NUCLEAR SHAPES AND SYMMETRIES SEEN THROUGH MEASUREMENT OF SHORT LIFETIMES*

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We have studied the signature and chiral symmetries in odd–odd nuclei ^{126}I and ^{130}La. In our earlier measurement, we observed signature splitting as well as inversion in ^{126}I. The reduced transition probabilities B(M1) and B(E2) are the critical observables for various nuclear phenomena. To extract these observables, we have measured the nuclear lifetimes in picoseconds using the Doppler shift attenuation method (DSAM). From our results, we were able to find the nuclear shapes explaining both signature splitting and inversion in a definitive way. While the axial deformation remained the same ($\beta \sim 0.13$) below and above the inversion, the triaxiality (γ) changed from $-10°$ to $+23°$. We proposed a set of two bands — with similar energy levels and the same range of lifetimes values — to possess chiral symmetry, for which there is no clear evidence. Another nucleus of our interest, ^{130}La, was found to possess weak chiral symmetry in literature. Our recent finding on lifetimes not only confirmed the earlier results, but also added some new data points near the bandhead.

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1. Introduction

Signature splitting and its inversion are very well studied phenomena for nuclei in the mass region of ∼130, but the underlying mechanism is still an open problem [1, 2]. The same is true for the chiral behavior as well [3, 4].

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Triaxial nuclear shape is an important ingredient in these mechanisms, and the reduced transition probability is the best observable to give unique result of the shape parameters.

In our earlier work [5], we explained the signature inversion in ^{126}I from the point of view of change in the axis of rotation. Our argument was solely based on the theoretical analysis using the total Routhian surface (TRS) and particle rotor model (PRM) calculations. However, a more refined picture has emerged from our results on B(E2) and B(M1) obtained from the lifetime measurements [6]. A near prolate-shaped nucleus changed its shape to triaxial with the change in sign above the signature inversion. We earlier identified two similar bands in ^{126}I as chiral partners [5]. Our recent results on the reduced transition probabilities were indeed close to those for a neighboring nucleus ^{128}Cs considered as the best case of chirality. Similarly, another nucleus ^{130}La with $N = 73$ was recently reported in the literature [7] to exhibit chiral vibration. We have extended their study recently.

In the present manuscript, at first, we describe the technique of Doppler shift attenuation method (DSAM) for finding the lifetimes in the picosecond range. The formulation for extracting B(M1) and B(E2) is also briefed. We then discuss our results in the light of particle rotor model followed by the conclusion with future scope.

2. Experiments and data analysis

We performed our experiments at the Pelletron facility at the Inter University accelerator center, New Delhi, India. The reactions used for ^{126}I and ^{130}La were ^{124}Sn(^{7}Li, 5n)^{126}I at $E_{\text{beam}} = 50$ MeV, and ^{116}Cd(^{19}F, 5n)^{130}La at $E_{\text{beam}} = 94$ MeV, respectively. We used the experimental set-up — named as the Indian National Gamma Array (INGA) [8] — consisting of 15–18 Compton suppressed Clover detectors placed at angles of 32° and 57° in the forward ring, 123°and 148° in the backward ring, and at 90°. We used self-supporting targets of thickness within the range of 2.7 to 4.6 mg/cm^2. The list mode data were collected by the CAMAC based in-house software Candle [9].

We analyzed the Doppler lineshapes using three asymmetric matrices — 32° *vs.* all to observe forward Doppler shift, 148° *vs.* all to observe backward shift, and 90° *vs.* all to examine the nearby gamma peaks as contaminants. Two data analysis procedures — gating above (GTA) and gating below (GTB) — have been utilized to obtain the consistent lifetime results independently [6]. The GTA analysis is free from any side-feeding parameter but suffers from somewhat low statistics, whereas reverse is the case for GTB. Further, the lifetime results were verified using two detector angles — one forward and another backward direction. Figure 1 presents a typical arrangement of detectors and the Doppler lineshape profiles described by

Eq. (1). In the lab frame within first order approximation for $\beta_r \ll 1$ [10]

$$E_\gamma = E_0(1 + \beta_r \cos\theta_{\text{lab}})\,, \tag{1}$$

where E_γ is the shifted gamma-ray energy, E_0 is its actual energy, $\beta_{\text{r}} = \frac{v}{c}$ is the recoil velocity, and θ_{lab} is the angle between the detector and beam axis.

