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Short Note

Investigations of low- and high-spin states of ^{132}La

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Abstract. The fusion evaporation reaction ^{122}Sn(^{14}N, 4n)^{132}La was used to populate the high-spin states of ^{132}La at the beam energy of 60 MeV. A new band consisting of mostly $E2$ transitions has been discovered. This band has the interesting links to the ground state 2^- and the isomeric state 6^-. A new transition of energy 351 keV connecting the low-spin states of the positive-parity band based on the $\pi h_{11/2} \otimes \nu h_{11/2}$ particle configuration, has been found. This has played a very important role in resolving the existing ambiguities and inconsistencies in the spin assignment of the band head.

PACS. 23.20.Lv Gamma transitions and level energies – 23.20.En Angular distribution and correlation measurements – 23.20.Gq Multipole mixing ratios – 27.60.+j $90 \leq A \leq 149$

1 Introduction

In the recent past, there has been a tremendous interest in the spectroscopic studies of odd-odd nuclei in the mass region ~ 130 because of the newly recognized phenomenon of chirality in nuclear rotation [1–8]. Two nearly degenerate bands based on the same particle configuration, called as chiral bands, were first found in ^{134}Pr [7].

We began our investigation of ^{132}La with the motivation of understanding the nuclear structure at both the low, as well as high spins. Very few energy levels of ^{132}La were known earlier [9] and their spin assignments were mostly tentative. Starosta *et al.* [1–3] later reported the existence of a chiral partner of the $\pi h_{11/2} \otimes \nu h_{11/2}$ band by identifying a series of $M1$ and $E2$ transitions. Though very weakly populated, our data has confirmed the chiral partner bands in ^{132}La. With our discovery of a transition of energy 351 keV, the band head has been reassigned to a new state 8^+ leading to a consistent picture among the earlier experimental [1,9] and theoretical works [1,10].

Owing to the isomeric nature of 6^- state ($T_{1/2}$ = 24.3 min), the interconnecting transitions to the ground state 2^- were completely missed in the earlier prompt coincidence measurement [9]. On the other hand, the interconnecting transitions of energy values 53 keV ($M3$), 135 keV ($M1$) and 188 keV ($E4$) were present in the electron conversion spectroscopic measurements [11,12]. With the identification of 3 new transitions namely, 96 keV, 129 keV and 160 keV, the spin difference of 4 units between the known ground state as 2^- and the isomeric state as 6^- has further been confirmed from our data.

The transitions 515 keV, 699 keV, 841 keV and 975 keV, constituting another band, have also been discovered.

2 Experiment and data analysis

The experiment using the fusion evaporation reaction ^{122}Sn(^{14}N, 4n)^{132}La, was performed at the Nuclear Science Centre, New Delhi, with the 15 UD Pelletron accelerator. The experimental set up consisted of 8 Compton suppressed HPGe detectors and a 14-element BGO multiplicity filter. The HPGe detectors were placed at angles of 50°, 98° and 144° with respect to the beam direction. The ^{122}Sn target of thickness 1.2 mg/cm^2 was rolled onto the 10 mg/cm^2 of Pb. The Pb thickness was chosen so as to stop the recoiling nuclei.

The energy calibration and the efficiency determination of individual HPGe detectors were done using the ^{133}Ba and ^{152}Eu radioactive sources. In order to measure the excitation function, the energy spectra of individual HPGe detectors were taken at the various beam energies. After matching the gains, the energy spectra from all the detectors were added to minimize the effect of the angular correlation of γ-rays. A comparison of the intensities

