Observation of rotational bands in the neutron-rich ^{107}Ru nucleus

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Levels in the neutron-rich, odd-mass ^{107}Ru nucleus have been reinvestigated with Gammasphere by measuring high-fold, prompt coincidence events following spontaneous fission of ^{252}Cf. The ground state band has been extended up to $\frac{27}{2}\hbar$. The structure associated with the $h_{11/2}$ excitation has been confirmed and extended to higher spin. The $h_{11/2}$ band head has been established to lie at 301.8 keV. These results clear up differences between our earlier work and results from another experiment published recently. A new collective band based on a $9/2^-$ level has been identified for the first time. Some distinct features of the level scheme are discussed.

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The neutron-rich Ru isotopes lie between $A=100$ well-deformed nuclei with $Z=38,40$, $N=58,60$ and spherical Sn nuclei with a $Z=50$ closed shell. Their level structures are expected to exhibit moderate collectivity and to be associated with a triaxial shape, especially in isotopes with neutron numbers close to $N=64$. Study of the level structure of the odd-A Ru nuclei in this region can provide important information on the nuclear shape, on the single-particle driving effects, and on the location and properties of the $h_{11/2}$, unique-parity intruder configuration. Generally speaking, it is difficult to study the high spin states of these neutron-rich nuclei as they cannot be probed by the usual heavy-ion induced fusion-evaporation reactions. An effective method to circumvent this problem is to measure the prompt γ rays from spontaneous fission of transuranium nuclei such as ^{252}Cf or ^{248}Cm [1].

Some of the low-lying states in ^{107}Ru have been established from the β decay of ^{107}Tc [2]. Using these β-decay results, new γ transitions in ^{107}Ru were subsequently identified and placed into collective band structures by measuring prompt γ rays following fission with the early implementation configuration of the Gammasphere array. These results were published a few years ago [3]. In that paper, two collective bands built on the ^{107}Ru ground state and on the $11/2^-$ level were reported for the first time. More recently, the level structures of odd $A\sim100$ Ru, Pd, and Cd isotopes were investigated following fission of compound nuclei formed in heavy-ion-induced reactions. The results included a neutron $h_{11/2}$ band in ^{107}Ru [4], which differed from the corresponding band structure proposed in Ref. [3]. In the recent report [4] the $h_{11/2}$ band was not reported to feed any of the low-lying known levels obtained in β decay [2] as was found in our previous [3] and present work. In order to clear up this inconsistency, we have carefully reinvestigated the level scheme of ^{107}Ru, using more recent, high statistics spontaneous fission data. The present results indicate that the $h_{11/2}$ structure proposed in Ref. [4] (see Fig. 6 in the latter work) is not correct. Rather, our previous results [3] for the transitions in this band are confirmed. Here, the ground state band and the $h_{11/2}$ sequence have been extended, and the $h_{11/2}$ band head is now established to be located at an excitation energy of 301.8 keV. Another collective band built on a 251.2 keV state with crossing transitions to the $h_{11/2}$ band has been observed for the first time. In addition, the two new bands with intertwined transitions were found to feed the ground state previously and are confirmed and extended.

The measurement was carried out at the Lawrence Berkeley National Laboratory using a ^{252}Cf source with a strength of about 60 μCi. This source was sandwiched between two Fe foils of 10 mg/cm^2 thickness. It was placed at the center of the Gammasphere array which, for this experiment, consisted of 102 Compton suppressed Ge detectors. A total of 5.7×10^{11} triple- and higher-order coincidence events were collected. Thus, these data have higher statistics than the earlier measurement of Ref. [3] by a factor of ~15. The coincidence data were analyzed with the Radware software package [5].

The level scheme of ^{107}Ru obtained in this work is presented in Fig. 1. The relative γ transition intensities are given in parentheses. In the figure four collective bands with $\Delta I=2$ stretched $E2$ transitions are labeled as (1), (2), (3), and (4). Bands (1) and (2) had been reported in our earlier work [3]. They are confirmed and extended here, with two

