Structure of Dipole Bands in ^{112}In: Through Lifetime Measurement

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Abstract. High-spin states of the ^{112}In nucleus have been populated via ^{100}Mo(^{16}O, p3n) reaction at 80 MeV beam energy. Lifetimes of excited states of dipole bands have been measured using Doppler-shift attenuation method. The B(M1) transition rates deduced from the measured lifetimes show a rapid decrease with increasing angular momentum. The decrease in B(M1) values are well accounted by the prediction of tilted axis cranking calculations. These measurements confirm the presence of shears mechanism in this nuclei.

1. Introduction

Experimental investigation of the high spin states of nuclei near A$\sim$110 have provided interesting and new features of novel nuclear excitations, like magnetic, anti-magnetic and chiral rotations[1, 2]. Magnetic rotational bands are observed in nuclei having high-spin particles and holes coupled to a near-spherical core [3, 4]. The nuclei in this region exhibit shears bands due to the occupancy of valence protons and neutrons in $g_{9/2}$ and $h_{11/2}$ orbitals, respectively. Such high-j orbitals are now well known for the generation of rotation-like sequences of M1 transitions called shears bands [5]. It was reported in Ref. [6] that the sequences of M1 transitions are regular for $56 < N < 62$ in A$\approx$110 mass region. Recently, the level scheme of ^{112}In published in Ref. [7, 8] indicated the presence of the regular magnetic dipole bands with increasing neutron number up to N = 63. Lifetime measurements are crucial for understanding the mechanism of generation of these dipole bands. The present experiment was performed using ^{100}Mo(^{16}O, p3n) reaction to have higher recoil velocity required for lifetime measurements using Doppler-shift attenuation method (DSAM). In addition, directional correlation of oriented states (DCO) and integrated polarization direction correlation (IPDCO) analysis have been carried out to establish the spin and parity of different bands required for detailed understanding of their configurations. The transition strengths derived from the lifetime measurements have been compared with the initial results of tilted axis cranking (TAC) calculations [9, 10] for confirmation of shears mechanism.

