identical bands in ^{108,110}Ru

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The levels in ^{108,110,112}Ru have been investigated in the spontaneous fission of ^{252}Cf using γ-γ-γ-, γ-γ-, x-x-, x-γ-, and x-γ-γ-coincidence techniques. The levels up to 16^+ and 9^+ in the yrast bands and γ-vibrational bands have been identified with very little energy staggering in ^{108,110,112}Ru. The ground bands in ^{108,110}Ru have identical γ-ray transition energies up to 8^+. These are the lightest observed even-even nuclei with extended identical ground bands. Calculations in a collective model which includes rotations and vibrations reproduce the level energies and γ band branching ratios above the 3^+ state rather well, while rigid triaxial rotor model calculations reproduce the branching ratios for the 2^+ and 3^+ states.

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I. INTRODUCTION

The ground state bands up to 4^+ in ^{108,110,112}Ru have been known from earlier spontaneous fission (SF) [1] and decay studies [2,3]. The states tentatively assigned as 2^+ and 3^+ from the radioactive decays [2,3] of fission fragments may be members of γ-vibrational bands. The lifetimes of the 2_1^+ states and composite 4^+ states in ^{108,110}Ru have also been measured in spontaneous fission and significant deformations of $\beta_2=0.28$, for ^{108}Ru and $\beta_2=0.30$ for ^{110}Ru have been extracted. A previous theoretical analysis has indicated that these Ru nuclei are triaxial with $\gamma\approx 20-25°$ [3]. Stachel *et al.* [7] described the $^{98-110}$Ru nuclei in terms of a transition between SU(5) to $O(6)$ symmetry in the IBA model.

We have employed the spontaneous fission of ^{252}Cf to investigate the levels in ^{108,110,112}Ru. The yrast ground state bands in these nuclei were reported in our earlier survey work [8]. More recently, from SF of ^{248}Cm, Shannon *et al.* [9] reported the level schemes of these three nuclei, which are similar to our work. They presented the evidence for rigid triaxial shapes extracted from the $\Delta I=1$ band built on the 2_γ^+ states. In this paper we wish to present additional high spin data and a different emphasis on the important physics that these nuclei provide.

In order to test how well the levels in ^{108,110,112}Ru can be understood in a simple standard collective model, we have performed an analysis in terms of the collective rotation-vibration model (RVM). The Hamiltonian consists of three parts: a rotational part, a β- and γ-vibrational part, and a third term which contains the rotation-vibration interaction. As will be seen, it is surprising how well this simple collective model reproduces the experimentally observed levels in both bands and the $B(E2)$ branching ratios in the γ band above 3^+ in these nuclei.

II. EXPERIMENTAL PROCEDURES

A ^{252}Cf source with a strength of about 6×10^4 fissions/s and covered with a 250-μm Be foil was used. The source was placed at the center of the 20 Compton-suppressed Ge-detector Compact Ball at the Holifield Heavy Ion Research Facility at Oak Ridge National Laboratory. Approximately 2×10^9 γ-γ coincidences were collected. Both double- and triple-coincidence events were analyzed. A second experiment was carried out with a source of similar strength using the early implementation of Gammasphere at Lawrence Berkeley Laboratory. In this experiment, 36 Compton-suppressed Ge detectors, one low energy photon spectrometer (x-ray detector), and four neutron scintillation detectors were employed. At the Idaho National Engineering Laboratory a third experiment was performed where x-x and x-γ coincidences were measured with two x-ray detectors and two Ge detectors. The typical resolution for the x-ray detector was 280 eV at 14 keV. The x-ray detectors recorded

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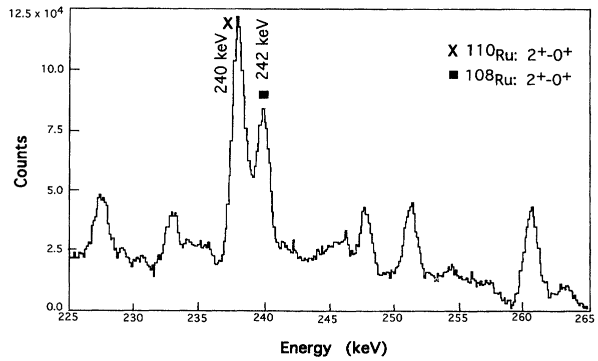

FIG. 1. The $2^+ \rightarrow 0^+$ transition in the high resolution x-ray detector in the x-γ coincidence setup.

events from 10 keV up to several hundred keV so that x-rays from Sr to Eu along with transitions above 300 keV were observed with intensities sufficient to set gates on the x rays and observe the low energy γ rays. The triple-coincidence technique is particularly powerful in eliminating or reducing background. This technique becomes very useful especially if γ-ray energies from different nuclei fall within the energy gate set on a single γ ray in a γ-γ-coincidence experiment. The x-x- and x-γ-coincidence spectra were particularly helpful in unraveling the transitions in the identical bands in ^{108,110}Ru.

