Candidates for Twin Chiral Bands in ^{102}Rh

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Excited states in ^{102}Rh, populated in the fusion-evaporation reaction ^{94}Zr(^{11}B, 3n)^{102}Rh at a beam energy of 36 MeV, were studied using the Indian National Gamma Array spectrometer at Inter University Accelerator Center, New Delhi. The angular correlations and the electromagnetic character of some of the gamma-ray transitions observed were investigated in detail. A new chiral candidate sister band was found. Lifetimes of exited states in both chiral candidate bands of ^{102}Rh were measured for the first time in the $A \sim 100$ mass region by means of the Doppler-shift attenuation technique. The derived reduced transition probabilities are compared to the predictions of the two quasiparticles plus triaxial rotor model. Both experimental results and calculations do not support the presence of static chirality in ^{102}Rh.

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Chirality is a phenomenon which is often found in nature. Examples of systems demonstrating chirality are present in chemistry, biology, high energy physics, etc. An interesting question arose last decade in nuclear physics, does chirality exists in this field? It is a novel feature of rotating nuclei which is among the most studied phenomena during the recent years. A spontaneous breaking of the chiral symmetry can take place for configurations where the angular momenta of the valence protons, valence neutrons, and the core are mutually perpendicular [1]. Under such conditions, the angular momenta of the valence particles are aligned along the short and long axes of the triaxial core, while the angular momentum of the core is aligned along the intermediate axis. The projections of the angular momentum vector on the three principal axes can form either a left-or a right-handed system and therefore, the system expresses chirality. Since the chiral symmetry is dichotomic, its spontaneous breaking by the axial angular momentum vector leads to a pair of degenerate $\Delta I = 1$ rotational bands, called chiral doublet bands. Pairs of bands, presumably due to the breaking of the chiral symmetry in triaxial nuclei, have been recently found in the mass regions $A \sim 130$ [2,3], $A \sim 105$ [4–7], $A \sim 195$ [8], and $A \sim 80$ [9]. However, only in few cases (^{126}Cs [10], ^{128}Cs [11]), the systematic properties [12] of the chiral bands, which originate from the underlying symmetry, were confirmed including the transition from chiral vibrations to static chirality in ^{135}Nd [3]. Thus, the yrast and side bands should be nearly degenerate. Characteristic selection rules for electromagnetic transitions, as discussed, e.g., in [13–15], provide a fingerprint of the ideal static chirality. In the region where the chiral symmetry sets in, the $B(E2)$ values of the electromagnetic transitions deexciting analog states of the chiral twin bands should be almost equal. Correspondingly, the $B(M1)$ values should exhibit odd-even staggering. The $B(M1)$ values for $\Delta I = 1$ transitions connecting the side to the yrast band should have odd-even staggering which is out of phase with respect to the $B(M1)$ staggering for transitions deexciting states in the yrast band. In many cases, the energy degeneracy of the chiral candidate bands is nearly observed but the corresponding transition probabilities are different, as in the case of ^{134}Pr [16,17].

The main goal of the present Letter was to check for the existence of chirality in the mass region $A \sim 100$. In previous works [4–6], an island of chiral candidates has been proposed around ^{104}Rh. The existing lifetime measurements in the nuclei ^{103,104}Rh do not report lifetime values in both chiral candidate bands [6]. Also, an interesting phenomenon was reported in the work [6] for the yrast band. The staggering of the $B(M1)/B(E2)$ ratios observed in Refs. [4,5] is due to a variation of the $B(E2)$values, while the $B(M1)$ transition strengths are showing a decreasing behavior. Therefore, it is very important to perform lifetime measurements in both chiral candidate bands in the mass region $A \sim 100$. Theoretical studies of the chiral phenomenon within the framework of the adiabatic and configuration-fixed constrained triaxial relativistic mean field (RMF) approaches have been recently performed in order to investigate the triaxial shape coexistence and possible chiral doublet bands [18]. A new phenomenon, the existence of multiple chiral doublets, i.e., more than one pair of chiral doublet bands in one single nucleus has been predicted for ^{106}Rh [18] and neighboring nuclei [19]. It has been recently confirmed in another mass region, $A \sim 130$, for ^{133}Ce [20]. The nucleus of ^{102}Rh, according to the work of Meng *et al.* [18], is one of the candidates to present such a phenomenon. All these recent results stimulated our work to check for the existence of chirality in ^{102}Rh.

