Vol. 40 (2009) ACTA PHYSICA POLONICA B No 3

NEW BAND STRUCTURES IN NEUTRON-RICH Mo AND Ru ISOTOPES*

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

[a]Physics Department, Vanderbilt University, Nashville, TN 37235, USA
[b]Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[c]Departament of Physics, Tsinghua University, Beijing 100084, China
[d]Department of Physics, University of Notre Dame, Note Dame, IN 46556, USA
[e]IAC of Idaho State University, Pocatello, ID 83209, USA
[f]Department of Physics, University of Tennessee, Knoxville, TN 37996, USA
[g]Department of Physics, University of Maryland, College Park, MD 20742, USA
[h]Department of Physics, University of Cologne, Koln 50937, Germany
[i]Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia
[j]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[k]University of Fedaral do Rio de Janeiro, CP 68518, RG Brazil

(Received October 10, 2008)

Rotational bands in ^{110,112}Ru and ^{108}Mo have been investigated by means of γ–γ–γ and γ–$\gamma(\theta)$ coincidences of prompt γ rays emitted in the spontaneous fission of ^{252}Cf. New $\Delta I = 1$ negative parity doublet bands are found. These bands in ^{110,112}Ru and ^{108}Mo have all the properties expected for chiral vibrations. Microscopic calculations that combine the TAC mean-field with random phase approximation support this interpretation.

PACS numbers: 23.20.Lv, 27.60.+j, 25.85.Ca

1. Introduction

The word chiral comes from the Greek word "chaire" which means hand. So charality stands for handness. Systems that can form "right"- and "left"-handed systems on reflection are chiral. Chirality is well known in chemical

* Presented by Y.X. Luo at the Zakopane Conference on Nuclear Physics, September 1–7, 2008, Zakopane, Poland.

molecules. The right and left handed molecules have slightly different energies to give rise to energy doublets. Chirality in chemistry comes from the geometry of the molecules. Nuclei were thought to be achiral because there are only two particles in the nucleus. Then Frauendorf and coworkers [1–3] proposed that well deformed rotating triaxial nuclei can exhibit chiral behaviour with a superposition of right and left handed symmetry associated with angular momentum where chirality is dynamic in nature. Such behavior gives rise to two sets of $\Delta I = 1$ rotational bands with the same parity where levels of the same spin are degenerate in energy. The simplest case for chirality [1] is a triaxial odd-odd nucleus 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 along with the intermediate axis as shown in Fig. 1. The first suggestion of such chiral

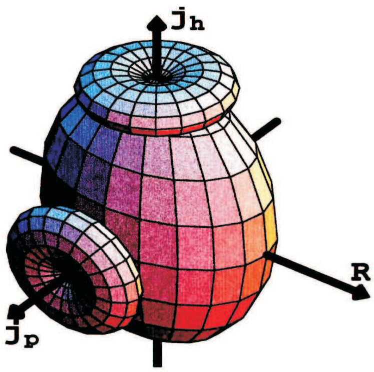

Fig. 1. A traxial nucleus with a proton orbital and a neutron-hole orbital aligned, respectively, along the short and long principal axes.

behaviour was reported in ^{134}Pr [3] followed by other doublets in this region (see Refs. [4–7]). Doublet bands were subsequently reported in the $A = 100$ region for odd–odd nuclei [8–11]. It was suggested [8] that the best observed chiral properties at that time were in ^{104}Rh. Then came the first reports of doublet bands in odd-A ^{135}Nd [5], ^{106}Rh [12]. At ENAM'04 we made the first report of chiral sister bands in an even–even nucleus ^{106}Mo [13] now 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 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).