III. RESULTS AND CONCLUSIONS

The ground bands have been extended from 10^+ [8,9] up to 16^+ in ^{108,110,112}Ru. The ground band transitions in ^{108,110}Ru are found to be remarkably identical up to 8^+ and essentially so up to 10^+ but are not identical to those in ^{112}Ru which has an even larger moment of inertia. These are the lightest even-even nuclei with extended identical ground bands. The γ-vibrational bands observed to 9^+ in ^{108,110,112}Ru are the first γ bands extended above 3^+ in neutron-rich nuclei in this region. While the 2_γ^+ bandhead energies are almost 100 keV apart in ^{108,110}Ru, many of the transitions in their γ bands have nearly similar energies (0.7–3% differences). The levels from 2^+ to 9^+ in the γ bands of all three nuclei exhibit very little signature splitting in contrast to the strong splitting expected for triaxial nuclei. Because of the additional parameters associated with signature splitting and bandhead energies, the observation of similar energy transitions in γ bands in neighboring even-even nuclei raises additional questions regarding the explanation of identical bands.

The energies of the ground-band transitions in ^{108}Ru and ^{110}Ru are so close all the way up to 8^+ that only the $2^+ \rightarrow 0^+$ and $8^+ \rightarrow 6^+$ transitions can be separated to provide independent gates for investigating these bands. The $2^+ \rightarrow 0^+$ transitions observed in a high resolution x-ray detector in the x-γ-coincidence setup are shown in Fig. 1. A spectrum obtained by summing all the double gated spectra that can result when gates are set on the first four members of the yrast cascade in ^{110}Ru is shown in Fig. 2(a). Figure 2(b) shows a double gate set on the $14^+ \rightarrow 12^+$ and $10^+ \rightarrow 8^+$ transitions in ^{110}Ru. The level schemes based on γ-γ, γ-γ-γ, and x-γ coincidences are shown in Figs. 3(a), 3(b), and 3(c). In the present work we have extended the ground bands in the three nuclei up to 16^+. An unusual feature of the ^{110}Ru level scheme is the sequence of three new transitions feeding the 6^+, 8^+, and 10^+ levels but with no observable transitions connecting them.

The transitions up to the 8^+ levels and essentially to the 10^+ levels in the ground bands of ^{108,110}Ru are among the most identical in energies and in moments of inertia, J_1 and J_2. The ^{108,110}Ru nuclei extend our knowledge of identical bands into new regions: those neighboring even-even nuclei have the lowest mass number of any such neutron-rich

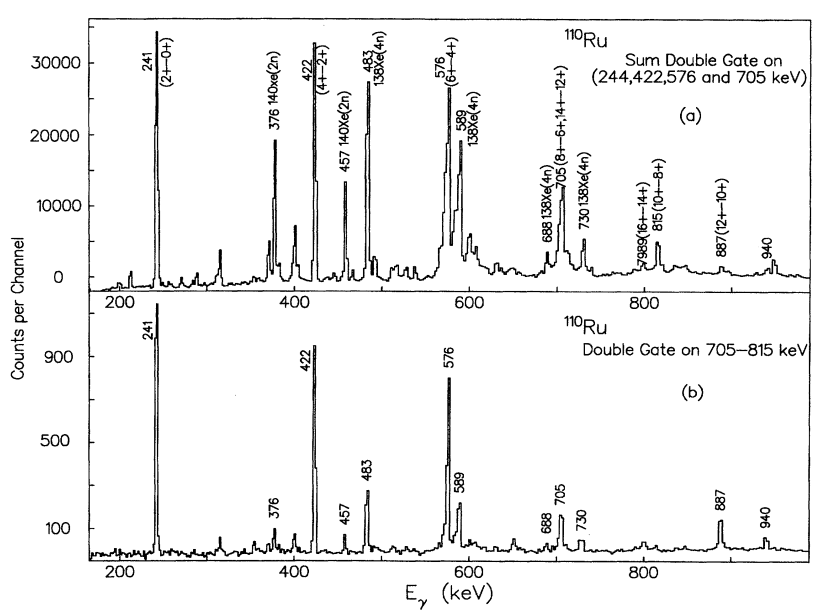

FIG. 2. (a) A sum over all the double gates for the transitions out of the yrast cascade from 2^+ to 14^+ in ^{110}Ru. (b) A double gate on the 705–815-keV transition in ^{110}Ru.