Excited states in ^{102}Rh were populated using the reaction ^{94}Zr(^{11}B, 3n)^{102}Rh at a beam energy of 36 MeV. The beam was delivered by the 15-UD Pelletron accelerator at the Inter University Accelerator Center (IUAC) in New Delhi [21,22]. The target consisted of 0.9 mg/cm^2 ^{94}Zr, enriched to 96.5%, evaporated onto a 8 mg/cm^2 gold backing. The recoils were leaving the target with a mean velocity v of about 0.9% of the velocity of light, c.

The deexciting gamma rays were registered by the Indian National Gamma Array (INGA), whose 15 clover detectors are accommodated in a 4π geometry [23]. For the purposes of the Doppler-shift attenuation method (DSAM) analysis, the detectors of INGA were grouped into rings with approximately the same position with respect to the beam axis. The rings where appreciable Doppler shifts are observed are these at angles of 32°, 57°, 123°, and 148°. Gain matching and efficiency calibration of the Ge detectors were performed using ^{152}Eu and ^{133}Ba radioactive sources before sorting the data in matrices and cubes.

In order to investigate the level scheme and electromagnetic properties of the transitions of interest in ^{102}Rh, we have performed four types of data analyses. Such complex approach is employed for the first time in the case of the investigation of chirality in nuclei. The ordering of the transitions in the level scheme was determined according to γ-ray relative intensities, γ-γ coincidence relationships, and γ-ray energy sums. The electric or magnetic character and multipolarity of the transitions were deduced by linear polarization and angular correlations measurements, respectively. We need to stress that the presently observed level scheme of ^{102}Rh is very rich and the information on the line shapes of consecutive transitions (i.e., effective lifetimes) was also used to construct the new band 2 indicated in Fig. 1. The lifetimes were derived by using the DSAM.

The angular correlation function for two successive transitions from oriented states depends on the spins of initial, intermediate, and final levels, and on the multipole mixing ratios [24]. The angular correlations are subject to symmetries which allow us to order the pairs of detectors in unique geometry groups specific for the multidetector spectrometer used (in our case, 25 correlations groups). In the present work, the angular correlation analysis was carried out with the computer code CORLEONE [25]. The spins of the members of the new band 2 were determined

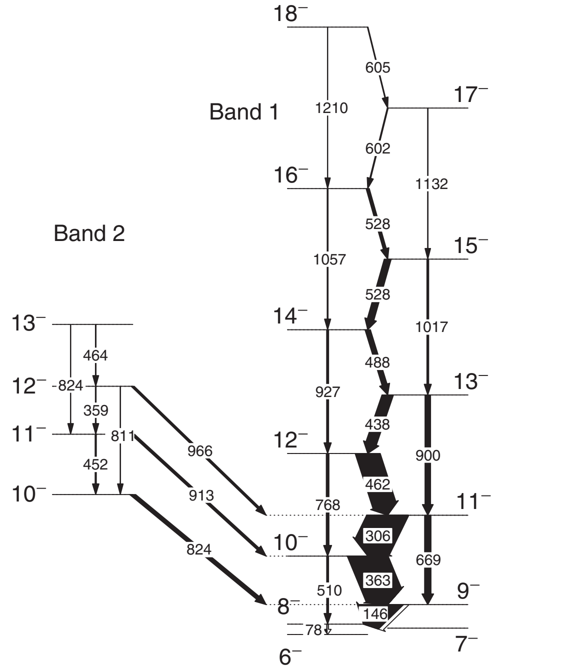

FIG. 1. Partial level scheme of ^{102}Rh. Two negative-parity bands, candidates for chiral partner bands, are indicated as band 1 and band 2. The states of band 2 are reported for the first time in the present Letter.

through investigation of different spin hypotheses for the cascades involving transitions in band 2 and transitions linking the chiral candidate bands. In Fig. 2, the angular correlation pattern involving the 452 and 824 keV transitions is shown. The best fit confirms the spin hypothesis $11^-_2 \rightarrow 10^-_2 \rightarrow 9^-_1$. The present Letter is the first application of angular correlation analysis at the INGA spectrometer. Complementary details on the analysis for ^{102}Rh have been presented in [26].

