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# Evolution of chirality from $\gamma$ soft $^{108}$Ru to triaxial $^{110,112}$Ru

Y.X. Luo [a,b], S.J. Zhu [a,c], J.H. Hamilton [a,*], J.O. Rasmussen [b], A.V. Ramayya [a], C. Goodin [a], K. Li [a], J.K. Hwang [a], D. Almehed [d], S. Frauendorf [d,e], V. Dimitrov [f], Jing-ye Zhang [g], X.L. Che [c], Z. Jang [c], I. Stefanescu [h], A. Gelberg [i], G.M. Ter-Akopian [j], A.V. Daniel [j], M.A. Stoyer [k], R. Donangelo [l], J.D. Cole [m], N.J. Stone [g,n]

[a] Physics Department, Vanderbilt University, Nashville, TN 37235, USA
[b] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[c] Department of Physics, Tsinghua University, Beijing 100084, People's Republic of China
[d] Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA
[e] Institut für Strahlenphysik, FZD-Rossendorf, Postfach 510119, D-01314 Dresden, Germany
[f] Idaho Accelerator Center, Idaho State University, Pocatello, ID 83209-8263, USA
[g] Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA
[h] PKU Leuven, Instituut voor Kern-en Stralingsfysica, Celestijnenlaan 200 D, B-3001 Leuven, Belgium
[i] University of Cologne, Institute of Kernphysics, Cologne D-50937, Germany
[j] Joint Institute for Nuclear Research, Dubna 141980, Russia
[k] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[l] Universidade Federal do Rio de Janeiro, CP 68528, RG, Brazil
[m] Idaho National Laboratory, Idaho Falls, ID 83415-2114, USA
[n] Department of Physics, Oxford University, Oxford OX1 3PU, United Kingdom

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ABSTRACT

Rotational bands in $^{108,110,112}$Ru have been investigated by means of $\gamma$–$\gamma$–$\gamma$ and $\gamma$–$\gamma(\theta)$ coincidences of prompt $\gamma$ rays emitted in the spontaneous fission of $^{252}$Cf. The positive parity bands are described by different versions of IBA, where $^{108}$Ru is best described as a $\gamma$-soft nucleus whereas $^{110,112}$Ru are more like rigid triaxial rotors. New $\Delta I = 1$ negative parity doublet bands are found. In case of $^{110,112}$Ru, these are interpreted as soft chiral vibrations. Many of the experimental findings can be explained by microscopic calculations that combine the TAC mean-field with random phase approximation but a simple geometrical explanation is not apparent.



Frauendorf and co-workers [1–3] have proposed that rotating triaxial nuclei may exhibit chiral behavior with a superposition of right- and left-handed symmetry, which gives rise to two $\Delta I = 1$ sets of rotational levels with the same parity and degenerate in energy for the same spin. Ref. [3] first suggested the observation of such a chiral doublet in $^{134}$Pr. A number of other doublets were reported in this region (see Refs. [4–7]). Several cases of doublet bands were subsequently reported in the $A \approx 100$ region for odd–odd nuclei [8–11] with the claim [8] that the best chiral properties observed to date are in $^{104}$Rh. These results were followed by the first report of doublet bands in the odd-$A$ nuclides $^{135}$Nd [5], $^{105}$Rh [12] and possible chiral sister bands in the even–even nucleus $^{106}$Mo [13] with a vibrational character. Recently the doublet bands in $^{135}$Nd were associated with a transition from a vibrational to a static chiral region [14].

The classic examples for chirality [1] are triaxial odd–odd nuclei where the angular momenta of a high-$j$ particle and a high-$j$ hole are aligned along the short and long axis, respectively, and the angular momentum of collective rotation is aligned with the intermediate axis. Ref. [2] pointed out the general character of chirality, which always arises when the angular momentum vector lies outside the three principal planes of the three axial nuclear shape. The observation of doublet bands in odd-$A$ nuclei [5,12], where two high-$j$ particles are aligned with the short axis, confirmed this.

* Corresponding author.
*E-mail address:* j.h.hamilton@vanderbilt.edu (J.H. Hamilton).

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The observation of doublet bands in even–even $^{106}$Mo [13] seems to further exemplify the general geometric character of chiral symmetry breaking [2], because the non-planar geometry of rotation cannot be directly related to the alignment of high-$j$ particles and holes with different principal axes (see [13] and discussion below).