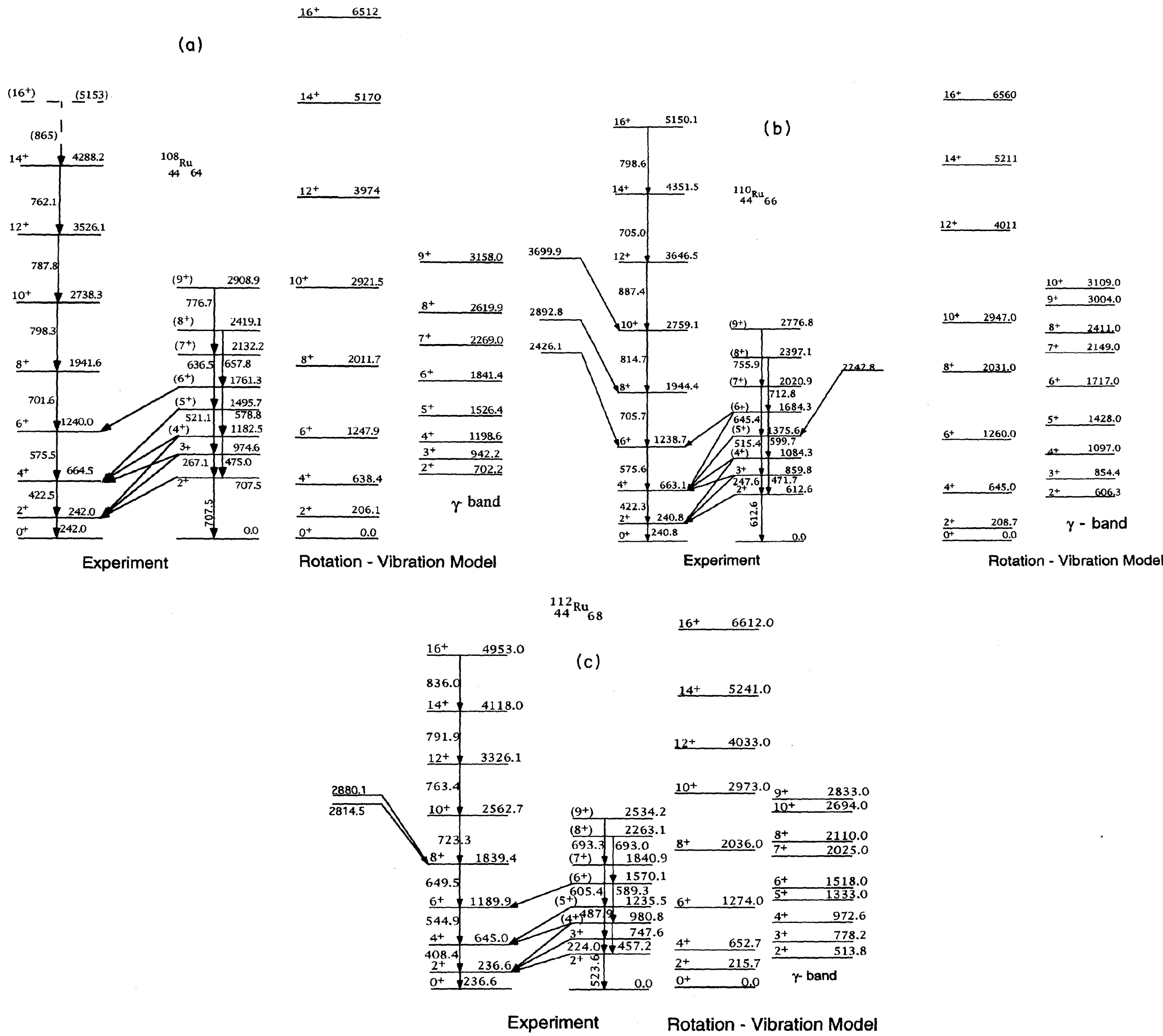

FIG. 3. (a) Levels in ^{108}Ru. (b) Levels in ^{110}Ru. (c) Levels in ^{112}Ru.

