Level scheme investigation of $^{102}$Rh

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Abstract. Excited states in $^{102}$Rh were populated in the fusion-evaporation reaction $^{96}$Zr($^{11}$B, 3n)$^{102}$Rh. 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 in the level-scheme of $^{102}$Rh.

1. Introduction

Chirality is a novel feature of rotating nuclei which is among the most studied phenomena in nuclear physics during the last decade. 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. In such a case 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 momentum vector leads to a pair of degenerate $\Delta I = 1$ rotational bands, called chiral doublet bands. Pairs of bands, possibly due to the breaking of the chiral symmetry in triaxial nuclei, have been recently found in the mass regions $A \sim 130$ [2, 3, 4], $A \sim 105$ [5, 6, 7, 8, 9] and $A \sim 195$ [10].

Due to the underlying symmetry, the pair of chiral twin bands should exhibit systematic properties [11]. The yrast and the side bands should be nearly degenerate. In the region where chiral symmetry sets up the $B(E2)$ values of the electromagnetic transitions de-exciting analogous 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 de-exciting states in the yrast band. The last condition means that the $B(M1)_{1n}/B(M1)_{Out}$ staggering in the side band should be in phase with the
B(M1) staggering in the yrast band. In many cases the energy degeneracy of the twin chiral bands is observed but the transition probabilities are different, like in the case of $^{134}$Pr [12, 13].

The goal of the present work is to check for existence of a chiral sister band of the yrast band in the nucleus of $^{102}$Rh. In previous works [5, 6, 7], an island of chiral candidates has been proposed around $^{104}$Rh. Next to identification of the twin chiral bands some lifetimes have been reported for the yrast band of $^{104}$Rh [7]. 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 [14]. 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 and neighboring nuclei. The $^{102}$Rh nucleus, according to the work of Meng et al. [14], is one of the candidates to present such a phenomenon. These results stimulated our work to check for existence of chirality in $^{102}$Rh.

2. Experiment

Excited states in $^{102}$Rh were populated using the reaction $^{96}$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 in New Delhi. The target consisted of 0.9 mg/cm$^2$ $^{94}$Zr, enriched to 96.5%, which was evaporated onto a 8 mg/cm$^2$ gold backing. The recoils were leaving the target with a mean velocity $v$ of 0.9(1)\% of the velocity of light, $c$. The type of the target and backing were chosen such in order to ensure lifetime determination in the sub-picosecond region using the Doppler-Shift Attenuation Method (DSAM).

The de-exciting gamma-rays were registered by the Indian National Gamma Array (INGA), whose 15 Clover detectors were accommodated in a 4\pi geometry [15]. For the purposes of the 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 degrees. Gain matching and efficiency calibration of the Ge detectors were performed using $^{152}$Eu and $^{133}$Ba radioactive sources.

The events were unfolded and sorted into different $\gamma$-$\gamma$ coincidence matrices. For the lifetime analysis, matrices were constructed where one of the gamma-rays was detected at an angle with a significant Doppler-shift whereas on the other axis detection by all detectors of INGA was allowed. To measure intensities, a matrix was constructed where the gamma-rays were detected on both axes by all detectors of INGA.

3. Data analysis and results

3.1. Angular correlation analysis

The angular correlation function $W(\theta_1, \theta_2, \phi)$ for a cascade of two consecutive transitions describes the probability to register, in coincidence, two $\gamma$ rays emitted from an excited nucleus at angles $\theta_1$ and $\theta_2$ with respect to the beam axis and angle $\phi$ between the two scattering planes. The angular correlation function is given by the expression:

$$W(\theta_1, \theta_2, \phi) = \sum_{\lambda_1, \lambda_2} B_{\lambda_1}(I_1) A_{\lambda_1}^{\lambda_1 \lambda_2}(\gamma_1) A_{\lambda_2}^{\lambda_2}(\gamma_2) H_{\lambda_1, \lambda_2}(\theta_1, \theta_2, \phi)$$

This function mainly depends on the spins of the initial, intermediate, and final states, on the multiplicities of the transitions and their multipole mixing ratios. The term $B_{\lambda_1}(I_1)$ describes the orientation of the upper nuclear state, the term $A_{\lambda_1}^{\lambda_1 \lambda_2}(\gamma_1)$ the orientation of the intermediate state due to emission of $\gamma_1$, and $A_{\lambda_2}^{\lambda_2}(\gamma_2)$ the emission of $\gamma_2$. With $H_{\lambda_1, \lambda_2}(\theta_1, \theta_2, \phi)$ is denoted the angular function. It is reduced to an ordinary Legendre polynomial if any of the $\lambda$'s vanishes. Detailed information about the angular correlation function and the theoretical formalism behind it can be found in [16].
The angular correlation function is subject to certain symmetries. Accordingly, the pairs of detectors can be sorted in unique geometry groups, which are characteristic of the multidetector spectrometer used. In the present work the angular correlation analysis was carried out with the computer code CORLEONE [17]. This code allows to determine the geometry groups of the spectrometer as well. Twenty five unique geometry groups were found for the INGA spectrometer. The large number of correlation groups ensures precise determination of the multipole mixing coefficients.