In DSAM, Monte Carlo technique is utilized to generate lineshapes. We used the Lineshape software package of Wells and Johnson [11], built on two computer programs — Dechist and Histaver. The program Dechist simulates the time-dependent velocity profile in the target and backing medium. In our analysis, the target and backing materials were the same. The Histaver program uses this time-dependent velocity profile convoluted with the detector angle. Finally, the theoretically generated profiles were fitted on to the experimental profiles using the Lineshape program. The program uses three χ^2-minimization routines — Seek, Simplex and Migrad — to evaluate lifetimes and their respective quadrupole moments. We determined the error in the lifetime values by finding how the chi-square got affected by changing the lifetime values. We arrived at the error value when the chi-square increased by one. Considering both statistical and systematic errors, we found them within 25% including errors due to stopping power and due to continuous production and stopping of recoils in the target.

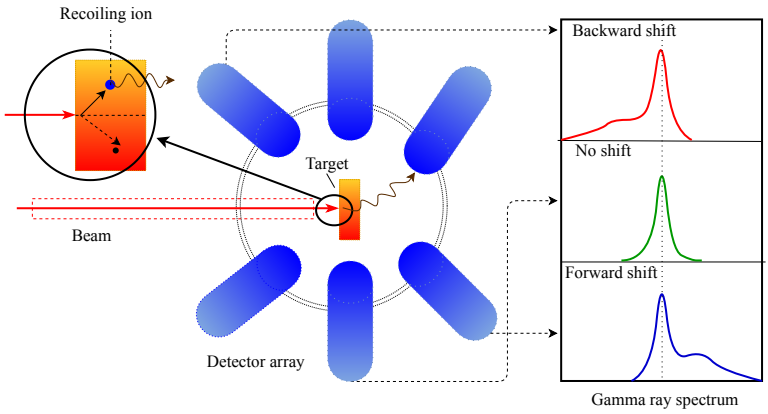


Fig. 1. Illustration of an experimental set-up with detectors at different angles exhibiting the Doppler lineshape profiles.

3. Results and discussion

We determined the reduced transition probabilities B(E2) and B(M1) from the experimental lifetime values using Eq. (2) and Eq. (3)

$$B(\mathrm{E2}) = \frac{0.0816 f_\gamma(\mathrm{E2})}{E_\gamma^5(\mathrm{E2})[1+\alpha_\mathrm{t}(\mathrm{E2})]\tau}\left[(e\,\mathrm{b})^2\right], \quad (2)$$

$$\frac{B(\mathrm{M1};I,I-1)}{B(\mathrm{E2};I,I-2)} = \frac{0.697}{\lambda}\frac{E_\gamma^5(I,I-2)}{E_\gamma^3(I,I-1)}\frac{1}{1+\delta^2}\left[\frac{\mu_N^2}{e^2\mathrm{b}^2}\right], \quad (3)$$

where f_γ and α_t are the branching ratio and total internal coefficient of the transition, λ is the intensity ratio of E2 and M1 transitions, δ is the mixing ratio assumed to be zero. The notations used for the units are μ_N for nuclear magnetron, e for electronic charge, and b for barn. The values of α_t were considered zero because of reasonably high energies of the gamma transitions ($E > 100$ keV).

3.1. ^{126}I

We have attempted to explain the behavior of signature splitting and inversion on the basis of the observed trend in the B(E2) values for the yrast negative-parity states of ^{126}I. The particle rotor model (PRM) was used for the theoretical calculations. Figure 2 (left side) presents a comparison of the experimental results with theory. It is worth to notice in the figure (right side) a sharp change in the B(E2) values at the point of signature inversion $13\hbar$. After many trials of using different combinations of the parameters (β,γ) in Lund convention, we arrived at the results presented in the figure. While $\beta \sim 0.13$ remained the same below and above the inversion, γ changed from $-10°$ to $+23°$. Simultaneously, we observed the nature of the wave function, especially corresponding to the valence proton. In our earlier work [5], we have argued that the valence proton in the $d_{5/2}$ orbit is compatible with the anomalous signature splitting going to normal splitting above the inversion. However, a significant mixing with the $g_{7/2}$ orbit was always present. Neutron being in the intruder $h_{11/2}$ orbit remained pure. The present work on lifetimes also provided a consistent picture [6]. Two positive-parity bands based on $\pi h_{11/2} \otimes \nu h_{11/2}$ with similar characteristics