In addition to $\Delta I = 1$ doublet bands with the same parity where states of the same spin are nearly degenerate in energies, chirality fingerprints include similar electromagnetic properties such as $B(\mathrm{E2})/B(\mathrm{M1})$ 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]. From their global calculations of axial symmetry breaking in nuclear ground states, Moller *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. In our studies of the odd-Z nuclides ^{99,101}Y, ^{101,105}Nb, $^{105-111}$Tc, and ^{111,113}Rh [17–20] we found a smooth evolution in the triaxial parameter γ from $\gamma = 0$ (axial symmetry) in ^{99,101}Y to $\gamma = -28^\circ$ (near maximum triaxiality) in ^{111,113}Rh. These data further support maximum triaxiality in ^{110,112}Ru. The agreement between our calculated [21] and experimental excitation energies and $B(\mathrm{E2})$ ratios was quite satisfactory for ^{108}Ru in IBM1 in accordance with ^{108}Ru being a γ soft SU(6) nucleus. The odd–even spin energy level staggerings in the quasi-γ bands in ^{110,112}Ru could not be fitted in these calculations. 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 our work we have identified for the first time $\Delta I = 1$ negative parity doublet bands in ^{108,110,112}Ru and ^{108}Mo. As will be shown for ^{110,112}Ru and ^{108}Mo these bands have all the properties expected for chiral vibrational bands.

2. Experimental results

The discoveries of these new weakly populated extended $\Delta I = 1$ bands were made possible by our high statistics data set, 5.7×10^{11} triple and higher fold coincidences, taken with a 62 μCi ^{252}Cf source in Gammasphere (see Refs. [17, 18]). This data set was recently subdivided by angle to allow us to measure γ–$\gamma(\theta)$ angular correlations to assign spins and transition multipolarities [22]. Our new negative parity $\Delta I = 1$, doublet bands in ^{110,112}Ru are shown in Fig. 2. Many double-gated triple coincidence spectra were analyzed to identify these bands, an example for ^{110}Ru is shown in Fig. 3.

Our new $\Delta I = 1$ bands in ^{108}Mo which are assigned negative parity are shown in Fig. 4. The new negative parity doublets are very similar to these in ^{106}Mo and in ^{110,112}Ru. Not as many levels are observed because ^{108}Mo is not as strongly populated in spontaneous fission. In this paper we will concentrate on the ^{110,112}Ru doublets.

Our γ–$\gamma(\theta)$ data were used to determine the spins and dipole character of the depopulating transitions to establish spins and to support our negative parity assignments for the following: 5^-, 2110.7 keV level in ^{108}Ru;