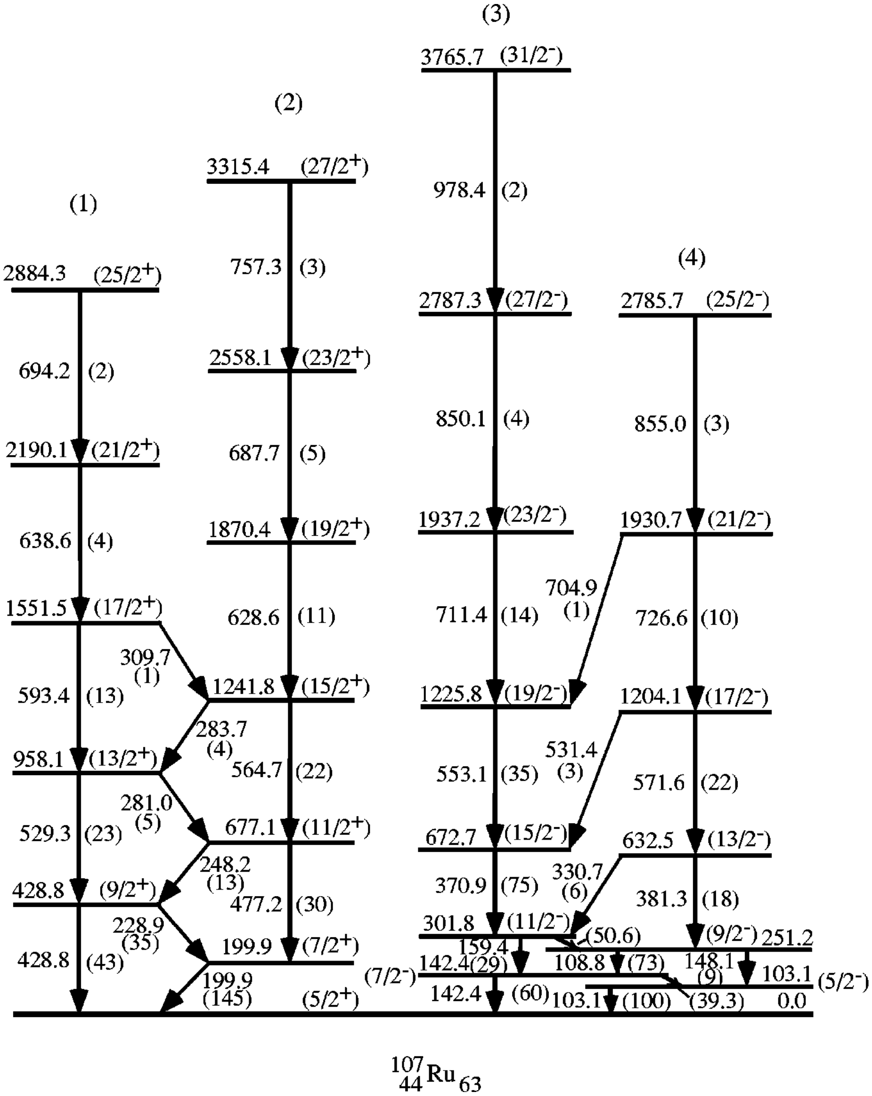

FIG. 1. Level scheme of ^{107}Ru.

new levels at 2558.1 and 3315.4 keV added at the top of band (2) because of the observation of the new 687.7 and 757.3 keV transitions. A new 309.7 keV γ ray has also been placed as a link between bands (1) and (2). For band (3), the sequence 711→553→371 keV published in Ref. [3] was also confirmed. Two new transitions, with respective energies of 850.1 and 978.4 keV, were added at the top of this band as well. At low spin, below the band head level of 301.8 keV, a 159.4 keV transition has been placed. The latter was not reported in the earlier work [3]. Although the 50.6 keV, $11/2^- \rightarrow 9/2^-$ transition is too low in energy to be observed as it is below the detector's thresholds, its existence is inferred from the available coincidence relationships. The newly established 301.8 keV state is assigned as the head of band (3) rather than a 250.6 keV level reported earlier [3]. Band (4) is new to this work. It is built on a 251.2 keV level and is characterized by a 855.0→726.6→571.6 →381.3 keV cascade along with linking transitions to band (3) at 330.7, 531.4, and 704.9 keV.