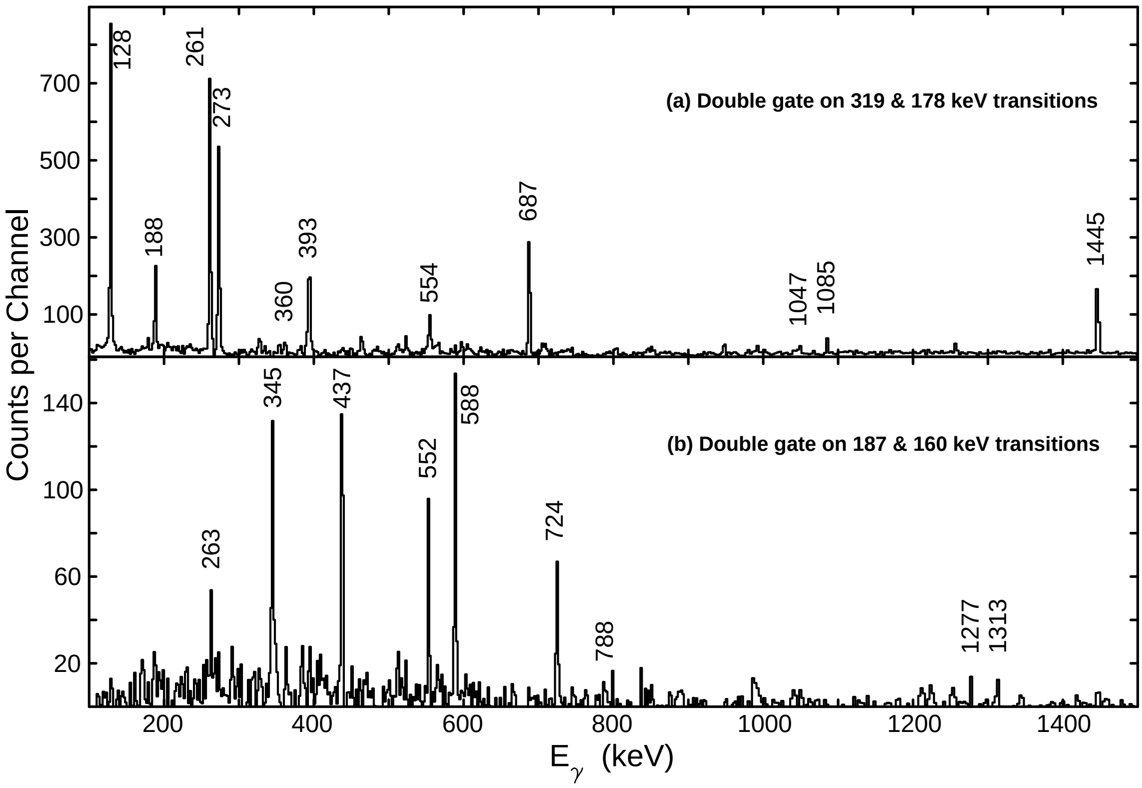

Figure 1. Double gated γ- ray coincidence spectra obtained by (a) gates on 319 and 178 keV transitions and (b) 187 and 160 keV transitions, showing the transitions of positive and negative-parity bands, respectively. Peaks associated with ^{112}In are labeled with their energies in keV.

2. Experimental Methods

High spin states in ^{112}In were populated using the ^{100}Mo(^{16}O, p3n)^{112}In reaction at 80 MeV beam energy. The ^{16}O beam was provided by 15-UD Pelletron accelerator at IUAC, New Delhi. The target consisted of 2.7 mg/cm^2 of ^{100}Mo on $\sim$ 12 mg/cm^2 thick Pb backing. Prompt $\gamma - \gamma - \gamma$ coincidences were detected with the Indian National Gamma Array (INGA)[11] consisting of 18 Compton suppressed Clover detectors. The detectors were arranged in five rings at angles 32°, 57°, 90°, 123°, and 148° with respect to the beam direction [11]. The front face of each detector was positioned $\sim$ 24 cm away from the target. The energy and timing information from the Clover detectors were processed using indigenously developed Clover electronics modules[12]. The data was collected in list mode when three or more detectors fired simultaneously using the CAMAC-based MULTI-CRATE synchronization mode coupled with PC-LINUX environment[13].

After gain matching of individual crystals, add-back spectra were generated for all the Clovers and the coincidence events were stored in $E_\gamma \times E_\gamma$ matrix and $E_\gamma \times E_\gamma \times E_\gamma$ cube with a dispersion of 0.5 keV/channel. The RADWARE software package was used for the analysis of these matrices and cube. For Doppler-shift attenuation analysis, line shapes were obtained from background-subtracted spectra projected from matrices consisting of events in the 148° or 32° detectors along one axis and all other detectors along the second axis.

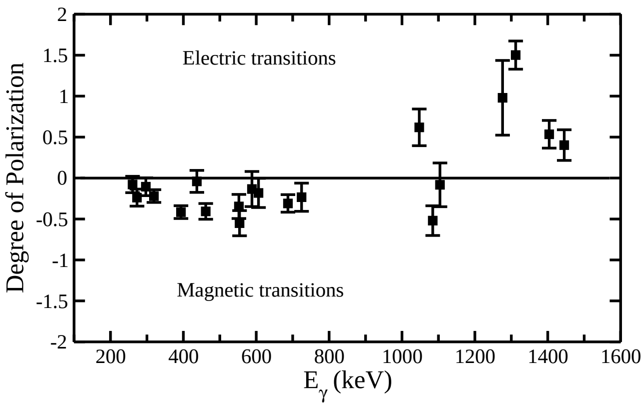

Figure 2. Plot for degree of polarization for different transitions of ^{112}In.