In the present experiment, we used the four clover detectors from the ring at 90° with respect to the beam axis as one composite Compton polarimeter. The coincidence signals from the respective arms of the polarimeter,

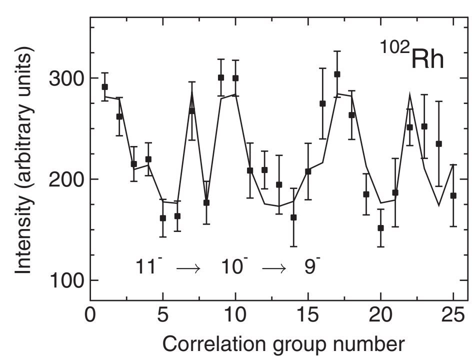

FIG. 2. Angular correlation pattern for the cascade involving the 452 keV and 824 keV transitions. The best fit shown with a line corresponds to the spin hypothesis $11^-_2 \rightarrow 10^-_2 \rightarrow 9^-_1$.

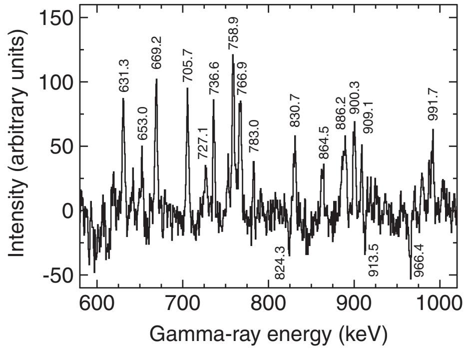

FIG. 3. The difference of the coincidence spectra registered by the perpendicular and parallel arms of the composite Compton polarimeter indicates predominantly magnetic or electric character of the transitions. It is clearly seen that transitions with energies 824.3, 913.5, and 966.4 keV have magnetic character.

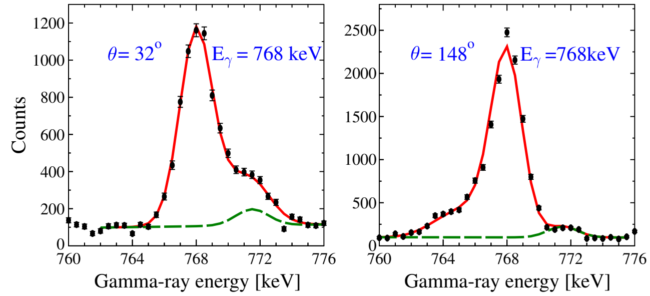

FIG. 4 (color online). Fits of line shapes of the transition of 768 keV in band 1 of ^{102}Rh at angles of 32° and 148°. A contaminating peak at energy of 772 keV is also indicated.

perpendicular and parallel to the reaction plane, were summed up to improve the statistics. The difference spectrum in Fig. 3 reflects the linear polarization of the transitions observed. The negative lines correspond to transitions of predominantly magnetic character while the positive lines correspond to transitions of predominantly electric character. The electromagnetic character of all previously known transitions was confirmed. As clearly seen, the transitions of 824 and 966 keV linking the two bands have predominantly magnetic character ($M1$) which leads to the assignment of negative parity to band 2. In this way, the level scheme shown in Fig. 1 was derived.

The Doppler-shift attenuation method was utilized to determine the lifetimes of excited states in ^{102}Rh. The analysis was carried out within the framework of the differential decay curve method [27] according to the procedure outlined in [28] where details about the Monte-Carlo simulation of the slowing down process, determination of stopping powers, and fitting of line shapes can be found. For each level, lifetimes were derived independently at the four rings with appreciable Doppler shifts. Examples of such analysis are shown in Fig. 4. The lifetimes of the levels with I^π from 11_1^- to 16_1^- and from 10_2^- to 11_2^- have been deduced for the first time. Their final values, obtained by averaging while paying attention to systematic errors are presented in Table I.

Thus, we have succeeded to extend the known level scheme [29] by a new $\Delta I = 1$ band with a negative parity and to determine eight new lifetimes. The present results come to supercede the preliminary level scheme published in [30].

