MULTIPLE CHIRAL DOUBLET BANDS IN ^{104}Rh*

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Multiple chiral doublet bands with two different quasiparticle configurations have been identified in the negative-parity band structure of the ^{104}Rh nucleus. Besides the previously reported chiral doublet, which belongs to the $\pi(1g_{9/2})^{-1}\otimes\nu(1h_{11/2})^1$ configuration, a new chiral-candidate band pair has been observed. Comparison of the experimental data with detailed theoretical calculations suggests that the newly observed band pair is also a chiral doublet based on the $\pi(1g_{9/2})^{-1}\otimes\nu(1g_{7/2})^{-2}(1h_{11/2})^1$ configuration.

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1. Introduction

The theoretical description of chirality as a form of spontaneous symmetry breaking was first presented by Frauendorf and Meng in 1997 [1]. Chiral rotation appears in rotating triaxially deformed nuclei. In the case of an odd–odd nucleus, the angular momentum vector of the core rotation at low

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energies aligns along the intermediate axis, for which the moment of inertia is the largest. The angular momentum vector of the particle-type valence quasiparticle aligns with the short axis, while the angular momentum vector of the hole-type one aligns with the long axis. These three angular momenta are mutually perpendicular and can be arranged in the opposite chiral directions, left or right. Experimentally $\Delta I = 1$ band pairs are observed with the same configuration. Thus, their corresponding levels have the same parities, as well as similar energies and electromagnetic behavior. The phenomenon was first identified in four $N = 75$ isotones in 2001 [2]. After this, many chiral nuclei have been reported experimentally in the $A \sim 80$, 100, 130, and 190 mass regions [3–22].

Comparison of the characteristics of chiral doublets in odd-mass nuclei with those of the neighboring odd–odd nuclei highlights the significant role of the triaxial core [19]. This suggests that chiral geometry in a nucleus can remain stable despite the changes in configuration, which raises the possibility of multiple chirality in a single nucleus. Using the adiabatic and configuration-fixed constrained triaxial covariant density functional theory (CDFT) calculations, Meng *et al.* [23–26] demonstrated the possible existence of multiple chirality in a single nucleus, and introduced the MχD abbreviation for it. The first experimentally reported case was the ^{133}Ce [27]. Recently, fivefold chirality has been reported in ^{136}Nd [28] and threefold chirality in ^{131}Ba [29]. Data tables on the experimentally observed chiral and MχD nuclei can be found in Ref. [30]. Previously threefold chirality were reported in the $A \sim 100$ mass region [31]. In ^{103}Rh, two chiral doublets were identified with the same $\pi(1g_{9/2})^{-1} \otimes \nu(1h_{11/2})^1(1g_{7/2})^1$ configurations and an additional chiral doublet with the $\pi(1g_{9/2})^{-1} \otimes \nu(1h_{11/2})^2$ configuration. However, MχD had not been reported in an odd–odd nucleus in the $A \sim 100$ mass region before the start of this work, the results of which are also presented in Ref. [32].

2. Experimental methods and results

An experiment aiming at studying medium- and high-spin states of ^{104}Rh was performed at the Lawrence Berkeley National Laboratory. The ^{104}Rh nucleus was populated in the ^{96}Zr(^{11}B,3n) heavy-ion fusion–evaporation reaction using a beam with an energy of 40 MeV provided by the 88-inch cyclotron. The beam impinged on a 500 μg/cm^2 thick Zr foil. The detector system used to observe the emitted γ rays was the Gammasphere, which consisted of more than 100 hyper-pure germanium detectors arranged spherically. The trigger condition used was four-fold gamma coincidence, and approximately 9×10^8 events were recorded and sorted off-line into 2-d and 3-d histograms.

The collected high-statistics data set enabled us to considerably extend the level scheme of the ^{104}Rh nucleus. Numerous gamma transitions and several new rotational bands were observed. The negative-parity part of the obtained level scheme is plotted in Fig. 1.