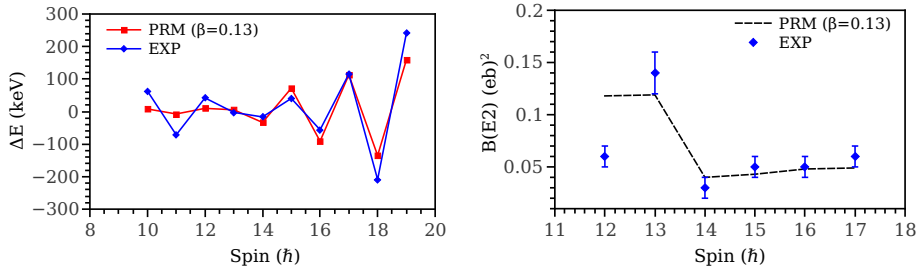


Fig. 2. Plots of signature splitting and inversion in comparison to the PRM results (left); trend in the B(E2) values (right).

were established in our earlier work [5], and we proposed them possible chiral bands. Later through our lifetime measurements using DSAM, we could identify five gamma transitions showing very clear lineshape profile. An example of 999 keV transition is shown in Fig. 3 (a). The B(E2) values for all five transitions were found to be close to the neighboring nuclei, particularly to ^{128}Cs considered as the best case of chirality [12].

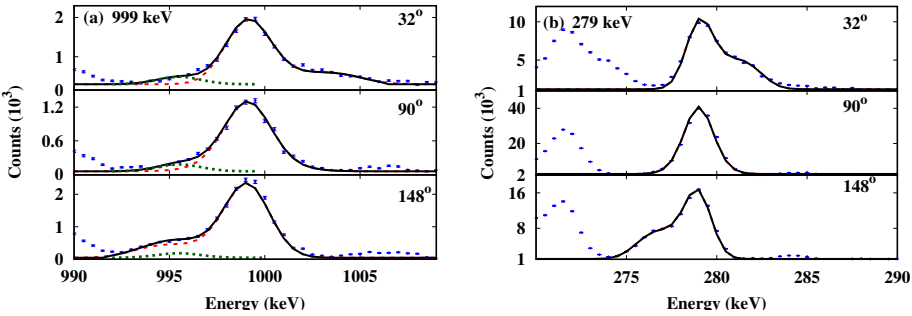


Fig. 3. Lineshape profiles of γ-transitions (a) 999 keV of ^{126}I, and (b) 279 keV of ^{130}La.

3.2. ^{130}*La*

The nucleus ^{130}La has been of importance to check for chirality because one of the adjacent odd–odd isotope ^{132}La was disputed and discarded as being chiral by Hamamoto [13] from the critical observation on the reduced transition probabilities. In our recent measurement with DSAM, we identified ^{130}La showing lineshapes for many transitions belonging to two similar bands based on $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration. While we were analyzing our data, lifetime results were published [7] claiming chiral vibration without stable chirality. Nevertheless, we succeeded in finding some new results near the bandhead. An example of 279 keV transition exhibiting clear lineshape is shown in Fig. 3 (b). The results on B(E2) values are also presented in Fig. 4.

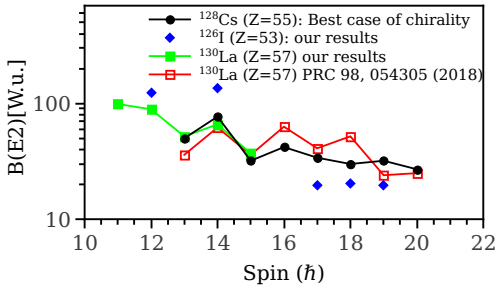


Fig. 4. Comparison of B(E2) values from our measurements with neighboring nuclei with $N = 73$.

4. Conclusion

Two cases of odd–odd nuclei ^{126}I and ^{130}La with $N = 73$ were studied for their shapes and symmetries. The sudden change in the B(E2) values at the spin of signature inversion in ^{126}I indicated the shape change or change in the axis of rotation or a combination of both. We inferred a combination of both because the triaxiality (γ) changed its value as well as the sign. As far as chiral behavior is concerned, just finding two similar bands does not fulfill the criteria, a definite pattern of B(E2) and B(M1) provides a more stringent test. Among ^{128}Cs and ^{132}La, both reported in the literature, the former shows the pattern, while the latter fails to do so. From our recent measurements for ^{126}I and ^{130}La, we could only tentatively assign the bands as chiral due to the similar values of B(E2) as reported for ^{128}Cs. To confirm the chiral symmetry for both the studied nuclei, we need to perform more lifetime measurements and careful data analysis in the future.

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