3. Analysis Procedure and Results

In the present work, we have confirmed the previously known level scheme [7, 8] by putting double gates on different transitions. The double gated spectrum (see Fig 1(a)) obtained in coincidence with 319 and 178 keV transitions shows the 128 - 273 - 393 - 554 - 708 keV cascade of positive-parity dipole band. Similarly, the 588 - 724 - 552 - 437 - 160 - 345 - 788 keV cascade for negative-parity band was confirmed by the 187 -160 keV gated spectrum shown in Fig 1(b). Another weakly populated negative-parity band consisting of 194, 297, 347, 362, 405, 409 and 470 keV transitions was also observed as reported in Ref. [8].

The Clover detectors at 90° were used as Compton polarimeter, for linear polarization measurement to determine the electric or magnetic nature of γ transitions [14, 15]. The polarization P of a γ transition is defined by the relation $P = \Delta/Q$. Where, Δ is experimental asymmetry of the transition and Q is polarization sensitivity of the polarimeter. For a Compton-polarimeter, the experimental asymmetry Δ of the transition is defined by [14]

$$\Delta = \frac{a(E_\gamma)N_\perp - N_\parallel}{a(E_\gamma)N_\perp + N_\parallel} \quad (1)$$

$N_\perp(N_\parallel)$ is the number of counts of γ transitions scattered perpendicular (parallel) to the emission plane. The correction factor $a(E_\gamma)$ is a measure of the perpendicular to parallel scattering asymmetry within the crystals of the Clover. For the 90° detectors this parameter has been found to be 0.98(1) from the analysis of decay data of the ^{152}Eu radioactive source. Furthermore, the polarization sensitivity Q of the Clover as a function of photon energy is defined as $Q(E_\gamma) = Q_o(E_\gamma)(CE_\gamma + D)$ [15], where $Q_o(E_\gamma)$ is the polarization sensitivity of a point detector. For linear polarization analysis two asymmetric matrices, corresponding to parallel and perpendicular segments of Clover detectors (with respect to the emission plane) along one axis and the coincident γ-rays along the other axis were constructed. A positive value of degree of polarization indicates an electric transition whereas negative value for magnetic

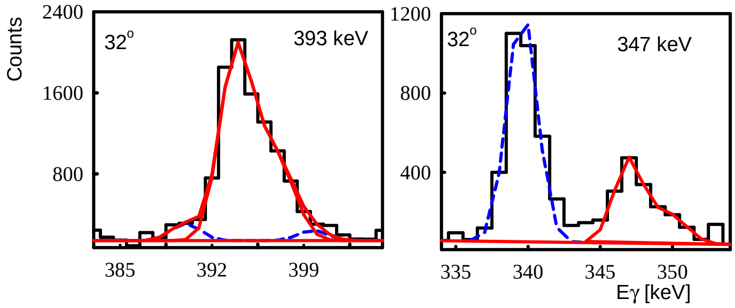

Figure 3. (Color online) Experimental and theoretical line shapes of 393 and 347 keV transitions of positive and negative bands of ^{112}In. The contaminant peaks are shown by dotted lines.

transition. The positive and negative degree of polarization parameters of different transitions depicted in Fig. 2 indicate their electric and magnetic nature, respectively. The positive-parity dipole band decays predominantly via 261 keV transition to the state at 3062 keV excitation energy. The DCO ratio of this transition is 0.97(7), when a gate is put on pure dipole transition and its degree of polarization is negative, proving the magnetic character. Similarly, the degree of polarization for 273, 393 and 554 keV transitions are found to be negative suggesting their magnetic character. Similar measurements were carried out for the negative-parity bands.

Lifetimes of high spin states of dipole bands in ^{112}In have been determined by DSAM technique. The LINESHAPE [16] code was used to perform the lifetime measurement of high spin states. For the stopping power option, we have used the shell-corrected Northcliffe and Schilling stopping powers. The value of time step and number of recoil histories were chosen to be 0.01 ps and 5000, respectively. In the fitting procedure, program obtains a χ^2 minimization of the fit for transition quadrupole moments (Q_t) for the transition of interest, transition quadrupole moments Q_t(SF) of the modeled side feeding cascade, the intensity of contaminant peaks in the region of interest and normalizing factor to normalize the intensity of fitted transition. The best fit was obtained through the least square minimization procedures SEEK, SIMPLEX, and MIGRAD. In the analysis, gating transitions were below the transitions of interest.