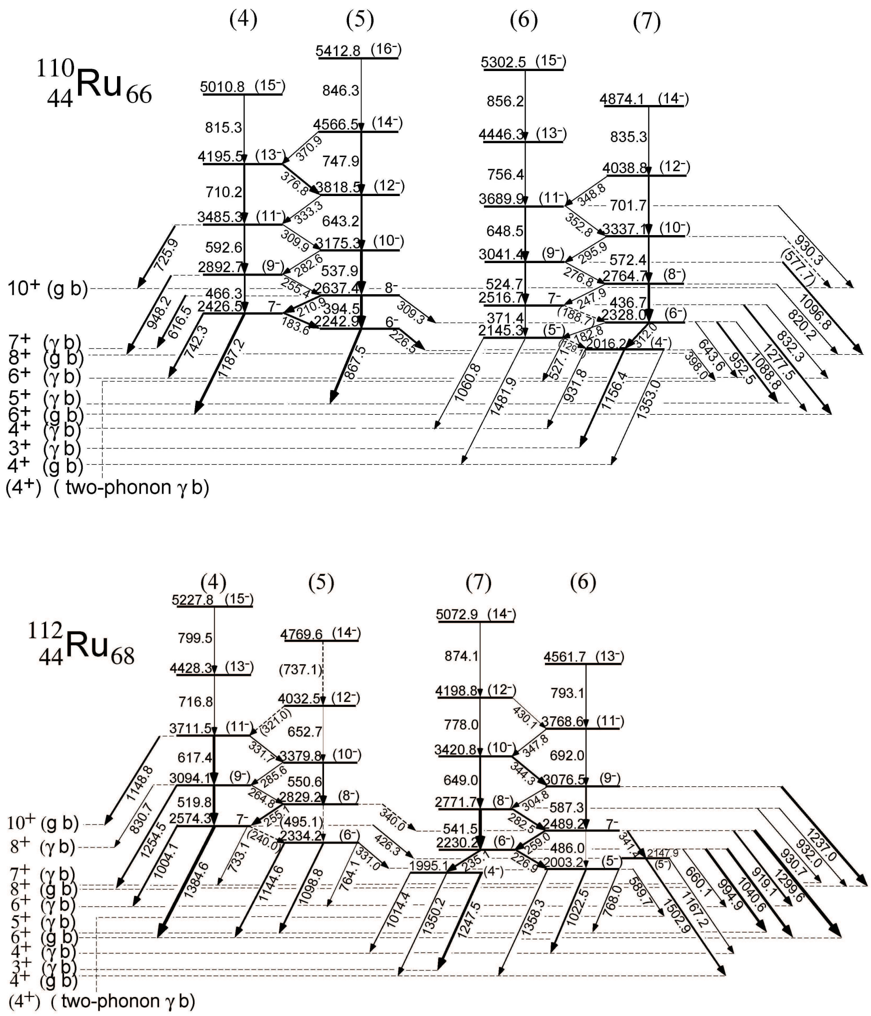

Fig. 2. Partial level schemes of new doublet bands in ^{110,112}Ru.

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 an example, the 8–6–5 cascade (394.5–867.5 keV) in ^{110}Ru has $A2 = -0.079(14)$, $A4 = 0.023(20)$. The theoretical $A2 = -0.071$ and $A4 = 0$ for a 8–6–5 cascade for the 6–5 transition being pure dipole and $A2 = -0.007$, $A4 = -0.023$ for pure quadrupole. For the 6–5–3 cascade (867.5–515.5 keV) where the 5 and 3 are known, $A2 = -0.052(14)$, $A4 = 0.002(21)$ and again $A2 = -0.071, A4 = 0$ for pure dipole for a 6^-–5^- transition. All of the band heads are measured to have lifetimes less than 1 ns so these cannot be high K rotational bands.

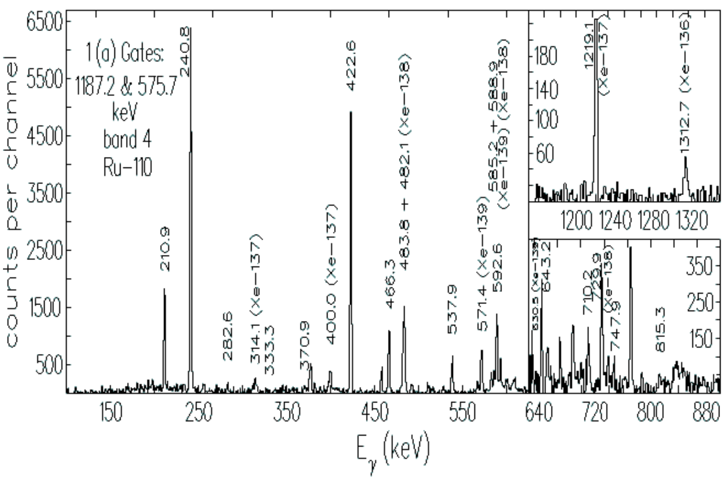

Fig. 3. Coincidence spectrum double-gated on 1187.2 and 575.7 keV (6^+–4^+ in ground band) transitions in ^{110}Ru.