It is worth pointing that the ^{107}Ru levels at 199.9 and 428.8 keV together with the 199.9, 228.9, and 428.8 keV transitions in bands (1) and (2), and the states at 103.1, 142.4, and 251.2 keV as well as the 39.3, 103.1, 108.8, 142.4, and 148.1 keV γ rays below bands (3) and (4) were identified in the earlier β-decay experiment [2]. This β-decay work was apparently not considered in Ref. [4]. The other levels and transitions presented in Fig. 1 are confirmed to feed these low-lying levels by coincidence relationships. Figures 2 and 3 present examples of the coincidence spectra from the new data. In the spontaneous fission of ^{252}Cf, the partners of the Ru isotopes are Xe nuclei. In Fig. 2(a), a spectrum obtained by double coincidence gates on the known 108.8 and new 381.3 keV transitions in band (4) is presented. In addition to the transitions belonging to ^{107}Ru, the corresponding partner transitions in the Xe isotopes can be clearly seen [287.1, and 403.5 keV in ^{142}Xe $(3n)$, 370.1 keV in ^{141}Xe $(4n)$, and 376.7 and 457.4 keV in ^{140}Xe $(5n)$]. The Xe partner transitions have the appropriate relative intensities of 1.6(5), 2.7(8), and 3.9(1.2) corresponding to the $3n$, $4n$, and $5n$ fission yields, respectively. These yields for ^{107}Ru within error are similar to those of ^{109}Ru, which has the yield ratios of 0.45(9), 0.30(7), and 0.58(11) [1,6] for the $3n$, $4n$, and $5n$ fission yields, respectively. Figure 2(b) shows coincidence spectra obtained by double gating on the

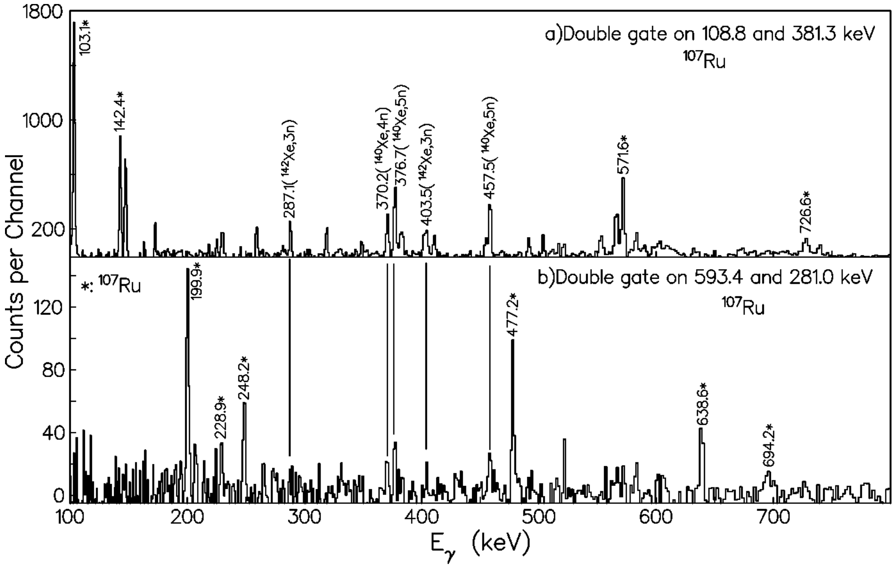

FIG. 2. (a) Upper panel: Coincidence spectrum obtained by double gates on the 108.8 and 381.3 keV transitions in ^{107}Ru. (b) Lower panel: Coincidence spectrum obtained by a double gate on the 593.4 and 281.0 keV transitions in ^{107}Ru.

593.4 and 281.0 keV transitions linking bands (1) and (2). Again, the coincidence γ transitions in ^{107}Ru as well as those of the Xe partners are clearly identified. In Fig. 2(b), the Xe partner transitions have the yield ratios of 2.0 and 3.1 for the $4n$ and $5n$ channels, respectively, which are similar to those of Fig. 2(a). In Fig. 2(b), it is not easy to get the correct intensity of 287.1 keV transition (^{142}Xe,3n) because of the poor statistics. In Figs. 3(a) and 3(b), two coincidence spectra with the double gates on 711.4 and 553.1 keV transitions, and 103.1 and 108.8 keV transitions in ^{107}Ru are shown. In these gates, the 370.9 keV transition is a doublet in ^{107}Ru (370.9) and ^{141}Xe(370.2). By examining the coincidence relations such as those displayed in Figs. 2 and 3, and by measuring the partner's relative intensities, the new level scheme of ^{107}Ru was firmly established.