neighbors having extended identical bands. The transition energies in ^{112}Ru are all considerably smaller than in ^{108,110}Ru, and the moments of inertia extracted from the energies are larger and increase more rapidly with spin [see Table I and Fig. 4]. The deformation of ^{112}Ru is therefore presumably larger than that of ^{108,110}Ru. The neutron number for $^{110}_{44}$Ru is at midshell between 50 and 82 with ^{108,112}Ru ($N=64,68$) to either side. The deformations, $\beta_2=0.28(2)$ for ^{108,110}Ru obtained from lifetime measurements, are significant [4–6]. If saturation of collectivity is the explanation for the identical ground bands in ^{108}Ru and ^{110}Ru as found in ^{183,185}Hg by Bindra *et al.*, [10] it is interesting to find this effect still operative in this lighter mass neutron-rich region. Also, if saturation of collectivity is the reason why the $N=64,66$ nuclei have identical energies, it is likewise interesting that ^{112}Ru with a larger moment of inertia is not identical. If these nuclei are rigid triaxial rotors as recently reported [9], this would make the identical nature of these bands even more unusual. Such identical energies are not seen in $N=64,66$ ^{110,112}Pd [3,11]. However, the ^{112,114}Pd have considerably smaller deformation, $\beta_2=0.21(2)$ and 0.12(2), respectively.

The clearly identified γ bands up to 9^+ in ^{108,110,112}Ru here, and also in [9], are the first extended γ-vibrational bands seen in neutron-rich nuclei. They have low energy 2^+_γ band heads. The 612.6- and 523.4-keV bandheads in ^{110,112}Ru are the next lowest in energy of all known γ bands, second only to the 558.0- and 489.1-keV bandheads in ^{190,192}Os [12,13]. What is more surprising is that apart from the lowest transitions between the 3^+ and 2^+ levels, the

TABLE I. The kinetic and dynamic moments of inertia J_1 and J_2 for the ground bands of ^{108,110,112}Ru. Notice the identical values for J_1 and J_2 for ^{108,110,112}Ru because of their identical energies.

	^{108}Ru			^{110}Ru			^{112}Ru	
$\hbar\omega$	J_1	J_2	$\hbar\omega$	J_1	J_2	$\hbar\omega$	J_1	J_2
0.121	12.40		0.120	12.46		0.118	12.67	
0.211	16.57	22.16	0.211	16.58	22.04	0.204	17.15	23.34
0.288	19.14	26.30	0.288	19.11	26.09	0.272	20.19	29.26
0.351	21.38	31.47	0.353	21.26	30.75	0.325	23.10	38.24
0.399	23.82	41.71	0.407	23.32	36.70	0.362	26.27	54.20
0.394	29.19	−408.16	0.444	25.92	55.17	0.382	30.13	99.75
0.381	35.43	−155.64	0.352	38.29	−21.93	0.396	34.10	140.35
0.432	35.85	38.95	0.399	38.82	42.73	0.418	37.13	92.81

transitions out of the 4^+ to 9^+ levels in ^{108,110}Ru have energies within 0.7 to 3.4% of each other (see Table II; the $3^+ \rightarrow 2^+$ energies differ by nearly 10%). The energies and relative intensities of γ transitions in ^{108,110,112}Ru are given in Table III. One can see from Table III that the two γ-vibrational bands in neighboring nuclei have nearly similar energies. While the ratio $R = E(4^+)\text{-}E(2^+)/E(3^+)\text{-}E(2^+)$ is somewhat different (1.78 in ^{108}Ru and 1.90 in ^{110}Ru) because of the different $E(3^+)\text{-}E(2^+)$ energies, there is very little odd-even spin staggering through the 9^+ levels. Thus, the nearly identical dynamical moments of inertia are related neither to the bandhead energies nor to their signature splitting parameters. As found in the ground bands, all transition energies of the γ band in ^{112}Ru are smaller than those in ^{108,110}Ru.