Chirality gives rise to $\Delta I = 1$ doublet bands with the same parity where states of the same spin would be nearly degenerate in energies. Additional fingerprints are similar electromagnetic properties such as $B(E2)/B(M1)$ ratios for the same spins states and constant and equal values of the parameter $S(I) = [E(I) - E(I-1)]/2I$ with spin for the two doublet bands [8,15].

In our work we have identified for the first time $\Delta I = 1$ doublet bands which are assigned negative parity in $^{108,110,112}$Ru. From their global calculations of axial symmetry breaking in nuclear ground states, Möller et al. [16] have identified a region centered around $Z = 44$, $N = 64$, $^{108}$Ru, as having the largest lowering of the nuclear ground state energy when axial symmetry is broken. This suggests the possibility that the observed doublet bands originate from breaking chiral symmetry. This interpretation is supported by the similarity of the electromagnetic transition rates in the two bands as found in our experiment.

The appearance of a triaxial shape is independently suggested by our recent comparison of the ground band and one-phonon

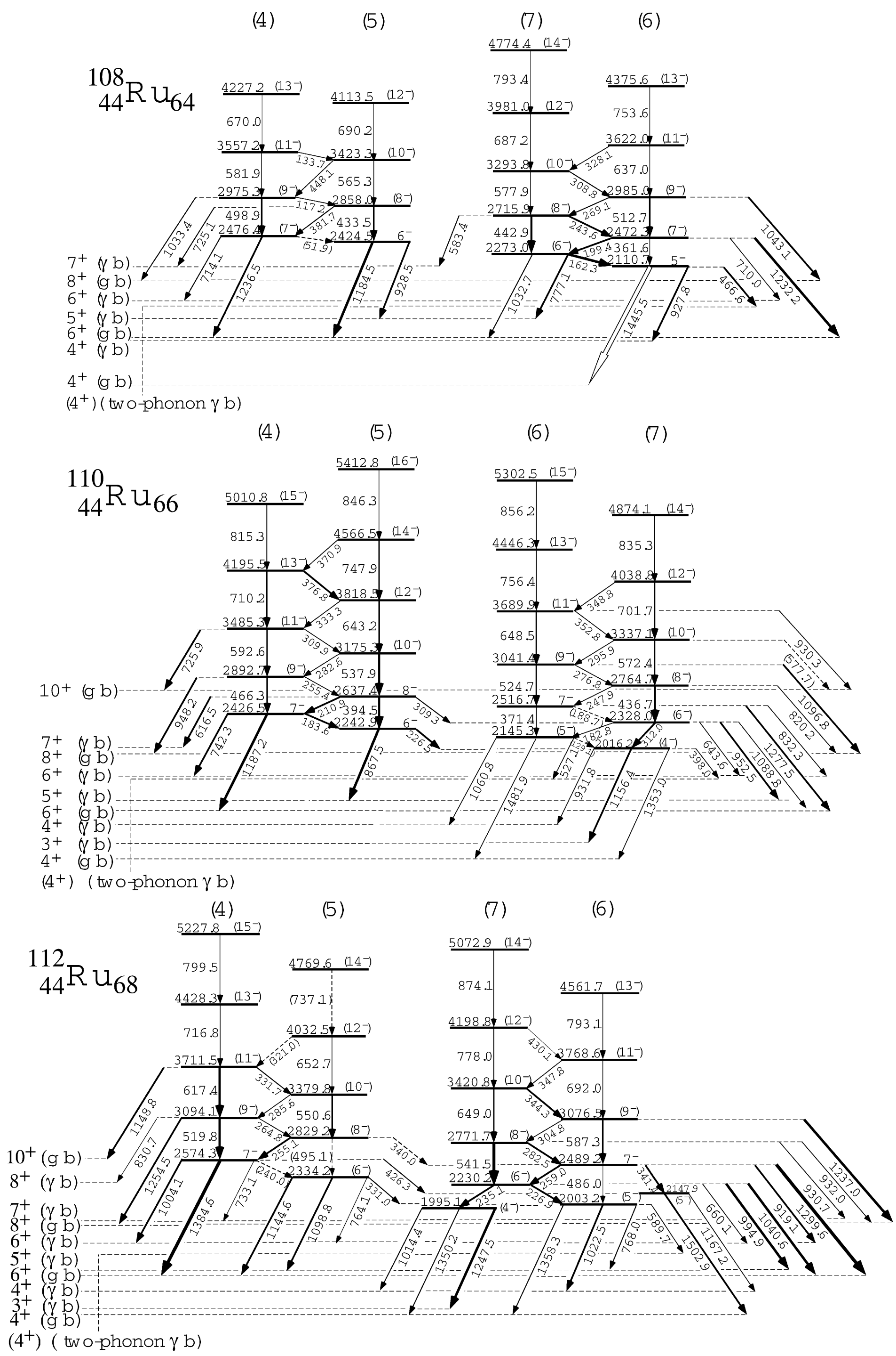


**Fig. 1.** New doublet bands identified in $^{108,110,112}$Ru.

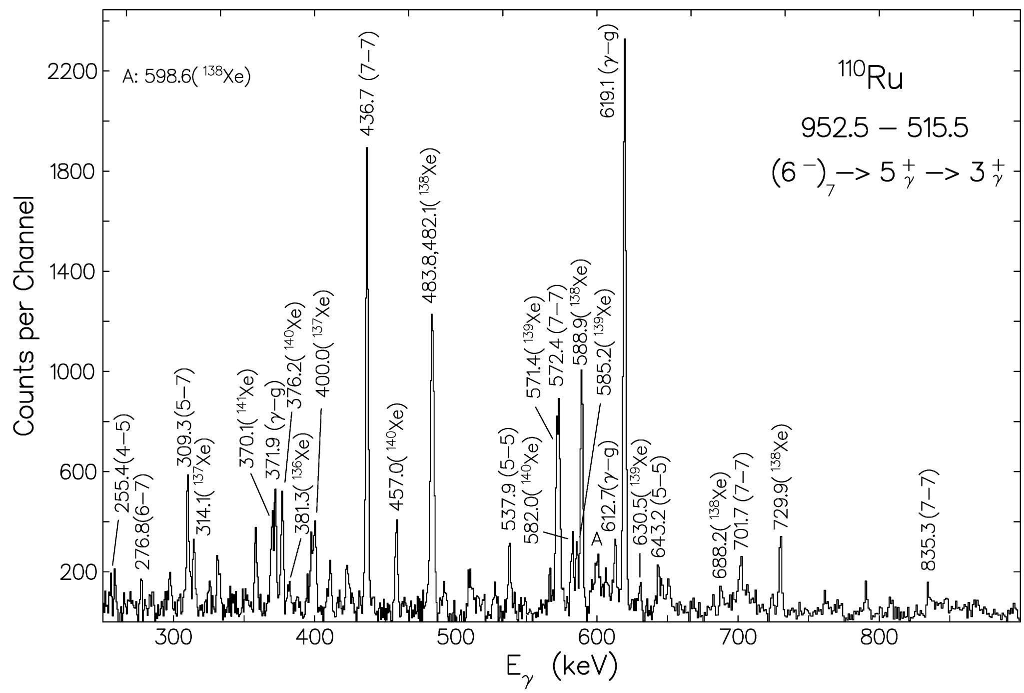


**Fig. 2.** Spectrum double-gated on the 952.5–515.5-keV transitions in $^{110}$Ru. The bands associated with the initial and final states or the partner isotopes are indicated in parentheses.

