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Chiral Degeneracy in Triaxial ^{104}Rh

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Chiral doublet bands based on the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration that achieve degeneracy at spin $I = 17$ in the odd-odd triaxial ^{104}Rh nucleus have been observed. Experimental verification of the interpretation has been tested against specific fingerprints of chirality in the intrinsic system.

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Chirality or handedness is a property that has important consequences in fields of science as diverse as biology, chemistry, and physics. In nuclear physics, the coupling of three mutually perpendicular angular momenta induces structure effects due to chirality [1]. Interesting chiral properties were observed for the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration of proton (π) and neutron (ν) single particle levels in triaxial odd-odd nuclei in the $A \approx 130$ mass region of the chart of atomic nuclei. It is important to show that these chiral symmetry properties are of a general nature and not related only to a specific nuclear mass region. The purpose of this study is to investigate a different region of triaxial nuclei, which necessarily involves a different configuration, to examine the general aspects of chirality in nuclei. The best chiral properties observed to date were discovered in the ^{104}Rh nucleus involving the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration where the valence proton and neutron play opposite roles to those in the $A \approx 130$ region.

Doublet rotational bands related to nuclear chirality were observed in odd-odd nuclei having triaxial shapes. Nuclear chirality results when the angular momenta of the valence proton, the valence neutron, and the core rotation tend to be mutually perpendicular. This occurs when high-j particlelike and holelike orbitals align their angular momenta along the short and long axes of nuclear deformation, respectively, minimizing the interaction energy, and the core-rotation angular momentum is oriented along the intermediate axis because it has the largest (irrotational flow) moment of inertia. The resulting aplanar total angular momentum can be arranged into a left- or a right-handed system, which differs by intrinsic chirality; the two systems are related by the chiral operator, a combination of time reversal and rotation by 180°. When chiral symmetry is thus broken in the intrinsic frame, the necessary restoration of the symmetry in the laboratory frame manifests itself as degenerate doublet $\Delta I = 1$ bands from the doubling of states. The merged states combine the left- and right-handed systems in a way that satisfies the laboratory chiral symmetry requirement.

Effects of chirality for odd-odd nuclei were first observed in the $A \approx 130$ region where triaxial deformations were expected. Two near degenerate bands in ^{134}Pr [2] were observed; microscopic calculations carried out using 3D tilted axis cranking resulted in triaxial deformations and chiral solutions over an extended frequency (spin) range for the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration [3]. Subsequently, experiments on $N = 75$ isotones [4] of ^{134}Pr and neighboring isotones [5] revealed near degenerate partner bands of the $\pi h_{11/2} \otimes \nu h_{11/2}$ yrast bands, suggesting an island of chirality near $A \approx 130$. Since the ^{134}Pr nucleus showed the smallest band separation, a GAMMASPHERE experiment [6] was performed which considerably extended the doublet bands showing the levels $\Delta E \leq 50$ keV apart at spin $I \approx 15\hbar$. The lack of perfect degeneracy ($\Delta E \leq 300$ keV) in several of these doublet bands suggested the possibilities of limited irrotational flow or that the triaxial deformation was not completely stable at $\gamma = 30°$ but perhaps more γ soft allowing planar along with the aplanar chiral components. Quasiparticle excitations within this configuration for a planar geometry would be on the order of 600 keV [7], by a factor of ≈ 10 larger than in ^{134}Pr and by a factor of ≈ 2 larger for other cases in the mass $A \approx 130$ region, and thus clearly cannot explain these near degenerate doublet bands.