Without information on the extended γ bands, the ^{108,110}Ru nuclei have been treated using an interacting boson model [7]. In a rigid asymmetric rotor model the 2_γ^+ energy drops below the 4_1^+ ground level for $\gamma \simeq 22°$. Since this occurs for ^{110,112}Ru and the fact that $E_{2_1^+} + E_{2_2^+} \approx E_{3_1^+}$ are consistent with the earlier reported γ values [3]. Recently, the branching ratios for the extended side bands have provided additional support for a rigid triaxial rotor interpretation of $^{108-112}$Ru with $\gamma = 22.6°$, 24.0°, and 25.9°, respectively [9]. However, the new levels above 3^+ do not show the strong signature splitting expected for a rigid γ where the $(2^+,3^+)$, $(4^+,5^+)$, $(6^+,7^+)$ pairs should be close in energy for such a rigid triaxial rotor (RTR) interpretation. Likewise the γ-soft model, which is closely related to the IBA-1 $O(6)$ dynamical symmetry [14], has a strong odd-even spin staggering with $(3^+,4^+)$, $(5^+,6^+)$ pairs of levels close in energy, which is also not seen. In ^{190,192}Os, which have similar 2_γ^+ bandheads, little or no odd-even spin [12,13] staggerings are also observed.

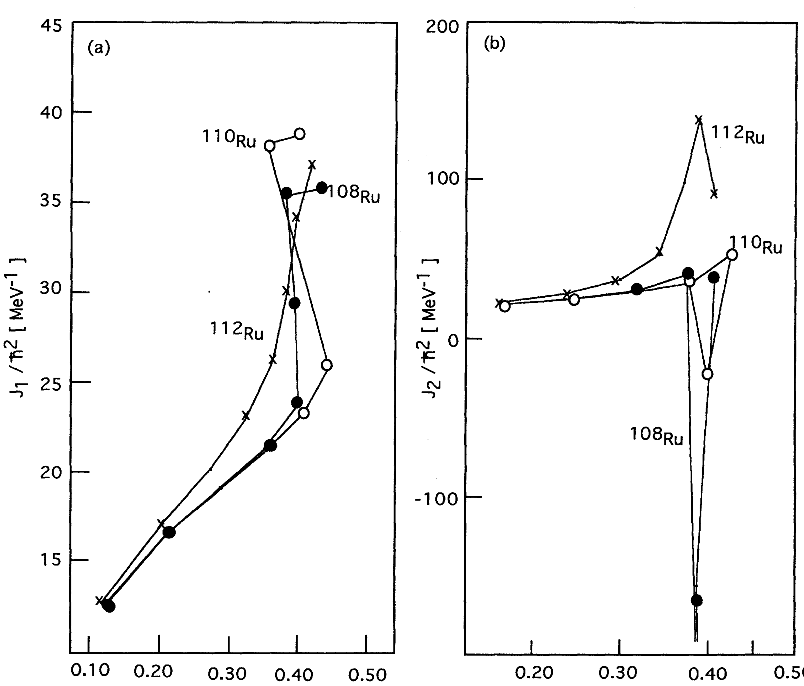

FIG. 4. Moments of inertia J_1 added J_2 for ^{108,110,112}Ru.

TABLE II. γ-ray energy differences in the γ bands between Ru isotopes.

Ru isotopes Transitions	^{108}Ru E_γ (keV)	Difference (%) ^{108}Ru-^{110}Ru	^{110}Ru E_γ (keV)	Difference (%) ^{110}Ru-^{112}Ru	^{112}Ru E_γ (keV)
$4^+_\gamma \to 2^+_\gamma$	475.0	0.7	471.7	3.1	457.2
$5^+_\gamma \to 3^+_\gamma$	521.1	1.1	515.4	5.3	487.9
$6^+_\gamma \to 4^+_\gamma$	578.8	3.4	599.7	1.7	589.3
$7^+_\gamma \to 5^+_\gamma$	636.5	1.4	645.4	6.2	605.4
$8^+_\gamma \to 6^+_\gamma$	657.8	7.7	712.8	2.8	693.0
$9^+_\gamma \to 7^+_\gamma$	776.7	2.8	755.9	8.3	693.3

To see how well the energies of the two bands can be reproduced in a standard collective model, we carried out an analysis in the rotation-vibration model [15,16]. The Hamiltonian consists of three parts: a rotational part $H_{\rm rot}$, a β- and γ-vibrational part $H_{\rm vib}$, and a third term which contains the rotation-vibration interaction H'. The last term arises from the dependence of the moments of inertia of the nucleus on the vibrational amplitudes.