$\gamma$ band energies and $B(\mathrm{E2})$'s in $^{108,110,112}$Ru with the standard IBM1 model and the version IBM1-V3 which includes higher order terms to account for triaxiality [17]. These comparisons suggest that $^{108}$Ru is $\gamma$ soft and $^{110,112}$Ru are more like rigid triaxial rotors [17], which is based on the observation that the odd–even spin staggering in the $\gamma$ band in $^{108}$Ru is exactly opposite to those in $^{110,112}$Ru. The agreement between the calculated and experimental excitation energies and $B(\mathrm{E2})$ ratios were quite satisfactory for $^{108}$Ru in IBM1 in accordance with $^{108}$Ru being a $\gamma$ soft SU(6) nucleus. The odd–even spin energy level staggerings in the quasi-$\gamma$ bands in $^{110,112}$Ru could not be fitted in these calculations. The staggering patterns are those of a rigid triaxial rotor in $^{110,112}$Ru which are opposite to the ones in a $\gamma$ soft SU(6) nucleus. This discrepancy was removed and better fits to the branching ratios and ground band energies were obtained by including three-body terms in the Hamiltonian denoted IBM1 + V3. This produces an energy surface with a triaxial minimum. In addition, we have found in our studies of the odd-$Z$ nuclides $^{99,101}$Y, $^{101,105}$Nb, $^{105-111}$Tc, and $^{111,113}$Rh [18–21] a smooth evolution in the triaxial parameter $\gamma$ from $\gamma \approx 0$ (axial symmetry) in $^{99,101}$Y to $\gamma \approx -28^\circ$ (near maximum triaxiality) in $^{111,113}$Rh. These data further support maximum triaxiality in $^{110,112}$Ru.