As shown in previous works (e.g., [31] and references therein) for odd-odd Rhodium isotopes around ^{106}Rh, the intrinsic structure of the yrast 6^- level is based on a $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration. To study the bands build on this configuration, we have performed two quasiparticles + triaxial rotor (TQPTR) calculations in the framework of the model presented in Ref. [32]. The Hamiltonian of this model includes the rotational energy of the core, the quasiparticle energies of the odd proton (π) and neutron (ν), and a residual proton-neutron interaction $V_{\pi\nu}$. The core is treated as a rigid body with a fixed overall quadrupole deformation ϵ and a triaxiality parameter γ. More details about the single-particle states involved and the Nilsson parameters used can be found in Ref. [31]. The parameters ϵ and γ were varied until a reasonable fit of the energies and transition probabilities in the lowest two negative-parity bands was obtained for the values of $\epsilon = 0.25$ and $\gamma = 20°$. It should be mentioned that for $\gamma = 30°$ (pure triaxial core), unrealistically large values of ϵ are needed to reproduce the $B(E2)$ transition strengths characterizing the levels at the bottom of the yrast band.

The optimal value of $\epsilon = 0.25$ is slightly higher than the mean deformation derived from the $B(E2, 2_1^+ \rightarrow 0_1^+)$ transition strengths in the four neighboring even-even nuclei ($\epsilon \approx 0.19$) which points to core-polarization effects of the odd proton and neutron. Our values of the quadrupole deformation parameters are consistent with the values predicted in Ref. [18] by means of constrained triaxial relativistic mean filed (RMF) calculations for ^{102}Rh ($\epsilon_{\rm RMF} \sim 0.22$, $\gamma_{\rm RMF} \sim 18°$) which take automatically into account such effects. To reproduce the band structures, the energy $E_{2_1^+}$ of the first excited state of the even-even core and the attenuation ζ of the Coriolis interaction were varied until the optimal values of $E_{2_1^+} = 180$ keV and $\zeta = 0.6$

TABLE I. Derived lifetimes τ in band 1 and band 2 of ^{102}Rh. The energies of the levels and analysed γ-ray transitions are given in keV.

band 1				band 2			
$E_{\rm level}$	I^π	E_γ	τ [fs]	$E_{\rm level}$	I^π	E_γ	τ [fs]
1576	11_1^-	669	458(44)	1731	10_2^-	824	163(52)
2038	12_1^-	768	227(58)	2183	11_2^-	913	156(60)
2477	13_1^-	900	320(71)				
2965	14_1^-	488	170(25)				
3494	15_1^-	1017	117(39)				
4022	16_1^-	1057	68(14)				

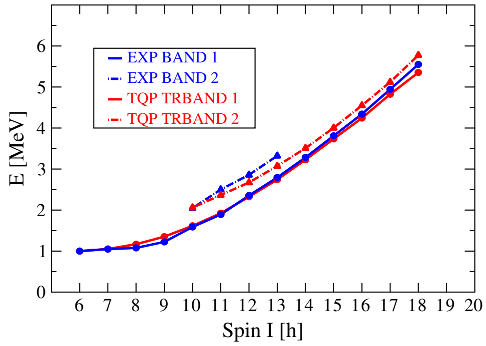

FIG. 5 (color online). Energies of the levels in the chiral candidate bands of ^{102}Rh as a function of the spin I compared to the results of the TQPTR calculations.

were adopted. Finally, the strength of the V_{pn} interaction was optimized and the best agreement was found for the values of the parameters $u_0 = -0.9$ MeV and $u_1 = -0.1$ MeV (see Ref. [33]). The standard model values [32] of the pairing strengths were reduced by 5% to account for the oddness of the neutron and proton systems. In the TQPTR calculation, both yrast and yrare negative-parity bands, the two candidates for chiral twin bands, are based on the 11th proton orbital with positive parity and on the 14th neutron orbital with negative parity. They originate from the $\pi g_{9/2}$ and $\nu h_{11/2}$ subshells and are associated at $\gamma = 0°$ with the Nilsson configurations $7/2^+[413]$ and $1/2^-[550]$, respectively. The dominant K component (K being the projection of the angular momentum on the z axis of the nucleus) for the yrast band is $4\hbar$ and for the yrare band $6\hbar$. This may point to the presence of different core excitations in the structure of the two bands, with the γ band of the even-even core giving essential contribution to the yrare band in odd-odd ^{102}Rh. An overall agreement is observed between the experimental and calculated level schemes of the two lowest negative parity bands. This is illustrated by the energies of the levels displayed in Fig. 5 as a function of the spin I.