We have diagonalized the interaction term H', numerically in terms of the eigenstates $|K,n_\gamma,n_\beta\rangle$ of the basis Hamiltonian $H_0 = H_{\rm rot} + H_{\rm vib}$. Here, K denotes the projection of the total angular momentum onto the intrinsic nuclear symmetry axis, and n_γ and n_β are the number of γ- and β-vibrational phonons present. In order to obtain convergence of the energy levels up to spin 12 to four significant digits, we found that 140 basis states are required in the diagonalization. Specifically, our basis contains all eigenstates with quantum numbers: $K=0,2,4,\ldots,12$; $n_\gamma=0,1,2,3$, and $n_\beta=0,1,2,3,4$. The three energy parameters used in the rotation-vibration model are $E_{\rm rot}=0.15$, 0.15, 0.15 MeV, $E_\gamma=0.62$, 0.52, 0.42 MeV, and $E_\beta=1.2$, 1.4, 1.4 MeV for ^{108,110,112}Ru, respectively. The results are shown in Figs. 3(a), 3(b), and 3(c). It is surprising how well this simple collective model reproduces the experimentally observed level schemes in contrast to a RTR model. The generalized collective model (see Ref. [16]) would almost certainly yield an even better agreement with the data, but only at the expense of introducing additional model parameters. This does not seem worthwhile, given the relatively small number of experimentally observed levels and the absence of other data such as $B(E2)$ values.

TABLE III. Energies and relative intensities of γ-transitions in ^{108,110,112}Ru. The uncertainties in the transition intensities range from 5% for strong transitions to 50% for very weak transitions.

^{108}Ru		^{110}Ru		^{112}Ru	
E_γ (keV)	I_γ (%)	K_γ (keV)	I_γ (%)	E_γ (keV)	I_γ (%)
242.0	100	240.8	100	236.6	100
422.5	74	422.3	74	408.4	77
575.5	46	575.6	44	544.9	53
701.6	12	705.7	16	649.5	17
798.3	4	814.7	6	723.3	10
787.8	2	887.4	2	763.4	6
762.1	1	705.0	1	791.9	4
865	0.3	798.6	0.7	836.0	2
707.5	8	612.6	12	523.6	12
267.1	2	247.6	6	224.0	7
521.1	12	515.4	23	487.9	20
636.5	7	645.4	8	605.4	10
776.7	2	755.9	2	693.3	2
475.0	9	471.7	12	457.2	13
578.8	6	599.7	10	589.3	7
657.8	2	712.8	4	693.0	2
521.3	1	867.2	9	380.2	1
831.2	6	445.6	0.8	590.5	1
518.0	5	1021.2	2	335.8	2
310.1	1	712.5	4	744.2	1
940.5	2	421.2	4	511.0	26
732.6	14	196.7	0.5	287.0	15
465.5	10	843.5	3	1040.7	5
		619.0	25	975.1	4
		371.6	14		
		1187.4	7		
		948.4	4		
		940.8	2		

Shannon *et al.* [9] compared the branching ratios with those predicted by a rigid triaxial rotor (RTR) model. Under the assumption that all transitions are pure $E2$, reasonable agreement was found between the experimental branching ratios and RTR calculated values for the 2^+_γ, 3^+_γ levels as seen in Table IV. However, for the 4^+_γ and 5^+_γ levels disagreements by a factor of 2–100 are observed compared to RTR values. Shannon *et al.* [9] suggested that a small $M1$ admixture in the $5^+_\gamma \to 4^+_\gamma$ transition could bring agreement, but such an approach seems insufficient to alter such a large disagreement. They concluded that the branching ratios are the most convincing evidence for rigid triaxial shapes for ^{108,110,112}Ru. They deduced γ values of 22.5°, 24.2°, 26.4° for ^{108,110,112}Ru, respectively, from the excitation energies of $E(2^+_\gamma)$ and (3^+_γ). These values are consistent with the values deduced from the γ-ray branching ratios of 2^+_γ and 3^+_γ levels for ^{108}Ru and ^{110}Ru and in reasonable agreement with ^{112}Ru. They suggested that the absence of energy staggerings could be accounted for by modifying the RTR model to include a variable moment of inertia [18] or shape vibrations [19].