To further investigate chiral properties and the underlying triaxial nuclear shapes, the $A \approx 110$ region, which shows γ softness, has been explored using the near yrast $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration. The roles of the proton and neutron in this region are reversed from those in the $A \approx 130$ region in that the $g_{9/2}$ proton is holelike and the $h_{11/2}$ neutron particlelike; thus, the proton hole is aligned along the long axis and the neutron particle along the short axis of the triaxial core. For triaxial core rotation along the intermediate axis, a chiral geometry is again achieved in the intrinsic system. The first nucleus studied in this region was ^{104}Rh, the heaviest Rh isotope easily produced with fusion evaporation reactions. The ^{96}Zr(^{11}B, $3n$) reaction at 38 MeV was used at Stony Brook to populate states in ^{104}Rh. Pulsed beam $\gamma - \gamma - t$ measurements

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were made using our suppressed Ge array with the LINAC to extract the band structure. A partner band approaching degeneracy was discovered that linked to the $\pi g_{9/2} \otimes \nu h_{11/2}$ yrast band. Earlier results for the yrast band were confirmed [8]. Angular correlation analyses were consistent with the two bands being linked by $\Delta I = 1$ $M1/E2$ transitions; thus, if correct and using unique parity arguments, the two bands belong to the same configuration. A time differential perturbed angular distribution (TDPAD) measurement of the magnetic moment of the $T_{1/2} = 42$ ns isomeric 6^- bandhead in ^{104}Rh was performed. The difference/sum ratio $R(t)$ extracted from the observed angular distribution at $\pm 45°$ for the 169 keV delayed transition ($B = 1.41$ T) yielded $g = 0.33(2)$ in good agreement with additivity calculations for the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration [9,10].

Because of the success of these measurements, a GAMMASPHERE experiment using the same reaction at 40 MeV was performed. Figure 1 shows a double-gated coincidence spectrum extracted from data unfolded into a 3D cube; the transitions between members of the ^{104}Rh doublet bands are identified. The g-factor data for the 169-keV delayed transition is inserted in Fig. 1. The resulting expanded doublet-band structure is shown in Fig. 2. Extensive directional correlation from oriented states (DCO) analyses were carried out for the intraband and interband transitions to determine the relative spin and parity of the band structures. The intraband transitions including the crossovers documented the $\Delta I = 1$ nature of the two bands. The three strong linking transitions, 745, 741, and 734 keV, had DCO ratios in agreement with $\Delta I = 1$ $M1/E2$ multipolarities and reasonable positive mixing ratios, although nonstretched $M1/E2$ could not be ruled out with these DCO ratios. Several crossover linking transitions (≥ 1.0 MeV) of reduced relative intensity were also observed with stretched $E2$ characteristics; these linking intensity patterns are consistent only with the relative I^π assignments shown in Fig. 2. A linear polarization measurement of the strong 741-keV transition agrees with the $\Delta I = 1$ $M1/E2$ assignment and also eliminates an $E1$ possibility. These linking transitions between the partner bands and the $\pi g_{9/2} \otimes \nu h_{11/2}$ yrast band prove that both of the doublet bands are of the same configuration. This is based on the fact that transitions between this configuration of two unique parity orbitals with other possible configurations would have to involve a change of both orbitals. Since electromagnetic transitions involve one-body operators, only one orbital can change, and thus the two linked bands have to be of the same $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration.

A sideband of the yrast $\pi g_{9/2} \otimes \nu h_{11/2}$ band having the same parity has been observed in ^{100}Rh, an isotope of ^{104}Rh [11]. Admixtures of spherical shell configuration $\pi p_{1/2} \otimes \nu(d_{5/2}, g_{7/2})$ into the $\pi g_{9/2} \otimes \nu h_{11/2}$ band at higher spins were pointed out in Ref. [11]. However, such admixtures would have to involve a two-body interaction potential which would connect a $p_{1/2}$ and $g_{9/2}$ proton with $\Delta l = 3$ and at the same time a $(d_{5/2}, g_{7/2})$ and $h_{11/2}$ neutron with $\Delta l = 3$ or 1; this is expected to be exceedingly small as a review of the literature indicates. Therefore, the perpendicular $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration is considered to be solely responsible for the partner bands in the odd-odd Rh isotopes.