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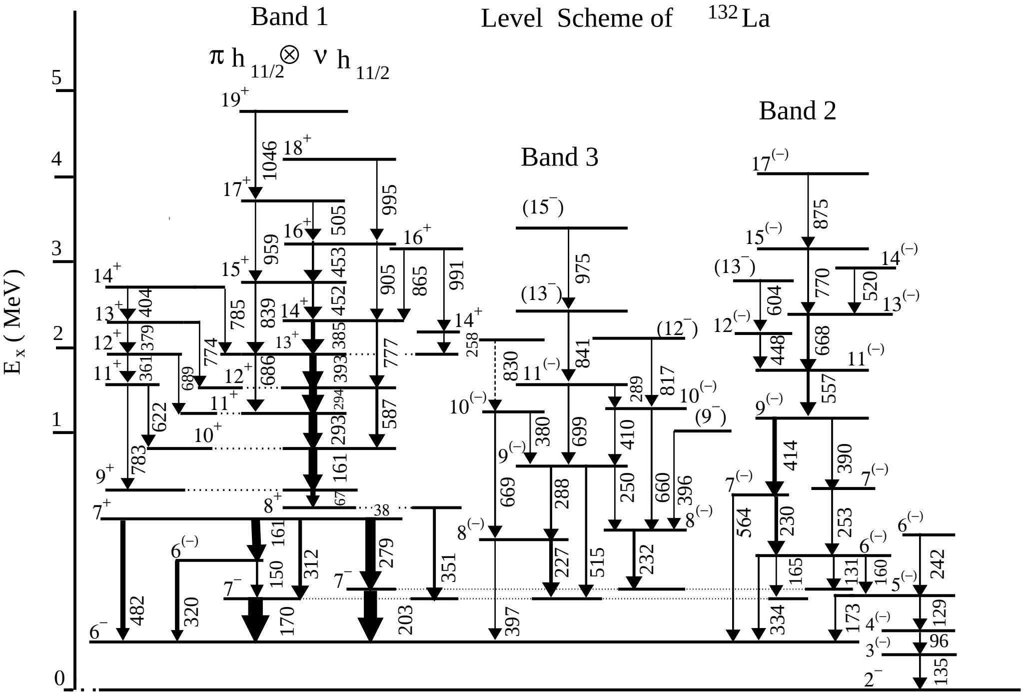

Fig. 1. The decay scheme of ^{132}La. The width of the arrows is proportional to the relative intensities of the transitions. The energy values have the uncertainties of ± 0.5 keV. The tentative placement of γ-transitions is shown with dotted lines. The spin-parity values in the bracket are the tentative values.

of the γ-rays belonging to various evaporation residues was then made to choose the suitable beam energy for the experiment. The reaction channels with measurable cross-section at the beam energy of 56 MeV, 59 MeV, 62 MeV and 65 MeV were 4n, 5n, 3n, 3np. The optimum beam energy was chosen to be 60 MeV for the population of intermediate- and high-spin states of ^{132}La which was about 60% of the total production of evaporation residues. The list mode data collection was made for the γ-γ coincidences and almost 1.45×10^7 events were collected.

Initially the symmetrized E_γ-E_γ matrix was constructed after calibrating the list mode data using the FREEDOM [13] software. To generate the projected spectra after appropriate background subtraction with gates on all the known as well as unknown γ-transitions of ^{132}La, the RADWARE [14] computer program was utilised. Using the coincidence and intensity relationships between various γ-transitions the entire decay scheme, shown in fig. 1, was built.

In order to determine the spins of the states, the method of finding the Directional Correlation (DCO) ratios was utilized. For this purpose, an E_γ-E_γ matrix was made with detector angles of 50°, 144°($\equiv$ 36°), on one axis and 98° on the other axis. This resulted in the averaged value of the detector positions as $\theta = 43°, 98°$ and $\phi = 0°$. Here "ϕ" is the angle between the two detector planes, each of which was created by the detector direction and the beam direction. To determine the DCO ratios, slices were taken with gate on $\theta = 43°$, projection on $\theta = 98°$, and *vice versa*. The experimentally determined values of the DCO ratios were compared with the theoretical ones to determine the multipolarity of the transition. The theory was based on the prescription given by Krane *et al.* [15]. Assuming the population parameter $\sigma/I = 0.3$, the theoretical curves were plotted as a function of the mixing ratio "δ". For the entire data analysis, $E2$ transitions were considered to be pure, *i.e.*, $\delta = 0$. For the dipole transitions, the property of $E1$ transitions having very small mixing with $M2$, was occasionally exploited to assign the parity of the states. After finding the multipolarity of transitions, the spins of the states were assigned assuming the ground state as 2^- [11] and the isomeric state as 6^- ($T_{1/2} = 24.3$ min) [12]. In addition, the increase in the spin value with increasing excitation energy is usually considered with a few exceptions mentioned later.