The new negative parity $\Delta I = 1$, doublet bands in $^{108,110,112}$Ru identified in the present work are displayed in Fig. 1. An example of our many double-gated triple coincidence spectra is shown in Fig. 2 where transitions in or between bands 4, 5, 6 and 7 in $^{110}$Ru are shown. The discoveries of these weakly populated extended $\Delta I = 1$ bands were made possible by our high statistics data set, $5.7 \times 10^{11}$ triple and higher fold coincidences, taken with a 62 μCi $^{252}$Cf source in Gammasphere (see Refs. [13,18,19]). Our data set was recently subdivided by angle to allow us to measure $\gamma - \gamma(\theta)$ angular correlations to assign spins and transition multipolarities [22].

From our $\gamma\gamma(\theta)$ data, we have determined the spins and dipole character of the depopulating transitions to support our negative parity assignments for the following: $5^-$, 2110.7-keV level in $^{108}$Ru; $6^-$, 2242.9-; $7^-$, 2426.5-; $7^-$, 2516.7- and $8^-$, 2637.4-keV levels in $^{110}$Ru; and $7^-$, 2489.2- and 2574.3-keV levels in $^{112}$Ru. As examples of our results, the 8–6–5 cascade (394.5–867.5 keV) in $^{110}$Ru has $A_2 = -0.079(14)$, $A_4 = 0.023(20)$. The theoretical $A_2 = -0.071$ and $A_4 = 0$ for a 8–6–5 cascade for the 6–5 transition being pure dipole and $A_2 = -0.007$, $A_4 = -0.023$ for pure quadrupole. For the 6–5–3 cascade (867.5–515.5 keV) where the 5 and 3 are known, $A_2 = -0.052(14)$, $A_4 = 0.002(21)$ and again $A_2 = -0.071$, $A_4 = 0$ for pure dipole. All of the band heads are measured to have lifetimes less than 1 ns so these cannot be high $K$ rotational bands.

In contrast to $^{110,112}$Ru, the non-yrast bands 4, 5 in $^{108}$Ru develop a strong even–odd spin level-energy staggering (signature splitting) whereas bands 6, 7 represent a good $\Delta I = 1$ sequence without much staggering. This may suggest that the two sequences belong to different quasi particle configurations. More likely, it is a consequence of the $\gamma$ softness disturbing the chiral doublets, because a similar difference of odd–even spin staggering between the yrast and non-yrast bands was found in $\gamma$ soft $^{106}$Ag [11], and attributed to different values of $\gamma$ and shapes. These bands in $^{108}$Ru will not be discussed further.

Fig. 3 shows energy differences between the levels of the same spin for $^{110,112}$Ru and $^{104,106}$Rh. Note that the energy differences in $^{110,112}$Ru are smaller than those of $^{104,106}$Rh, suggested to be the best examples of chiral doublets ([8,11], respectively). The still noticeable energy splitting in $^{110,112}$Ru points to a dynamical character of chirality, being intermediate of a slow vibrational excursion into left- and right-handed regions and a tunneling motion between the two regions [4]. In addition, the parameter $S(I) = [E(I) - E(I-1)]/2I$ should be constant with increasing spin and be equal for the two doublets if they are chiral doublets [8]. We compare in Fig. 4 the $S(I)$ values for $^{110,112}$Ru with those for $^{106}$Rh suggested more recently [11] to be the best example of chiral bands. Our cases are comparable to those for the two bands in $^{106}$Rh [9] and $^{104}$Rh (not shown) [8] for being constant with spin and equal.