A theoretical approach involving a phenomenological particle-hole plus rotor model with a rigid triaxial rotor and quadrupole-quadrupole interactions between the core and the valence particles has been applied to odd-odd triaxial nuclei. Since this approach is carried out in the laboratory frame, the Hamiltonian is necessarily chiral invariant. Calculations [12,13] with varying γ deformation yielded degenerate doublet bands when γ approached

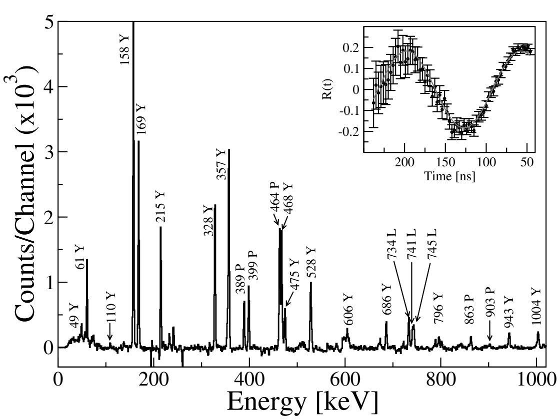

FIG. 1. Sum of double gates: 571/590 keV in the yrast and 486/556 keV in the partner band. The Y, P, and L labels represent Yrast, Partner, and Linking transitions, respectively. The inset shows the 169-keV Larmor precession $R(t)$, measured in a TDPAD experiment at Stony Brook ($B = 1.41$ T).

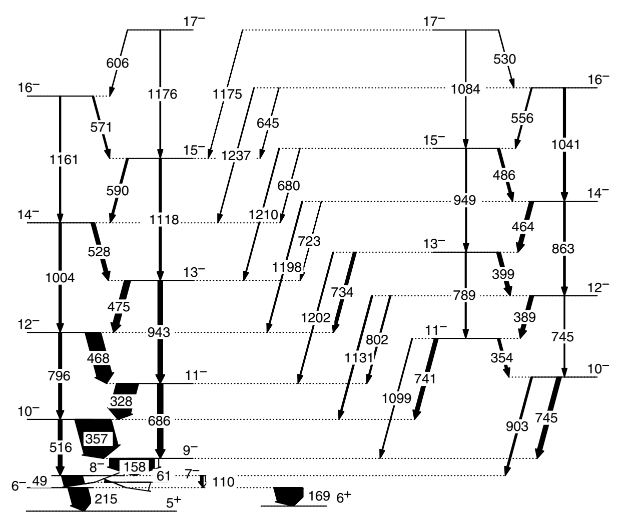

FIG. 2. Partial level scheme showing the $\pi g_{9/2} \otimes \nu h_{11/2}$ chiral bands in ^{104}Rh.

30° in agreement with the experimental results; expectation values of the angular momentum orientation parameter are peaked at $\gamma = 30°$ consistent with the aplanar chiral geometry. Studies involving γ soft cores showed deviations from degeneracy for the doublet bands as seen in this experiment. Similar calculations with pairing have been carried out with success [14].

Properties related to chirality should be independent of the models used. Thus, alternative particle-hole plus rotor calculations have been carried out. The model Hamiltonian consists of a triaxially deformed central potential for a single particle and the rotational energy of the collective core. Together with the maximum triaxiality assumption, the choice of the intermediate axis as the quantization axis resulted in a significant simplification of the wave function. This allowed the examination of chiral characteristics involving energy and electromagnetic properties as a function of spin I [9].