3 Results and discussion

From the analysis of our data, we have found three bands namely band 1, band 2 and band 3, as shown in fig. 1. In the following sections we discuss the results obtained for each band separately.

3.1 Band 1

The positive-parity band, populated most intensely as compared to other bands, was considered to be the main band. This band was earlier identified [9] to be based on the $\pi h_{11/2} \otimes \nu h_{11/2}$ particle configuration and was also confirmed by Starosta *et al.* [1–3].

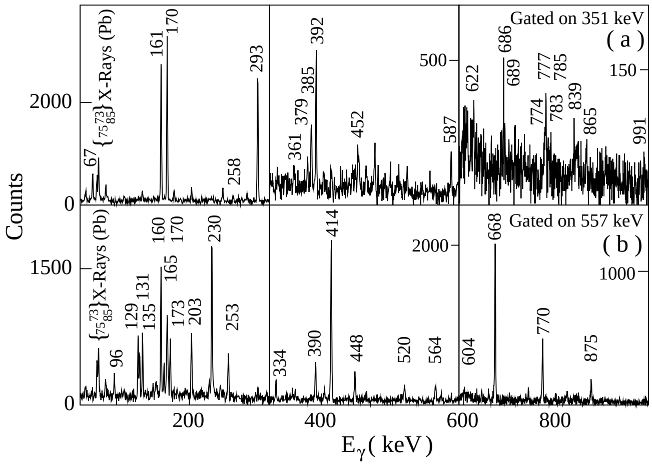

Fig. 2. The projected spectra with gates on 351 keV and 557 keV transitions belonging to ^{132}La. The γ-lines marked with the energy values are the coincident transitions belonging to (a) band 1 and (b) band 2.

Our data showed the weak population of the chiral band up to spin 14$^+$ (fig. 1). Gate on a newly discovered 351 keV transition fig. 2(a) showed a strong coincidence with transitions 170 keV, 67 keV, 161 keV, 293 keV, 587 keV etc. In fact, the presence of the 351 keV transition can also be easily noticed in the projected spectrum of the 380 keV transition reported by Starosta *et al.* [1]. Following the general rules of intensity and coincident relationship, we have placed the 351 keV transition above the 170 keV transition. In order to connect it to the state decaying via the 67 keV transition, we needed a 38 keV transition to be placed below 67 keV. The highly converted 38 keV transition was not clearly seen in any of the projected spectra because of the presence of the La X-rays in the same energy range. The definite presence of the 351 keV transition above 170 keV, indirectly established the existence of the 38 keV transition below 67 keV. For low-spin states, there were many pathways for the decay of a particular state. This gave an opportunity to find many possible combinations of coincident γ-transitions to determine the DCO ratios. An example is shown in fig. 3. In part (a), a comparison of the experimental DCO value of 0.44 ± 0.07 between 587 keV and 482 keV transitions was made with the theoretical curves for the various values of the intermediate spin I. Here the pure quadrupole nature of the 587 keV transition was assumed. As a result of the comparison, we get $I = 7$ for the state decaying via the 482 keV transition. The parity of this state was assigned to be positive in view of the small mixing of quadrupole component for the 482 keV transition consequently considering it to be $E1$. In part (b) of fig. 3, we considered the DCO ratio of 170 keV and 587 keV transitions and found the 170 keV transition to be $M1$ with $E2$ mixing of 4.2% and the decaying state was assigned to be 7$^-$. Resulting from the fig. 3(c), the spin of the state decaying via the 351 keV transition was assigned to be 8$^+$. Although the spin value of 7$^+$ was another possibility, it was avoided because of the large δ value. The $E1$ nature of the 351 keV transition was again derived because of its low δ value. As evident from fig. 3(d), the state decaying via the 150 keV transition may be either 6$^\pm$ or 8$^\pm$. We have assigned it to be 6$^-$ because it was supported by the DCO analysis of 161 keV transition, lying just above, with the 783 keV transition.