Chiral doublet bands should have similar electromagnetic transition probabilities. Recent experiments on $^{134}$Pr found substantial differences between the inband $B(\mathrm{E2})$ values of the two chiral

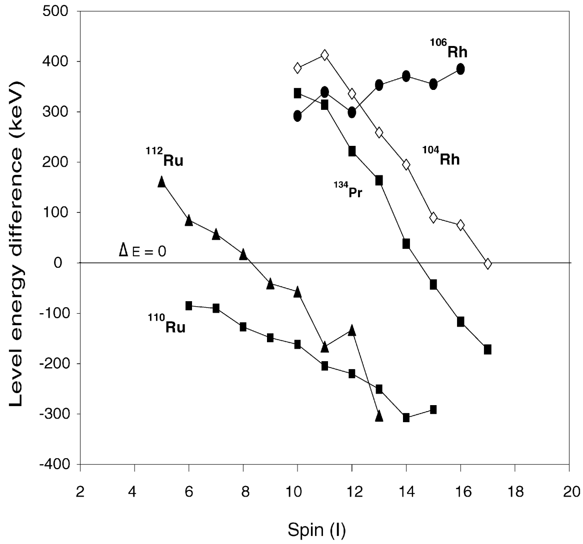


**Fig. 3.** Energy differences between states of the same spin in the chiral doublets for $^{110,112}$Ru, $^{104,106}$Rh and $^{134}$Pr.

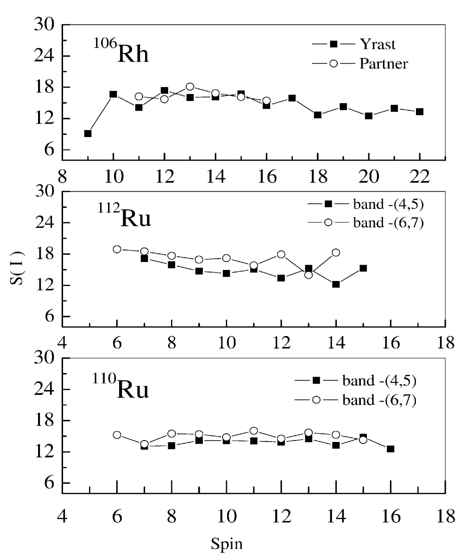


**Fig. 4.** Energy staggering parameter $S(I)$ for doublet transitions in $^{106}$Rh and $^{110,112}$Ru.

**Table 1**
$B(\mathrm{E2})/B(\mathrm{M1})$ ($e^2b^2/\mu_N^2$) ratios in doublet bands 4–5 and 6–7 in $^{110,112}$Ru and bands 1–2 in $^{134}$Pr.

| Spin | $^{110}$Ru | | $^{112}$Ru | | Spin | $^{134}$Pr | |
|---|---|---|---|---|---|---|---|
| | 4–5 | 6–7 | 4–5 | 6–7 | | 1 | 2 |
| 13 | > 1.3 | | | | 18 | 0.48 | |
| 12 | 3.1 | 1.6 | > 1.1 | 1.4 | 17 | 0.55 | 0.08 |
| 11 | 2.4 | 4.4 | 2.9 | 1.5 | 16 | 0.80 | 0.14 |
| 10 | 3.5 | 2.1 | 2.6 | 2.5 | 15 | 0.48 | 0.19 |
| 9 | 2.5 | 4.2 | 5.1 | 3.4 | 14 | 0.38 | 0.05 |
| 8 | 2.6 | 3.3 | | 2.0 | 13 | 0.25 | |