Some fine details as the compression of the levels on the bottom of the bands are not reproduced, which may be related to the quadrupole deformation and the triaxiality undergoing some evolution with increasing spin as predicted for ^{102}Ru on the basis of cranked Hartree-Fock-Bogoliubov calculations [34]. The calculated transition strengths are compared to the experiment in Fig. 6. The theoretical $B(E2)$'s reproduce quite well the absolute values and the increasing trend of the experimental data after spin I $= 14\hbar$. At lower spins, the description is worse since the rigid rotor approach cannot explain the small drop of the experimental values between spins 9 and $13\hbar$. It should be mentioned that the behavior of the $B(E2)$ transition strengths in ^{102}Rh is very similar to what has been observed in ^{134}Pr [16].

The comparison between the experimental and calculated $B(M1)$ transition strengths leads to the conclusion that the TQPTR calculations reproduce roughly the data in

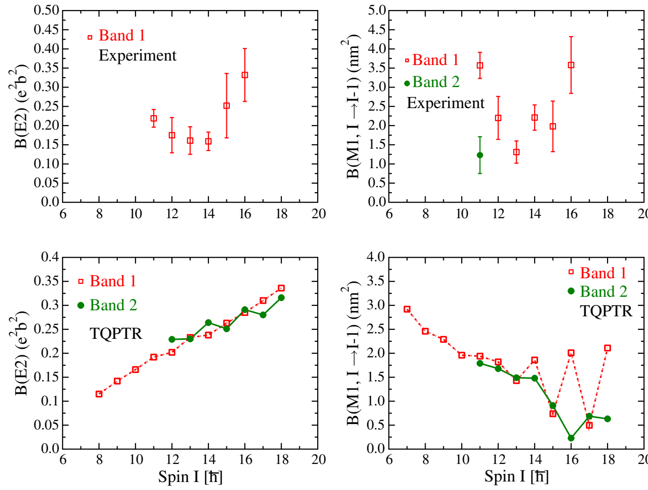

FIG. 6 (color online). Experimentally derived and theoretically calculated $B(E2)$ and $B(M1)$ transition strengths in chiral candidate bands of ^{102}Rh. In the upper panels are presented experimental $B(E2)$ and $B(M1)$ values for transitions in band 1 and band 2. In the second row, the results of TQPTR calculations are displayed.

band 1 and are consistent with the transition strength in band 2 at spin $11\hbar$. The absence of an appreciable staggering of the data in band 1 indicates that the expectations for the observation of a static chirality in ^{102}Rh are not realized. Also, the TQPTR calculations reveal that the optimum value of the triaxiality parameter $\gamma = 20°$ differs from the value of 30° characterizing the static chiral case. It should be noted, however, as commented in [35], that for the asymmetric configuration $\pi g_{9/2} \otimes \nu h_{11/2}$, the best chirality occurs at $\gamma = 27°$. The differences in the core contributions to the yrast and yrare negative-parity bands mentioned above point that dynamic effects as coupling of the quasiparticles to fluctuations of the shape of the core may lead to differences in the properties of these two bands.

It is interesting to note the different behavior of the experimental transition strengths within the chiral candidate bands in ^{102}Rh and some neighboring nuclei (^{103}Rh [4], ^{104}Rh [6]). Thus, the staggering of the experimental $B(E2)$ values in the yrast band observed [6] in ^{104}Rh is not seen in ^{102}Rh. Instead, some staggering of the $B(M1)$ transition strengths is observed, coming close to the expectations of the present TQPTR calculations. These differences point to the influence of fine nuclear structure effects as occupation of valence subshells on the electromagnetic properties of the chiral candidate bands.

In summary, our Letter presents for the first time in the $A \sim 100$ mass region an unique data set providing information on electromagnetic transition strengths in both chiral candidate bands. Our lifetime measurements and the theoretical analysis do not support static chirality in ^{102}Rh. This means that the chirality in ^{102}Rh, if it exists, has mainly a dynamical character. Thereby, the coupling due to shape fluctuations may play a central role [12,16,17] but chiral vibrations cannot also be excluded [3,36–38].

Further experimental work is needed in order to find realizations of static chirality in real nuclei where dynamic effects obscure the pure observation of this phenomenon.

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