In theory, the $\gamma$-$\gamma$ coincidence matrices obtained for all pairs of detectors from one geometry group should be the same and therefore can be summed-up to improve the signal-to-noise ratio. In practice though this is far from being true because each detector has a different efficiency curve. Furthermore, the efficiency of the detectors under high load (during the experiment) may differ [18] from the efficiency found with standard sources. Therefore, besides determining the shape of the efficiency curves with the sources, one has to adjust their height as appropriate to the experimental conditions by using a set of lines of the sample itself as an internal intensity standard. The quality of the efficiency calibration should then be evaluated by applying angular correlation analysis to a known cascade of pure $E2$ transitions. Two cascades, $4_1^+\rightarrow 2_1^+\rightarrow 0_1^+$ and $6_1^+\rightarrow 4_1^+\rightarrow 2_1^+$, in the even-even nucleus of $^{102}$Ru were chosen by us as the most appropriate for the evaluation.

The quality of the efficiency calibration of the detectors is demonstrated in Fig. 1, where the good fit between the experimental results for the angular correlation function and the theoretical predictions are clearly seen. The same approach was applied to investigate data from a GASP experiment and it provided excellent results [19]. We need to stress that this is the first experiment where angular correlation analyses are performed using the approach [17]. The results obviously are very successful.

![Figure 1](image.png)

**Figure 1.** Angular correlation patterns for the cascades $4_1^+\rightarrow 2_1^+\rightarrow 0_1^+$ (on the left hand side) and $6_1^+\rightarrow 4_1^+\rightarrow 2_1^+$ (on the right hand side) involving transitions of $^{102}$Ru. For these spin hypotheses, the best fit confirms the pure $E2$ character of the transitions.

3.2. **Linear polarization measurements**

Each clover detector is made up of four Ge segments that are packed together side by side. Photons that are Compton scattered in one segment can be detected efficiently in an adjacent segment. The scattering is polarization sensitive. The gamma-rays are more efficiently scattered perpendicularly to their polarization. The mutually perpendicular pairs of segments of one Clover detector therefore form a four-fold Compton polarimeter. The efficiency with which the
pairs of segments of one Clover detector register the Compton scattering events was determined with the $^{152}$Eu and $^{133}$Ba sources that emit gamma rays of natural polarization isotropically.

![Graph](image)

**Figure 2.** Sum (on the left hand side) and difference (on the right hand side) of the coincidence spectra registered by the perpendicular and parallel arms of the composite Compton polarimeter.

In the present experiment we used all the four Clover detectors from the ring at 90 degrees with respect to the beam as one composite Compton polarimeter. The coincidence signals from the respective arms of the polarimeter, perpendicular and parallel to the reaction plane, were summed-up to improve the statistics. The sum and difference of the coincidence spectra, registered by the perpendicular and parallel arms of the composite polarimeter, are shown in Fig. 2. The difference spectrum in Fig. 2 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. For example, the negative lines that appear around 305.8 and 363.0 keV in Fig. 2 are due to $M1/E2$ transitions in $^{102}$Rh [20]. According to DCO ratios measurements [20], the lines around 283.3, 334.4, 352.1 and 385.4 keV are due to transitions of dipolar character in $^{102}$Rh. The positive sign of these lines in the linear polarization spectrum, Fig. 2, proves that the corresponding transitions are of predominantly electric ($E1/M2$) character.

The results obtained from linear polarization measurements were essential for the spin and parity assignments of the new candidate for chiral sister band in $^{102}$Rh. These results are published at the present work for the first time. The newly established level-scheme of the $^{102}$Rh will be published in a forthcoming paper [21].

4. Conclusions

In order to investigate the level-scheme and to determine lifetimes of the excited states in the chiral candidate nucleus of $^{102}$Rh we have performed an experiment at the IUAC in New Delhi using the INGA spectrometer. The usual way of ordering of transitions in a level-scheme is according to the $\gamma$-ray relative intensities, the $\gamma-\gamma$ coincidence relationships, and the $\gamma$-ray energy sum. Next to these approaches we have used for the first time for INGA spectrometer the powerful techniques of angular correlation analysis [17] and linear polarization measurements. Based on the known transitions of the level-scheme published in [20] we have succeeded to extend the level-scheme with a new $\Delta I = 1$ band with a negative parity. The comparison of the excitation energies of the analogous states of the two sister bands in $^{102}$Rh together with their electromagnetic properties will give an answer whether the chiral phenomenon is present in this nucleus [21].
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