The spin and parity of the ^{107}Ru ground state have been tentatively assigned as $5/2^+$, following the work of Ref. [2]. Based on the regular energy spacings and the γ-ray intensities, the transitions in bands (1) and (2) have been assigned a stretched $\Delta I=2$, $E2$ character. These two bands are then linked by $\Delta I=1$, $E2/M1$ crossover transitions. These assignments result in the spins and parities proposed in Fig. 1 for the levels in bands (1) and (2). These bands form a typical strongly coupled rotational structure built on the ground state, and resemble closely the ground band structures observed in the neighboring odd-A isotopes ^{103}Ru [7] and ^{109}Ru [3,8]. Based on a systematic comparison with the neighboring isotopes ^{109}Ru [3] and ^{111}Ru [9], band (3), built on the 301.8 keV $11/2^-$ state, was assigned a negative parity. In this negative parity band, the 301.8 keV band head is different from that reported earlier [3]. However, the new data confirm the $711\rightarrow553\rightarrow371$ keV cascade as reported in Ref. [3], and there is no evidence for the 906.7, 824.1, 721.9, 583.1, 371.9 keV sequence proposed in Ref. [4]. Band (4) is new to this work. It is built on the 251.2 keV level, for which there is no previous spin and parity assignment. However, bands with similar properties have been observed in the neighboring isotopes ^{109}Ru and ^{111}Ru [7], where they are based on $9/2^-$ states. Based on this structural similarity with the neighboring nuclei, the quantum numbers of the 251.2

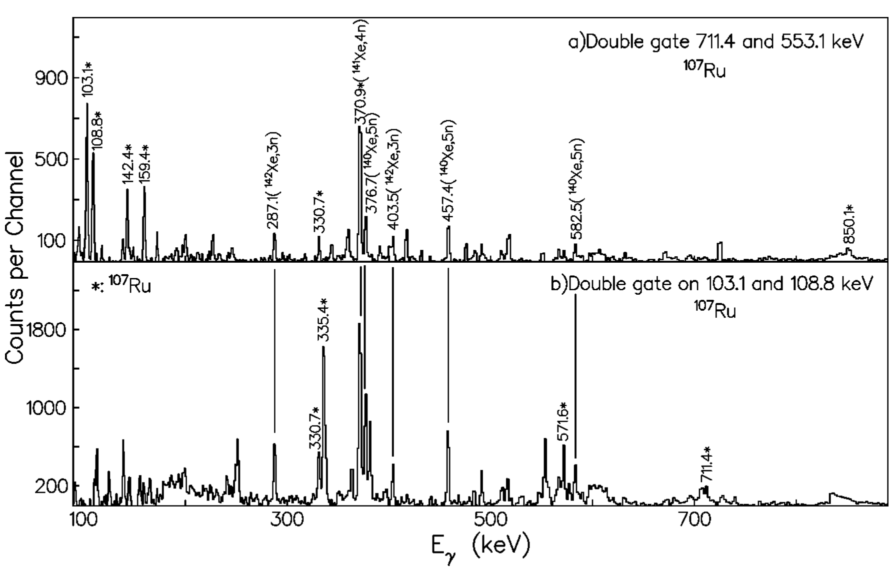

FIG. 3. (a) Upper panel: Coincidence spectrum obtained by double gates on the 711.4 and 553.1 keV transitions in ^{107}Ru. (b) Lower panel: Coincidence spectrum obtained by a double gate on the 103.1 and 108.8 keV transitions in ^{107}Ru.