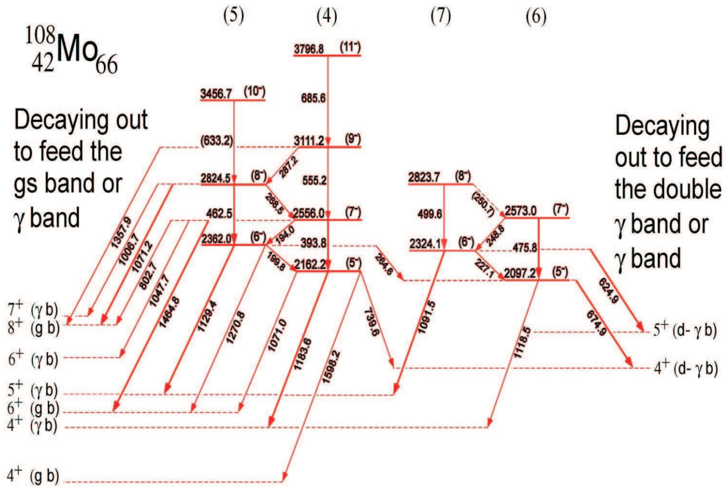

Fig. 4. Partial level scheme of new doublet bands in ^{108}Mo.

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 γ softness disturbing the chiral doublets, because a similar difference of odd–even spin staggering between the yrast and non-yrast bands was found in γ soft ^{106}Ag [11], and attributed to different values of γ and shapes. These bands in ^{108}Ru will not be discussed further.

Fig. 5 shows the energy differences between the levels of the same spin for ^{110,112}Ru, ^{104,106}Rh and ^{134}Pr. 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. 6 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.

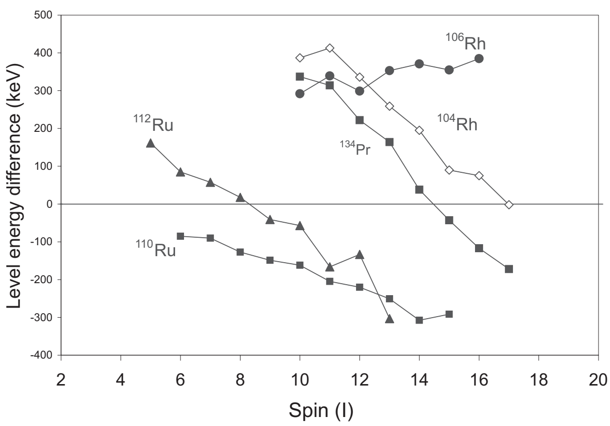

Fig. 5. Energy differences between states of the same spin in the chiral doublets for ^{110,112}Ru, ^{104,106}Rh and ^{134}Pr.

Chiral doublet bands should have similar electromagnetic transition probabilities. Recent experiments on ^{134}Pr found substantial differences between the inband B(E2) values of the two chiral partners [23, 24], which Ref. [23] considered as evidence for a possible misinterpretation of nearly degenerate pairs of bands as chiral partners. Table I 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 γ 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 for the two bands (*cf.* Table I). The microscopic TAC calculations described below give very

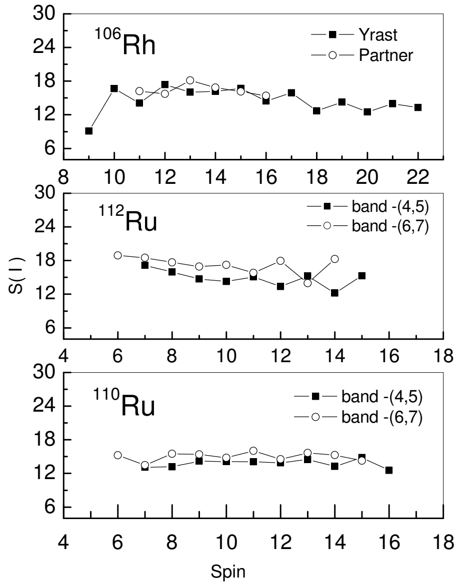

Fig. 6. Energy staggering parameter $S(I)$ for doublet transitions in ^{106}Rh and ^{110,112}Ru.

TABLE I

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

	^{110}Ru		^{112}Ru			^{134}Pr	
Spin	4–5	6–7	4–5	6–7	Spin	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	

different (factor of 10) B(E2)/B(M1) ratios for different configurations. Thus these similar B(E2)/B(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. 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.