The Doppler-broadened line shapes were observed for 273, 393, 554 and 708 keV transitions of positive-parity dipole band above the I^π=14$^+$ state. The line shapes of these transition were obtained by putting gate on the 178 keV transition. The lifetime of the topmost state was extracted without taking into account the side feeding and used as an input to fit the line shape of lower transitions. The side feeding into each level of the band was considered as a cascade of five transitions having a fixed moment of inertia comparable to that of the in-band sequences. The energies of γ-rays and side-feeding intensities were used as an input parameters for the line shape analysis. Side-feeding intensities were calculated by using an asymmetric γ-γ matrix comprising γ-rays detected at 90° along one axis and all other detectors along the second axis. Once the χ^2 minimization was obtained by the MINUIT [17] program, the background and the contaminant peak parameters were fixed and the procedure was followed for the next lower level. After obtaining χ^2 minimization for each level, a global fit was carried out. The side feeding lifetimes were found to be faster than the level lifetimes similar to the measurements reported in other nuclei in this mass region [4, 10].

The final values of lifetimes were obtained by taking weighted averages of the results obtained from the two separate fits which were performed at 32° and 148°. For each band, B($M1$) values were calculated from measured lifetimes using the following relationship:

$$B(M1) = \frac{0.05697}{E_\gamma^3(M1)\tau\left[1+\alpha_t(M1)\right]}\left[\mu_N^2\right], \qquad (2)$$

where, E_γ is the transition energy in MeV, τ is partial lifetime of the transition deduced from the fitted line shape of the state and α_t is total internal conversion coefficient of the transition.

Similarly, line shapes for 347 and 362 keV transitions of negative-parity band were determined. The line shapes of representative transitions of 393 and 347 keV from positive and negative-parity bands observed at 32° forward detectors are shown in Fig. 3. In the right panel of Fig 3, the 339.5 keV decaying transition is from low-lying excited states of ^{111}In with a longer lifetime and is assumed to be a contaminant stopped peak in the line shape analysis of 347 keV transition of the negative-parity band of ^{112}In.

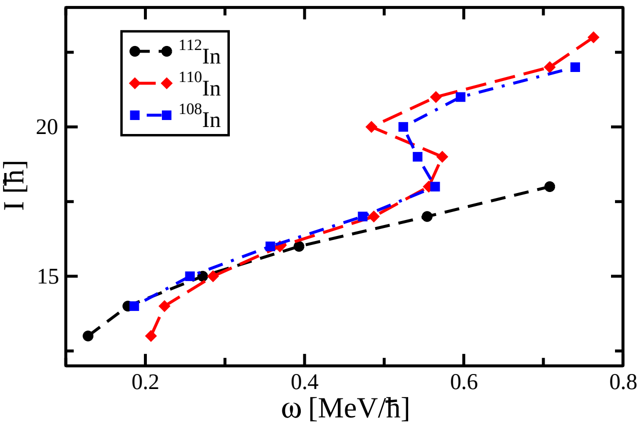

Figure 4. (Color online) Comparison of experimentally observed angular momentum as a function of rotational frequency for dipole band 3 of ^{108}In, ^{110}In [4] with ^{112}In.

4. Discussions

The positive-parity dipole band with band-head excitation energy 3.062 MeV has been observed upto $I^\pi = 18^+$. Similar dipole bands have been seen in ^{108}In and ^{110}In with $\pi g_{9/2} \otimes \nu((h_{11/2})^2(d_{5/2}/g_{7/2})$ quasi-particle configuration [4]. In Fig. 4 we have compared the experimentally observed spin (I) with rotational frequency (ω) for these bands. Except for the rotational frequency higher than 0.6 MeV in ^{112}In, all three In isotopes have a very similar variation, which confirms the similar configuration for the positive-parity dipole band of ^{112}In.