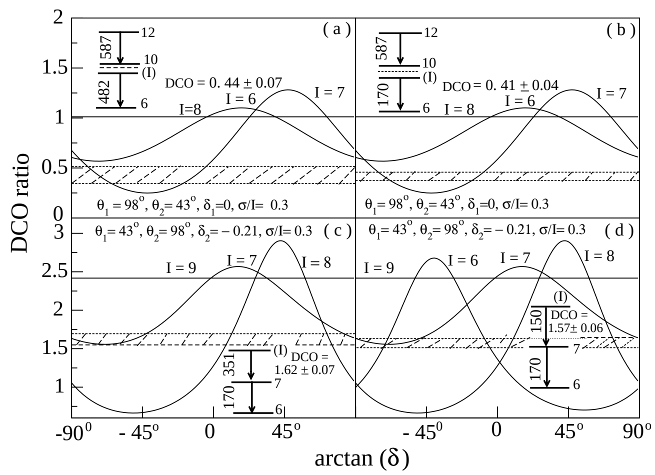

Fig. 3. A comparison of the experimentally determined values of the DCO ratios with the theoretical curves plotted with respect to the dipole-quadrupole mixing ratio "δ" for different values of the unknown spin I. Here the DCO ratio is defined as $W(I \rightarrow \theta_1, II \rightarrow \theta_2, \phi)/W(I \rightarrow \theta_2, II \rightarrow \theta_1 \phi)$, where W is the intensity when the two coincident transitions are detected at θ_1 and θ_2; and the indices I and II refer to the upper and the lower transitions, respectively. The population alignment parameter σ/I, described in ref. [15], was assumed to have a value of 0.3.

It is worth discussing here the importance of the 351 keV transition in the decay scheme. The spin-parity of the isomeric state 6$^-$ is definite because of many reported experimental results [9,12,16] in the past. The DCO analysis of the present work and the earlier work by Starosta *et al.* [1] indicated clearly the $E1$ nature of the 482 keV transition resulting as the 7$^+$ assignment of the decaying state. The same result was obtained by Oliveira *et al.* [9] too. In spite of their experimental result, Starosta *et al.* have preferred the 8$^+$ assignment because of two reasons. Firstly, the agreement with the theory was much better for all the states with the 8$^+$ assignment than with the 7$^+$ assignment. Secondly, when compared with the band head energies of many nighbouring odd-odd isotopes of La systematically, 8$^+$ was preferred [10]. The incorporation of the 351 keV transition in the decay scheme has now resolved all the ambiguities between theory and experiment. In this new decay scheme the band head is 8$^+$ decaying via the 351 keV transition and the lower spin state 7$^+$ decays via the 482 keV transition. The spins of all the above states remain the same as given by Starosta *et al.* [1]. In fact, the agreement with their theoretical calculations will now be even better because of the increased excitation energy by 38 keV of all the states involved.

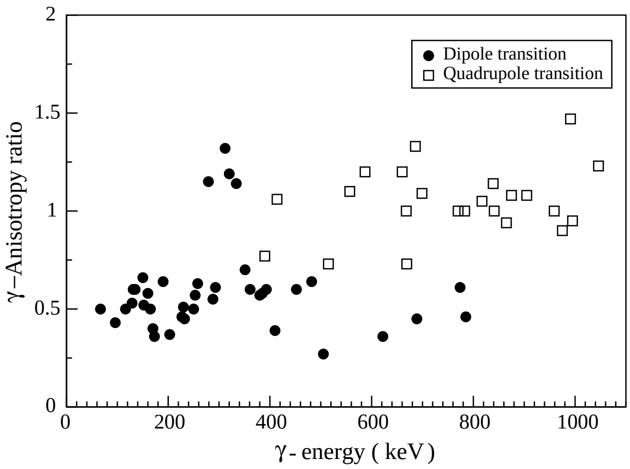

Fig. 4. A plot of the anisotropy ratio *vs.* the energy of the γ-transition for all the transitions belonging to ^{132}La. The anisotropy ratio was calculated by taking the intensity ratio of the γ-transition when detected at $\theta = 43°$ and at $\theta = 98°$.