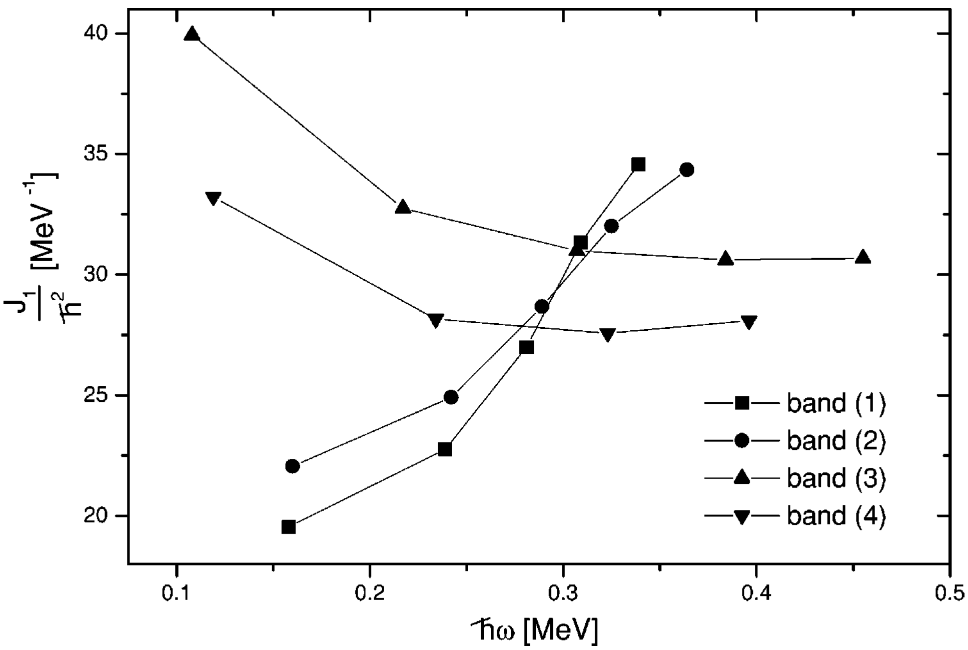

FIG. 4. Plots of the moments of inertia J_1 against the rotational frequency $\hbar\omega$ for the four bands in ^{107}Ru.

keV level have been tentatively assigned as $9/2^-$ and the other states of the sequence then range in spin from $13/2^-$ to $25/2^-$. The 142.4 and 103.1 keV levels observed in β^- decay work [2] below the 251.2 keV level might have spins and parities of $7/2^-$ and $5/2^-$, respectively.

Bands (1) and (2) are signature partners of a strongly coupled ground state band that exhibits signature splitting and inversion. A plot of the kinematic moments of inertia (J_1) against the rotational frequency $\hbar\omega$ is shown in Fig. 4 for the two bands. Both values of J_1 display a similar behavior with frequency: they increase with $\hbar\omega$. However, the slope of the J_1 curve for band (1) is a little different from that for band (2) and the two curves cross at $\hbar\omega \approx 0.29$ MeV. This is the result of signature splitting. Furthermore, from Fig. 5, which presents the energy differences $E(I)$-$E(I-1)$ as a function of spin I for bands (1) and (2), one can clearly see not only the signature splitting mentioned above, but also the signature inversion that occurs at $I \approx 9.5\hbar$. The reason for this inversion is at present not clear, but it implies a structural variation around $I \approx 9.5\hbar$ worthy of further theoretical investigation. The signature splitting in the ground state band is most likely linked to triaxial deformation. In earlier reports [9,10], the level schemes of ^{108,109,110}Ru were interpreted satisfactorily by introducing a degree of triaxiality with $\gamma \approx 20° - 25°$. It is then reasonable to assume a similar shape for ^{107}Ru. In fact, in our earlier