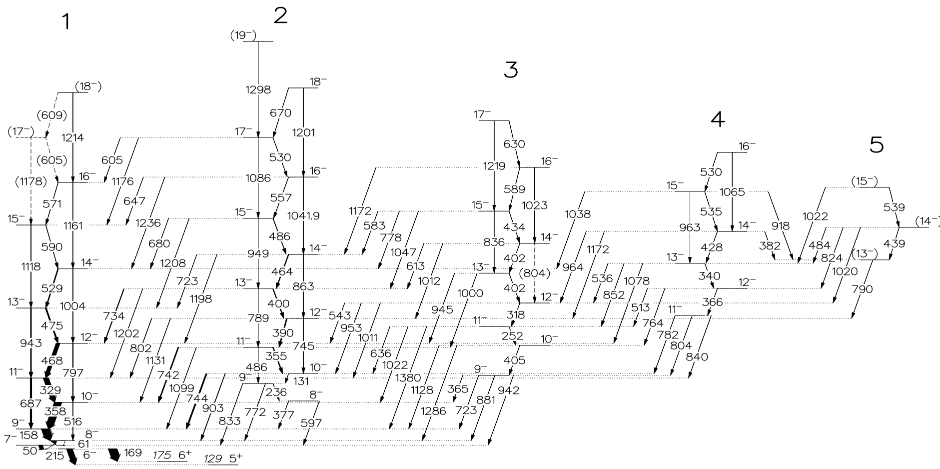

Fig. 1. Negative parity part of the level scheme of ^{104}Rh. Gamma transition energies are given in keV.

The $\gamma\gamma\gamma$-coincidence analysis was performed using the RadWare software package [33]. Figure 2 shows typical $\gamma\gamma\gamma$-coincidence spectra. The spin and parity values of the excited states were determined from the measurements of angular-intensity ratios, based on the method of directional correlation from oriented states (DCO) [34]. It was assumed during the analysis that the quadrupole transitions have E2, while the dipole transitions have M1+E2 multipolarities.

The analysis has been carried out in two steps. As a result of the first step of the analysis, bands 1 and 2 were identified as a chiral band pair with the $\pi(1g_{9/2})^{-1}\otimes\nu(1h_{11/2})^1$ configuration [14]. In the present second step of the analysis, bands 3, 4, and 5 were firmly placed in the level scheme.

The spin-parities of the upper levels in band 3 are based on the E2 character of the 953, 1000, 1012, and 1047 keV transitions, while the spin-parities of the lower levels are based on the dipole character of the 252, 318, and 402 keV transitions. The spin-parity values of the band 4 levels are based on the E2 character of the 804 and 1172 keV transitions. For the levels in the short band 5, we could not derive unambiguous spin and parity values due to the rather low intensity of the depopulating gamma transitions.

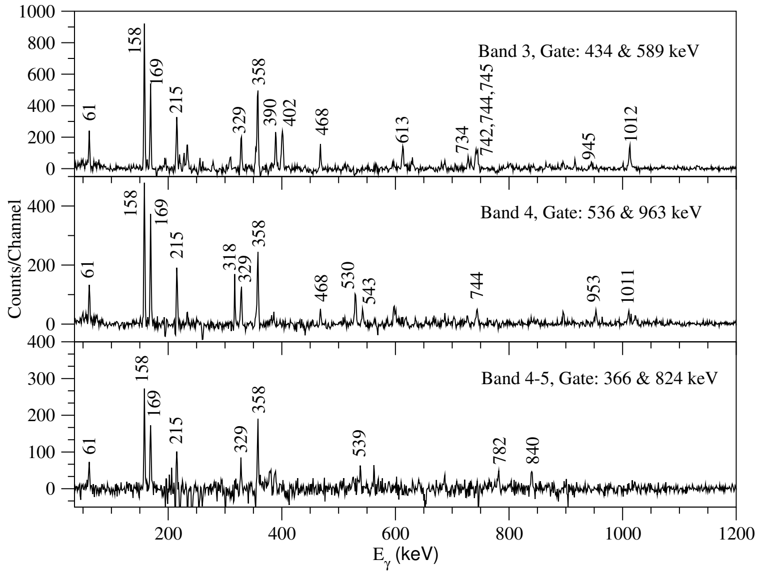

Fig. 2. Typical $\gamma\gamma\gamma$-coincidence spectra obtained showing the placement of the γ rays in bands 3, 4, and 5.

3. Discussion

In order to investigate the possible chiral nature of the new band pair of bands 3 and 4, the adiabatic and configuration-fixed constrained CDFT calculations [23] as well as the quantum triaxial particle rotor model (PRM) [35–39] calculations were performed, and their results were compared with the experimental results. According to the results of the CDFT calculations, it is the $\pi(1g_{9/2})^{-1} \otimes \nu(1g_{7/2})^{-2}(1h_{11/2})^1$ configuration which is expected at low energy with chiral features besides the configuration of the known chiral band pair (bands 1 and 2). The calculated deformation parameters for this configuration are $\beta = 0.26$ and $\gamma = 18.9°$ (see a more detailed comparison in Ref. [32]). PRM calculations were performed for this configuration with the obtained deformation parameters and the calculated quasiparticle alignment, $S(I)$ and $B(\mathrm{M1})/B(\mathrm{E2})$ ratio values were compared with the corresponding experimental values for bands 3 and 4.