As an alternate test, we used the collective rotation vibration model (RVM) [15,16] to calculate the branching ratios for $^{108-112}$Ru. Under the assumption that all are $E2$ transitions, the experimental and theoretical results are compared in Table IV. Now the reverse situation occurs: there is good agreement for branching ratios from the 4^+_γ, 5^+_γ, and 6^+_γ levels but the agreement for the ratios from the 2^+_γ and 3^+_γ levels is not as good. RTR assignments rest on the low 2^+_γ

TABLE IV. $B(E_2)$ branching ratios. The theoretical results were calculated in a generalized collective model [15,16] and in a rigid triaxial rotor model [17].

$B(E_2)$ ratios	$\frac{2^+_\gamma\to 2^+_{g.s.}}{2^+_\gamma\to 0^+_{g.s.}}$	$\frac{3^+_\gamma\to 2^+_{g.s.}}{3^+_\gamma\to 4^+_{g.s.}}$	$\frac{3^+_\gamma\to 2^+_{g.s.}}{3^+_\gamma\to 2^+_\gamma}$	$\frac{4^+_\gamma\to 2^+_\gamma}{4^+_\gamma\to 4^+_{g.s.}}$	$\frac{4^+_\gamma\to 2^+_\gamma}{4^+_\gamma\to 2^+_{g.s.}}$	$\frac{5^+_\gamma\to 3^+_\gamma}{5^+_\gamma\to 4^+_{g.s.}}$	$\frac{6^+_\gamma\to 4^+_{g.s.}}{6^+_\gamma\to 6^+_{g.s.}}$
^{108}Ru	10.2(15)	0.19(3)	0.045(5)	2.7(3)	137(36)	21(4)	3.6(20)
^{110}Ru	14.2(13)	0.16(2)	0.043(4)	1.7(2)	110(19)	29(5)	2.8(3)
^{112}Ru	25.3(21)		0.053(4)	1.4(1)	149(18)	35(20)	1.6(1)
^{108}Ru [a]	10.2	0.22	0.052	2.0	105	22	
^{110}Ru [a]	14.1	0.19	0.041	1.1	116	28	
^{112}Ru [a]	24.7		0.042	1.0	159	32	
^{108}Ru [b]	9.3	0.18	0.065	1.3	48	188	
^{110}Ru [b]	16	0.11	0.050	1.4	24	442	
^{112}Ru [b]	42	0.05	0.029	1.6	20	4210	
^{108}Ru [c]	3.9	0.68	0.090	2.4	125	18	4.6
^{110}Ru [c]	4.8	0.52	0.090	2.6	* [d]	24	4.8
^{112}Ru [c]	6.7	0.40	0.088	2.4	* [d]	36	4.1

[a]Reference [9].
[b]Theoretical calculations: Rigid triaxial rotor.
[c]Theoretical calculations: Collective model with rotation, vibration interaction [20].
[d]Suspect related to a cancellation effect.

energies and the branching ratios from the 3^+_γ levels. However, the 2^+_γ branching ratios do not provide a unique test to claim that a nucleus is a rigid triaxial rotor. A possible interpretation of these results is that the 2^+_γ and 3^+_γ states have a triaxial shape or are soft to γ deformation and that the nuclei take on a more axially symmetric shape by the 4^+_γ state. To say the least, the new extended bands built on the 2^+_γ levels in these nuclei present an interesting challenge for nuclear models.

In summary, the levels in the ground bands were observed up to 16^+, spins being assigned tentatively from systematics in ^{108,110,112}Ru, and the γ-vibrational band was observed to 9^+ in ^{108,110}Ru. The ground band transitions and moments of inertia are remarkably identical in ^{108,110}Ru but not in the more deformed ^{112}Ru. The γ band transition energies in ^{108,110}Ru are also very nearly identical. While somewhat less identical than the ground bands, these are the first nearly identical γ-vibrational bands reported. An analysis of the energies of the ground and γ bands in a rotation-vibration model yielded rather good agreement between the predicted and observed energy values and relative $B(E2)$ values above 3^+_γ. This result is in contrast to the poor agreement yielded by a rigid triaxial rotor model which was able to provide a good fit for the relative $B(E2)$'s from the decay of the 2^+_γ and 3^+_γ levels. To explain both the level energies and branching ratios requires additions to either model or a change from RTR to an axially symmetric shape below the 4^+_γ state.

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