3. Theoretical results

In order to substantiate our chiral interpretation, tilted axis cranking (TAC) and random phase approximation (RPA) calculations were performed for different two-quasi neutron configurations in ^{110}Ru and ^{112}Ru. The results are quite similar for both nuclei. The combination of the TAC method 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]. 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 $N_{\mathrm{up}} = 5$) was used.

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

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

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

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 K_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 γ vibration.

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, 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 6,7 as the zero-phonon state, which is given by the TAC solution, and bands 4,5 as the one-phonon state, which is given by the RPA solution. The results of the TAC and RPA calculations are plotted in Fig. 7 together with the experimental data.

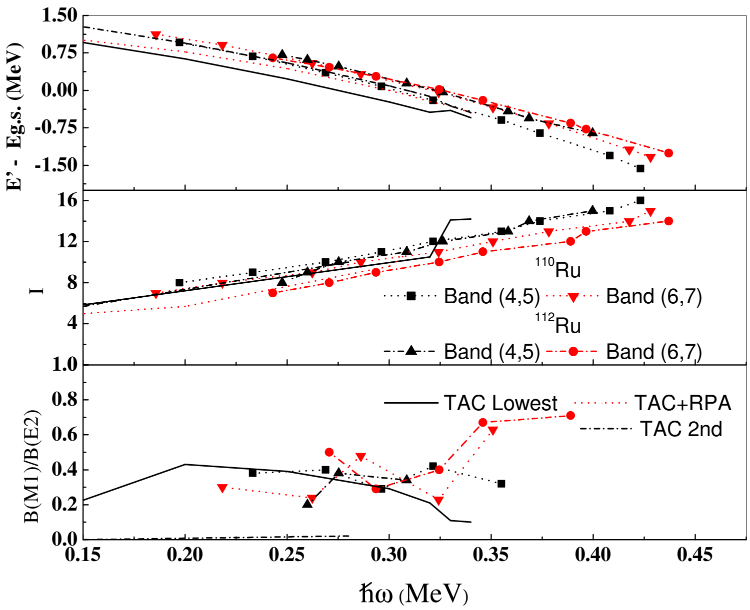

Fig. 7. Energy in the rotating frame (upper panel), angular momentum (middle panel) and $B(\mathrm{M1})/B(\mathrm{E2})$ in-band values of the negative parity bands in ^{110,112}Ru as a function of rotational frequency. Within the present approach both are equal and given by the TAC calculations.

The TAC calculations give a γ-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 $B(\mathrm{M1})/B(\mathrm{E2})$ are also well described up to $\omega = 0.3$ MeV/$\hbar$. The TAC solution has a tilt angle θ 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 $\phi = 0°$, which indicates that the configuration does not develop static chirality.

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. 7, 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 θ and ϕ. 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 see if band 6,7 can be interpreted as an alternative neutron configuration the TAC equations were solved for the second lowest odd–parity, two-quasi-neutron configuration. In Fig. 7 we can see that this configuration has similar energy and moment of inertia as the lower configuration, but has very different $B(\mathrm{M1})/B(\mathrm{E2})$ 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 $B(\mathrm{M1})/B(\mathrm{E2})$ ratios for the lowest neutron configurations. It is clear that the doublet bands in ^{110}Ru make the best example of a soft chiral vibration.

In ^{112}Ru, band 6,7 crosses band 4,5, while both bands stay very close together. Ref. [26] demonstrated chiral instability, where RPA breaks down. Thus a direct comparison of the ^{112}Ru data with our TAC+RPA solution is inappropriate. At this point, we interprete the crossing of the bands as a signal of chiral instability. A large amplitude description of the chiral motion is needed and such is in progress [28].