The quasiparticle alignments (see definition in [40]) are compared for bands 3 and 4 in Fig. 3. Both bands have quite similar alignment values over a wide frequency range, which suggests that the configuration of the high-j orbitals are the same. The theoretical calculations agree reasonably with the experimental data for the low rotational frequency. For the large rotational frequency, the theoretical alignments show an increasing trend, while the experimental one a decreasing trend. The different trend might be attributed to that the theoretical calculations are done with a fixed configuration.

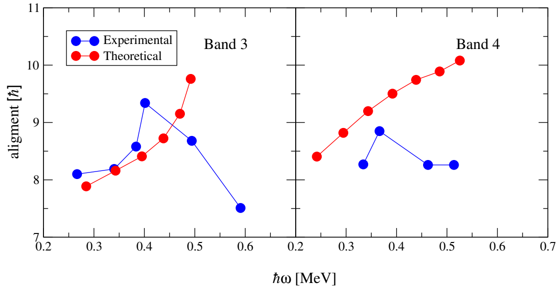

Fig. 3. Comparisons between the experimental and theoretical quasiparticle alignments of bands 3 and 4 calculated using $K = 4\ \hbar$ and the Harris parameters $\mathcal{J}_0 = 8.9\ \hbar^2/\mathrm{MeV}$ and $\mathcal{J}_1 = 15.7\ \hbar^4/\mathrm{MeV}^3$.

Figure 4 shows a comparison between the theoretical and the experimental staggering parameter $S(I) = [E(I) - E(I-1)]/2I$ and $B(\mathrm{M1})/B(\mathrm{E2})$ ratios. In the PRM calculations, the moment of inertia is adopted as irrotational flow type $\mathcal{J}_k = \mathcal{J}_0 \sin^2(\gamma - 2k\pi/3)$, with $\mathcal{J}_0 = 24\ \hbar^2/\mathrm{MeV}$ for bands 3 and 4. This value is adjusted to reproduce the energy spectrum of the doublet bands. For the electromagnetic transitions, the empirical intrinsic quadrupole moment $Q_0 = (3/\sqrt{5\pi})R_0^2 Z\beta$ is used, where $R_0 = 1.2A^{1/3}$ fm. Additional parameters include the gyromagnetic ratio $g_R = Z/A = 0.44$, along with g-factors: $g_\pi(g_{9/2}) = 1.26$, $g_\nu(h_{11/2}) = -0.21$, $g_\nu(g_{7/2}) = 0.70$, and $g_\nu(d_{5/2}) = -0.46$. Both the PRM calculations and the experimental data follow the expected similar electromagnetic behavior and the approximately constant staggering parameter for bands 3 and 4, which are the

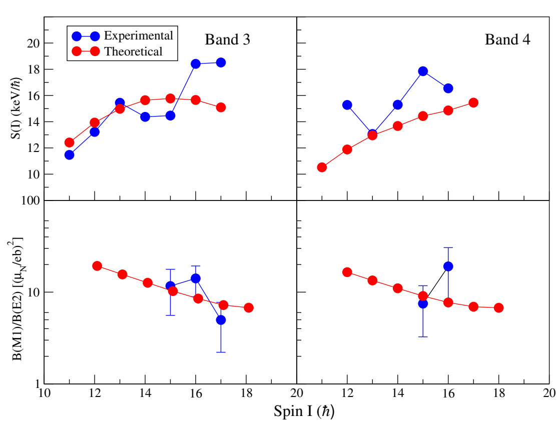

Fig. 4. Comparisons between the experimental and theoretical staggering $S(I) = [E(I) - E(I-1)]/2I$ parameters, and ratios of reduced transition probabilities $B(\mathrm{M1})/B(\mathrm{E2})$ for the doublet bands 3 and 4 in ^{104}Rh.

fingerprints of chirality. As illustrated in Fig. 4, the PRM calculations agree with the experimental data, thus supporting the chiral nature of the newly observed doubet bands, and consequently the existence of MχD in ^{104}Rh.

4. Conclusion

In summary, the level scheme of negative parity part of ^{104}Rh has been extended with three new bands. We found that two of these three bands probably form a chiral doublet. In order to explore the presence of MχD in this nucleus, the properties of bands 3 and 4 have been compared with results of adiabatic and configuration-fixed constrained CDFT and triaxial PRM calculations. We arrived at the conclusion that in addition to the reported chiral doublet bands 1 and 2 with $\pi(1g_{9/2})^{-1} \otimes \nu(1h_{11/2})^1$ configuration, bands 3 and 4 also exhibit chiral structure with $\pi(1g_{9/2})^{-1} \otimes \nu(1g_{7/2})^{-2}(1h_{11/2})^1$ configuration. This is the first experimental evidence of multiple chirality in an odd–odd nuclide in the $A \sim 100$ mass region.

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