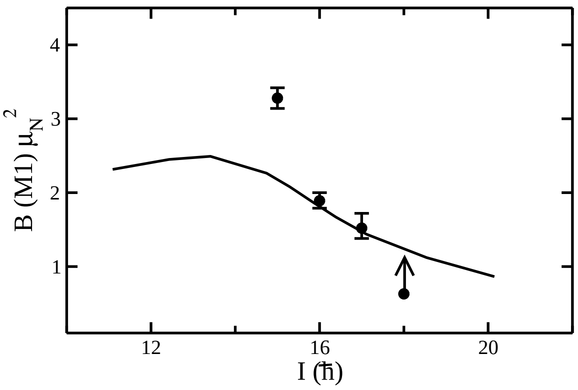

Figure 5. Result of TAC calculations and its comparison with the experimental data for positive-parity dipole band of ^{112}In.

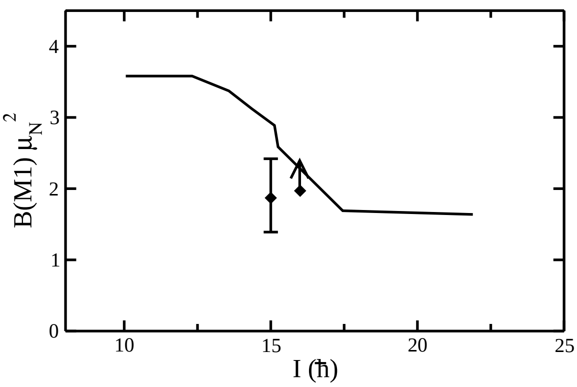

Figure 6. Result of TAC calculations and its comparison with the experimental data for negative-parity band of ^{112}In.

The experimental data of the dipole bands from present measurements are compared with the predictions of TAC model calculations. The values of proton paring gap parameter $\Delta_\pi = 0.99$ and neutron pairing gap parameter $\Delta_\nu = 0.85$ were used in the TAC calculations. The chemical potentials λ_ν (for both neutron and proton) were chosen so that the particle number is conserved for N = 63 and Z = 49. The values of deformation parameter ϵ_2 and γ were obtained by the Nilsson Strutinsky minimization procedure [18]. A quasi-particle configuration $\pi g_{9/2} \otimes \nu(h_{11/2})^2(d_{5/2}/g_{7/2})$ is used in the tilted axis cranking (TAC) calculation for the positive-parity dipole band. Similar configuration has been assigned in lighter odd-odd In isotopes and supports magnetic rotation. A minimum is found at deformation of $\epsilon_2 = 0.12$ and $\gamma = 6°$. The calculated $B(M1)$ *vs.* I plot based on this global minimum given in Fig. 5 qualitatively explains the measured data. The low deformation of these states indicates that the contribution from the core in angular momentum generation is negligible and the whole of the the angular momentum generation along the band can be attributed to the shears mechanism. The measured variation of excitation energy and B(M1) values with spin for the positive-parity band is reproduced from the results of TAC calculations as shown in Fig. 5. This firmly establishes magnetic rotation for this band.

A negative-parity dipole band with excitation energy of 3153 keV studied in the present work and $\pi g_{9/2} \otimes \nu(h_{11/2})^3$ configuration has been used in TAC for comparison of this band which gives a minimum with $\epsilon_2 = 0.13$ and $\gamma = 0°$. Fig. 6 shows the variation of calculated B(M1) with spin (I) based on the global minimum. The measured B(M1) values for $I^\pi = 15^-, 16^-$ are also reproduced with the results of TAC calculations. This confirms the quasi-particle configuration of this negative-parity band. In future, it will be interesting to perform the Recoil Distance Measurements (RDM) to determine the lifetime of the lower states for testing the prediction of higher B(M1) values at lower spin states.

In summary, the present lifetime measurements of dipole bands demonstrated the phenomena of magnetic rotation in ^{112}In. The TAC calculations based on $\pi g_{9/2} \otimes \nu(h_{11/2})^2(d_{5/2}/g_{7/2})$ configuration reproduces the measured trend of B(M1) with increasing spin. A fair agreement of TAC calculations with the measurement suggests weak prolate deformation for the dipole bands of ^{112}In.

5. Acknowledgments
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