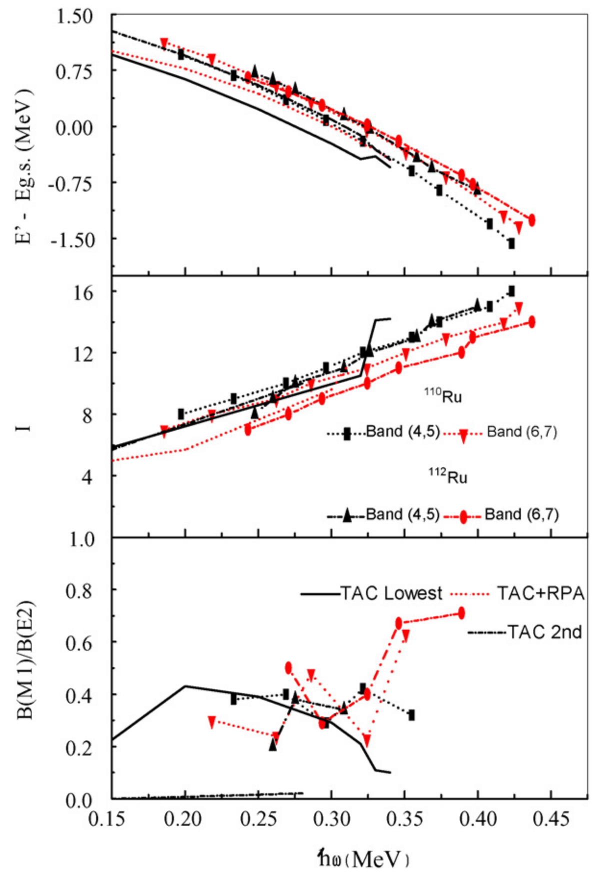


**Fig. 5.** Energy in the rotating frame (upper panel), angular momentum (middle panel) and $B(\mathrm{M1})/B(\mathrm{E2})$ in-band values of the negative party bands in $^{110,112}$Ru as a function of rotational frequency. Within the present approach both are equal and given by the TAC calculations (in color online).

partners [23,24], which [23] considered as a possible misinterpretation of nearly degenerate pairs of bands as chiral partners and which [23] related to the coupling of the orientation of the nucleus to its shape. Table 1 compares the $B(\mathrm{E2})/B(\mathrm{M1})$ ratios of the $\Delta I = 2 - \mathrm{E2}$ to $\Delta I = 1 - \mathrm{M1} + (\mathrm{E2})$ strengths for the two sets of doublet bands. The $\Delta I = 1$ transitions are assumed to be M1. The relative $\gamma$ ray intensity branching ratios were mostly determined from double-gating from above each level. These $B(\mathrm{E2})/B(\mathrm{M1})$ ratios for each spin state in $^{110,112}$Ru are in reasonable agreement, which indicates that the bands in $^{110,112}$Ru have very similar structures as required for chiral doublets. For comparison, the ratios for $^{134}$Pr differ by 2.5 to 7.6 (cf. Table 1). The similar $B(\mathrm{E2})/B(\mathrm{M1})$ values rule out the possibility that doublets originate from two accidentally degenerate configurations from the coupling of say an $h_{11/2}$ neutron to two different neutron bands in $^{109,111}$Ru. The microscopic TAC calculations described below give very different $B(\mathrm{E2})/B(\mathrm{M1})$ ratios for different configurations (cf. Fig. 5).

Summarizing the preceding discussion, the $^{110,112}$Ru $\Delta I = 1$ doublet bands have very similar electromagnetic properties, identical and constant with spin $S(I)$ values and are the most nearly degenerate in energy of any of the proposed chiral bands. Thus since they have all the properties of good chiral vibrational bands, we propose that these $\Delta I = 1$ doublet bands in $^{110,112}$Ru are indeed zero and one phonon chiral vibrational bands.

In order to substantiate this interpretation, we have performed tilted axis cranking (TAC) and random phase approximation (RPA) calculations for different two-quasi neutron configurations with $Z \approx 44$ and $N \approx 66$. The results are quite similar for both nuclei and we will only describe the results for $^{112}$Ru below. The combination of the TAC method [25] with RPA is described in detail in Ref. [26], where it is applied to odd–odd nuclei. The method has been used successfully to describe the chiral vibration in $^{135}$Nd [14]. We use a self-consistent TAC Hamiltonian in a harmonic oscillator basis with the $QQ$-force in three major harmonic oscillator $N$-shells ($N_{\mathrm{low}} = 3$ and $N_{\mathrm{up}} = 5$)

$$H' = h_0 + \sum_{m=-2}^{2} \frac{\kappa_0}{2} \sum_{N=4}^{5} \bar{Q}_m^{(N)} \bar{Q}_m^{(N)} (-)^{m+1} - \Delta(P^+ + P) - \vec{\omega} \cdot \vec{J}, \tag{1}$$

where $h_0$ is the spherical Woods–Saxon energy [27]. The

$$\bar{Q}_m^{(N)} = \left(\frac{N_{\text{low}} - B}{N - B}\right) \left(\frac{2A_{n(p)}}{A}\right)^{1/3} Q_m^{(N)} \tag{2}$$

are the dimensionless quadrupole operators for each $N$-shell multiplied by a $N$ and isospin-dependent quenching factor [26,27], and $A_{n(p)}$ are the neutron and proton numbers, i.e. $A = A_n + A_p$. We use the values of $\kappa_0$ (0.0605 [MeV]) and $B$ ($-0.5$) that give a good agreement with data on the ground state band and the energy of the $\gamma$ vibration. The angular velocity in the cranking term, $\vec{\omega} \cdot \vec{J}$, is defined as $\omega_1 = \omega \sin\vartheta \cos\varphi$, $\omega_2 = \omega \sin\vartheta \sin\varphi$, and $\omega_3 = \omega \cos\vartheta$, where $\vartheta$ and $\varphi$ are the tilt angles [14]. $P$ is the pairing operator and the pair field is set to $\Delta_{\text{proton}} = 1.27$ MeV and $\Delta_{\text{neutron}} = 0.60$ MeV.