It was shown that, for decreasing spin where the rotational vector becomes small, planar components are admixed with the chiral aplanar components resulting in a gradual increase in the energy separation of the two bands as I decreases. At higher spins, both doublet bands are aplanar yielding the chiral energy degeneracy above a specific spin I. In addition, it was shown that the quantity $S(I) = [E(I) - E(I-1)]/2I$ is independent of spin I in this chiral region identifying an important new criterion for chirality. Qualitatively, this $S(I)$ independence of spin I can be understood by the fact that the two orbital angular momenta are both perpendicular to the rotation axis (intermediate axis) and thus are not affected by the rotation, just as a strongly coupled band built on a particle with angular momentum aligned perpendicular to the rotational axis for an axially symmetric rotor has no signature splitting. With these simplified wave functions, the electromagnetic transition probabilities can also be more clearly examined [9]. The structure of the wave functions imposed by the chiral geometry create important phase consequences from the restoration of chiral symmetry in the laboratory frame. These phases result in $M1$ and $E2$ selection rules which can manifest as $B(M1)/B(E2)$ and $B(M1)_{\rm in}/B(M1)_{\rm out}$ staggering as a function of spin I where $B(M1)_{\rm in}$ and $B(M1)_{\rm out}$ refer to reduced electromagnetic probabilities for intraband and interband $\Delta I = 1$ transitions, respectively, for the partner band. The experimental and theoretical electromagnetic transition comparisons for the $A \approx 130$ chiral region show systematic agreement [15].

The three fingerprints currently established for chirality in odd-odd triaxial nuclei are as follows: (i) near degenerate doublet $\Delta I = 1$ bands for a range of spins I; (ii) $S(I) = [E(I) - E(I-1)]/2I$ independent of spin I; (iii) chiral symmetry restoration $M1$ and $E2$ selection rules vs I. The currently observed properties of the ^{104}Rh doublet bands can be tested against these three

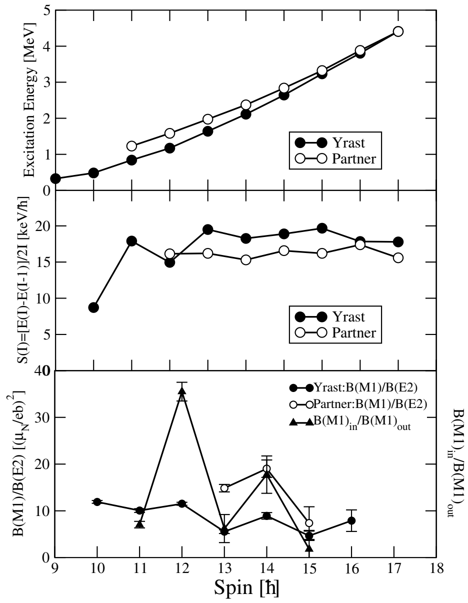

FIG. 3. Chiral fingerprints: (a) excitation energy vs spin; (b) $S(I)$ vs spin; (c) $B(M1)/B(E2)$ and $B(M1)_{\rm in}/B(M1)_{\rm out}$.

chiral fingerprints. The energy separation between the partner bands in ^{104}Rh decreases to less than 2 keV at $I = 17$. A plot of the excitation energies and the $S(I)$ vs spin I are displayed in Fig. 3; these document the first two fingerprints outlined above for chirality, namely, near degenerate doublet bands and a constant $S(I)$ as a function of spin. The reduced transition probability ratios $B(M1)/B(E2)$ and $B(M1)_{\rm in}/B(M1)_{\rm out}$, which were extracted from the data, are shown in the lower part of Fig. 3. The staggering, the third fingerprint, is consistent with theoretical predictions and opposite in phase to those for the $A \approx 130$ region because the proton orbital changed from $h_{11/2}$ to $g_{9/2}$. These three experimental features nicely document the chiral interpretation for this region.

In summary, a new region of chirality has been discovered within the chart of nuclei from studies of the odd-odd ^{104}Rh nucleus involving the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration. Observed chiral doublet bands show the characteristic fingerprints related to the restoration of chiral symmetry in the laboratory frame. Preliminary results on $^{102\,106}$Rh show the existence of similar partner bands, which suggests the possibility of a larger region of chirality near $A \approx 110$.

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