4. Conclusions

In conclusion, we have found pairs of negative parity bands in ^{110,112}Ru and ^{108}Mo, which have the same parity and come very close in energy. Their $B(\mathrm{E2})/B(\mathrm{M1})$ ratios of their electromagnetic in-band transition rates are very similar and their $S(I)$ values are nearly equal and constant with spin. These data and its fact that the interband ratios are weak suggest these bands are a soft chiral vibration, *i.e.* a 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. These features can be explained by tilted axis cranking calculations, which are extended by RPA calculations, which describe the slow vibrational motion but a simple geometrical explanation is not apparent.

The work at Vanderbilt University, University of Tennessee, University of Notre Dame, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Idaho National Laboratory are supported by U.S. Department of Energy under Grant Nos. DE-FG05-88ER40407, DE-FG02-96ER40983, DE-FG02-95ER40093 and Contract Nos. W-7405-ENG48, DE-AC03-76SF00098, and DE-AC07-76ID01570. The work at Tsinghua University was supported by the NNSFC under Grant No. 10575057 and 10775078 and MSBRDP under Grant No. 2007CB815005.

REFERENCES

[1] S. Frauendorf, J. Meng, *Nucl. Phys.* **A617**, 131 (1997).

[2] S. Frauendorf, *Rev. Mod. Phys.* **73**, 463 (2001).

[3] V.I. Dimitrov, S. Frauendorf, Proc. Third Int. Conf. Fission and Properties of Neutron-Rich Nuclei ed. J.H. Hamilton *et al.*, World Scientific, Singapore 2003, p. 93.

[4] E. Grodner *et al.*, *Phys. Rev. Lett.* **97**, 172501 (2000).

[5] K. Starosta *et al.*, *Phys. Rev. Lett.* **86**, 971 (2001).

[6] S. Zhu *et al.*, *Phys. Rev. Lett.* **91**, 132501 (2003).

[7] N. Toner *et al.*, *Phys. Rev.* **C76**, 04431 (2007).

[8] C. Vaman *et al.*, *Phys. Rev. Lett.* **92**, 032501 (2004).

[9] P. Joshi *et al.*, *Phys. Lett.* **B595**, 135 (2004).

[10] P. Joshi *et al.*, *Eur. Phys. J.* **A24**, 23 (2005).

[11] P. Joshi *et al.*, *Phys. Rev. Lett.* **98**, 102501 (2007).

[12] J. Timar *et al.*, *Phys. Lett.* **B598**, 178 (2004).

[13] S.J. Zhu *et al.*, *Eur. Phys. J.* **A25**, s01, 459 (2005).

[14] S. Mukhopadhyay *et al.*, *Phys. Rev. Lett.* **99**, 172501 (2007).

[15] T. Koike *et al.*, *Phys. Rev. Lett.* **93**, 172502 (2004); *Phys. Rev.* **C67**, 044319 (2003).

[16] P. Moller *et al.*, *Phys. Rev. Lett.* **97**, 162502 (2006).

[17] Y.X. Luo *et al.*, *Phys. Rev.* **C69**, 024315 (2004).

[18] Y.X. Luo *et al.*, *Phys. Rev.* **C70**, 044310 (2004).

[19] Y.X. Luo *et al.*, *J. Phys. G* **31**, 1303 (2005).

[20] Y.X. Luo *et al.*, *Phys. Rev.* **C74**, 024308 (2006).

[21] I. Stefanescu *et al.*, *Nucl. Phys.* **A789**, 125 (2007).

[22] A. Daniel *et al.*, *Nucl. Instrum. Methods* **B262**, 399 (2007).

[23] C.M. Petrache *et al.*, *Phys. Rev. Lett.* **96**, 112502 (2006).

[24] D. Tonev *et al.*, *Phys. Rev. Lett.* **96**, 052501 (2006).

[25] S. Frauendorf, *Nucl. Phys.* **A677**, 115 (2000).

[26] D. Almehed, S. Frauendorf, submitted to *Phys. Rev.* **C**; `arXiv:0709.0969 [nucl-th]`.

[27] M. Barranger, K. Kumar, *Nucl. Phys.* **A110**, 490 (1968).

[28] D. Almehed, S. Frauendorf, to be published.