Since the two-quasi proton states lie at higher energy than the two-quasi neutron states in this region, our new negative parity bands are interpreted as two-quasi neutron excitations. The lowest configuration is obtained by exciting a neutron from the highest $h_{11/2}$ level to the low-lying mixed $d_{5/2}$–$g_{7/2}$ levels. The microscopic TAC calculations give a total routhian (energy in the rotating frame), which depends only very weakly on the orientation of the rotational axis with respect to the triaxial shape. This softness cannot be reduced to the simple picture discussed for odd–odd nuclei [1,2], where instability toward a non-planar orientation of the rotational axis is the consequence of combining a high-$j$ particle and a high-$j$ hole with collective rotation. The tendency to chirality comes about from the interplay of all the neutrons in the open shell, and we could not find a simple partition.

The soft energy surface obtained from the mean field calculations implies a low-lying collective mode in the orientation degree of freedom, i.e. a soft chiral vibration. Thus, we interpret the bands 4, 5 as the zero-phonon state, which is given by the TAC solution, and bands 6, 7 as the one-phonon state, which is given by the RPA solution. The results of the TAC and RPA calculations are plotted in Fig. 5 together with the experimental data.

The TAC calculations give a $\gamma$-deformation of 22° with the same moment of inertia and similar energy relative to the ground state as bands 4, 5 and 6, 7 in the experimental data. The inband ratios $B(\text{M1})/B(\text{E2})$, which are given by the TAC solution, are also well described up to $\omega \approx 0.3$ MeV/$\hbar$. The TAC solution has a tilt angle $\vartheta$ that changes rapidly from 0° at $\omega = 0.10$ MeV/$\hbar$ toward 60° at $\omega = 0.30$ MeV/$\hbar$. The second tilt angle remains at $\varphi = 0°$, which indicates that the configuration does not develop static chirality. However, it is nearly instable in this direction. At a rotational frequency of $\omega \approx 0.3$ MeV/$\hbar$, the TAC self-consistent calculations give a rapid transition toward $\gamma \approx 40°$, which indicates a change of the quasi particle configuration. We could not identify a counterpart of this structural change in experiment.

We find a low-lying RPA phonon at an excitation energy of 300 keV, which we associate with bands 6, 7 in $^{110}$Ru. It has about 1$\hbar$ less aligned angular momentum than the zero phonon state, which is in agreement with the data. As seen in Fig. 5, the TAC + RPA one-phonon energy agrees very well with the distance between the routhians of bands 6,7 and 4,5 in $^{110}$Ru. Using the method described in [26], we analyzed the microscopic structure of the RPA solution. We found that it represents a collective motion in the orientation variables $\vartheta$ and $\varphi$. The oscillations of the deformation parameters are weak. Hence, the RPA calculations confirm the interpretation as a chiral vibration. Also the RPA values for the interband M1 and E2 transitions are very small, and are consistent with our experimental intensity upper limits for these weak transitions, to further support our interpretation.

To investigate if band 6, 7 can be interpreted as an alternative neutron configuration we also solved the TAC equations for the second lowest odd-parity, two-quasi-neutron configuration. In Fig. 5 we can see that this configuration has similar energy and moment of inertia as the lower configuration, but has very different $B(\text{M1})/B(\text{E2})$ ratios and is an unlikely candidate for the interpretation of this band. The TAC results are consistent with the additional calculations in the framework of the triaxial-rotor-plus-two-quasi-neutron model, which give substantially different $B(\text{M1})/B(\text{E2})$ ratios for the lowest neutron configurations.