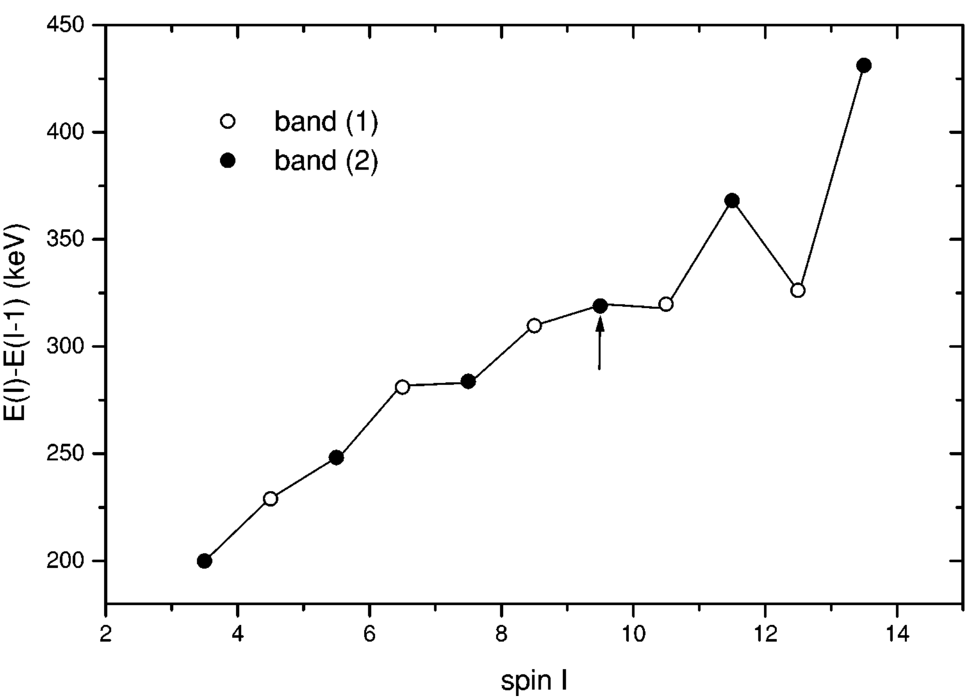

FIG. 5. Plots of the excitation energy differences $E(I)$-$E(I-1)$ against spin I for bands (1) and (2) in ^{107}Ru illustrating the presence of signature splitting and inversion.

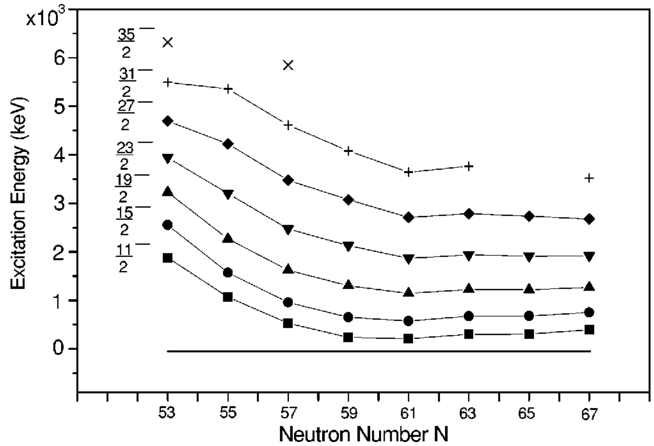

FIG. 6. Excitation energy systematics for the $\nu h_{11/2}$ bands in odd-A Ru isotopes. The data are taken from Ref. [10] for the $N \leqslant 61$ isotopes, the present work for the $N=63$ isotope, and Refs. [3,7,8] for $N=65$ and 67 isotopes.

work of Ref. [3], the triaxial rotor plus quasiparticle model with a variable moment of inertia prescription for the core was used to describe the collective bands in ^{107,109}Ru. The data could be reproduced with deformation parameters $\beta_2 \approx 0.20$ and $\gamma \approx 24°$. These calculations further indicated that the ground state band of ^{107}Ru most likely originates from a quasiparticle configuration involving the coupling of the $\nu d_{5/2}$ and $\nu g_{7/2}$ orbitals to the even-even core, while band (3) is understood as resulting from a similar coupling of the core with the $\nu h_{11/2}$ orbital. Hence, band (3) is built on a unique parity orbital and can be labeled as an intruder band.

As shown in Fig. 4, the kinematic moment of inertia (J_1) for this $\nu h_{11/2}$ intruder band in ^{107}Ru differs from that of the ground state band [bands (1) and (2)]: there is a decrease with increasing frequency $\hbar\omega$. As already discussed above, this $\nu h_{11/2}$ band has been observed in many neighboring odd-A Ru isotopes, including ^{109,111}Ru [3,8,9]. It has also been seen in other nuclei with $N \leqslant 63$ (see Ref. [11]). The level energies of $\nu h_{11/2}$ bands in odd-A Ru isotopes are compared in Fig. 6. As the neutron number increases, the band head energies decrease until neutron number $N=61$ is reached, after which a small, gradual rise with N occurs. This pattern can be related to the enhancement of collectivity as the neutron number approaches midshell. In ^{107}Ru, the excitation energy of the $h_{11/2}$ neutron state lies between those in ^{105}Ru (209 keV) and in ^{109}Ru (304 keV). The level systematics also support the assignment proposed for the other $\nu h_{11/2}$ band members as all trends with N in Fig. 6 are very similar. The origin of band (4) is at present not entirely clear. The J_1 moment of this band is lower than that of band (3), but the behavior with frequency is essentially the same in the two bands. Hence, it is plausible that band (4) originates from the $\nu h_{11/2}$ single-particle orbital as well and belongs to the unique-parity (intruder) band also.

In summary, the levels of the neutron-rich ^{107}Ru nucleus have been thoroughly reexamined. Our previous results have been confirmed and extended further. No evidence was found to support the $\nu h_{11/2}$ band reported recently in Ref. [4]. Some characteristics of the ground state band and of the $\nu h_{11/2}$ band have been briefly discussed.

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