In $^{112}$Ru, band 7, 6 crosses band 4, 5, while both bands stay very close together. Ref. [26] demonstrated for the odd–odd $N = 75$ isotones, that this signalizes chiral instability, where RPA breaks down. Depending on $Z$, the following regimes were found: (i) The one-phonon state has less aligned angular momentum than the zero-phonon state, like our solution, which means that the chiral vibration becomes more stable with increasing $\omega$. (ii) The one-phonon state has more aligned angular momentum than the zero-phonon state, which means that the chiral vibration becomes less stable or chiral instable with increasing $\omega$. (iii) The one-phonon state has more aligned angular momentum than the zero-phonon state. With increasing $\omega$, it becomes instable and the TAC solution chiral. After some further increase, the TAC solution becomes planar with respect to another principle plane. Then the one-phonon state has less aligned angular momentum than the zero-phonon state, and its energy increases with $\omega$. Regime (iii) corresponds to crossing bands in experiment. However, a large amplitude approach beyond RPA is needed for a quantitative description. Thus a direct comparison of the $^{112}$Ru data with our TAC + RPA solution is inappropriate. At this point, we interpret the crossing of the bands as a signal of chiral instability. A solid underpinning of this interpretation must wait for a large-amplitude description of the chiral motion, which is on the way [28].

In conclusion, we have found pairs of negative parity bands in $^{110,112}$Ru, which have the same parity and come very close in energy. Their $B(\text{E2})/B(\text{M1})$ ratios of their electromagnetic in-band transition rates are very similar and their $S(I)$ values are equal and constant with spin. These data and facts that the two bands cross and the interband ratios are weak suggest the interpretation that these bands are a soft chiral vibration or more complicated slow motion of the angular momentum relative to the three-axial nuclear shape between left-handed and right-handed geometries, where it resides for most of the time. Many of these features can be explained by tilted axis cranking calculations, which are extended by RPA calculations, which describe the slow vibrational motion but the need for a large-amplitude description is apparent.

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## References

[1] S. Frauendorf, J. Meng, Nucl. Phys. A 617 (1997) 131.
[2] S. Frauendorf, Rev. Mod. Phys. 73 (2001) 463.
[3] V.I. Dimitrov, S. Frauendorf, in: J.H. Hamilton, et al. (Eds.), Proceedings of Third International Conference on Fission and Properties of Neutron-rich Nuclei, World Scientific, Singapore, 2003, p. 93.

[4] K. Starosta, et al., Phys. Rev. Lett. 86 (2001) 971.
[5] S. Zhu, et al., Phys. Rev. Lett. 91 (2003) 132501.
[6] E. Gaodner, et al., Phys. Rev. Lett. 97 (2000) 172501.
[7] N. Toner, et al., Phys. Rev. C 76 (2007) 04431.
[8] C. Vaman, et al., Phys. Rev. Lett. 92 (2004) 032501.
[9] P. Joshi, et al., Phys. Lett. B 595 (2004) 135.
[10] P. Joshi, et al., Eur. Phys. J. A 24 (2005) 23.
[11] P. Joshi, et al., Phys. Rev. Lett. 98 (2007) 102501.
[12] J. Timar, et al., Phys. Lett. B 598 (2004) 178.
[13] S.J. Zhu, et al., Eur. Phys. J. A 25 (Suppl. 1) (2005) 459.
[14] S. Mukhopadhyay, et al., Phys. Rev. Lett. 99 (2007) 172501.
[15] T. Koike, et al., Phys. Rev. Lett. 93 (2004) 172502;
T. Koike, et al., Phys. Rev. C 67 (2003) 044319.
[16] P. Möller, et al., Phys. Rev. Lett. 97 (2006) 162502.
[17] I. Stefanescu, et al., Nucl. Phys. A 789 (2007) 125.
[18] Y.X. Luo, et al., Phys. Rev. C 69 (2004) 024315.
[19] Y.X. Luo, et al., Phys. Rev. C 70 (2004) 044310.
[20] Y.X. Luo, et al., J. Phys. G 31 (2005) 1303.
[21] Y.X. Luo, et al., Phys. Rev. C 74 (2006) 024308.
[22] A. Daniel, et al., Nucl. Instrum. Methods B 262 (2007) 399.
[23] C.M. Petrache, et al., Phys. Rev. Lett. 96 (2006) 112502.
[24] D. Tonev, et al., Phys. Rev. Lett. 96 (2006) 052501.
[25] S. Frauendorf, Nucl. Phys. A 677 (2000) 115.
[26] D. Almehed, S. Frauendorf, arXiv: 0709.0969, Phys. Rev. C, in press.
[27] M. Barranger, K. Kumar, Nucl. Phys. A 110 (1968) 490.
[28] D. Almehed, S. Frauendorf, in preparation.