3.2 Band 2

Band 2 was a new band, fully constructed from our data and found to have lesser intensity than band 1. As an example, the projected spectrum with gate on 557 keV γ-line is shown in fig. 2(b). The low-lying characteristic γ-transitions of energy values 170 keV and 203 keV are clearly seen in this projected spectrum, apart from the new transitions. The sequence of the energy levels was found from the intensities of all the constituent γ-transitions with individual gates and also confirmed by the intensities of transitions found from the total projected spectrum of the original E_γ-E_γ matrix. The DCO analysis resulting in the spin assignment was mostly certain because of the good coincidence intensities of the γ-transitions. However, the ambiguity of pure $E2$ or mixed $M1$, $E2$ with $\delta \approx +0.9$ persisted for the transitions 414 keV, 390 keV and the transitions lying above them in fig. 1. This was resolved by finding out the anisotropy ratios for all these transitions and inferred them to be $E2$. The anisotropy ratios were, in fact, deduced for all the transitions belonging to ^{132}La, as shown in fig. 4. Starting with the $E_\gamma(\theta = 43°)$-$E_\gamma(\theta = 98°)$ matrix, constructed for finding the DCO ratios, the anisotropy ratio for a particular gamma was found by taking the ratio of its intensities in the 43° detector and 98° detector with no specific gate. The anisotropy ratio values were nearly 0.5 and 1.0 for the mixed $M1$, $E2$ and pure $E2$ transitions, respectively. The points in fig. 4 not falling on the general pattern are for 279 keV, 312 keV, 320 keV, 334 keV transitions connecting $I \to I$ states. The implication was that these transitions have a large quadrupole content consistent with the result derived from the DCO analysis.

The series of transitions, namely, 160 keV, 129 keV, 96 keV and 135 keV bypassing the isomeric state 6^- and landing on the ground state 2^-, were all found to be dipoles with approximately the same quadrupole mixing of 2%. We also noted here that with the electron conversion spectroscopic measurement, a mixed $M1$, $E2$ transition of energy 135 keV decaying from 3^- to 2^- (ground state) was observed earlier [12]. Since all the transitions in the sequence were felt to be of the same kind, they were assigned to be of $M1$, $E2$ type. This led us to believe band 2 to have the negative parity.

Inspecting the transitions belonging to this band above 7^-, their energies were found to be almost identical to that of the ground-state band of the neighbouring even-even nucleus ^{130}Ba. This gave an indication of its nature as a "doubly decoupled band".

3.3 Band 3

Many transitions belonging to this band were newly found from our data. Up to the state 11^-, the spins of the states were uniquely found by the DCO analysis of many pairs of coincident γ-transitions. On the other hand, the transitions 841 keV and 975 keV were weak, therefore only a tentative spin assignment of the decaying levels was possible. The negative-parity assignment for all the energy levels was tentatively done. This could be a band based on the $\pi g_{7/2} \otimes \nu h_{11/2}$ particle configuration, as suggested by Oliveira *et al.* [9].

4 Conclusions

The excited states of ^{132}La were populated up to spin of 19 $\hbar$ and excitation energy of 4.76 MeV via the ^{122}Sn(^{14}N, 4n)^{132}La reaction with a very good production cross-section at 60 MeV of beam energy.

The well-studied positive-parity band based on the $\pi h_{11/2} \otimes \nu h_{11/2}$ particle configuration has been critically examined after locating a new transition of energy 351 keV. This has led to a consistent picture among all the results obtained in the past for assigning the band head spin and comparing the experimental excitation energy with the theoretical ones.

A new band connected to the ground state 2^- as well as the isomeric state 6^- via two different paths, has been discovered. The spins up to 17 $\hbar$ were assigned to the states belonging to this band by the rigorous DCO analysis and the anisotropy-ratio determination. The parity of the states has been tentatively assigned as negative, which in future may be ascertained from the possible particle configuration determined by the theoretical model calculations. Another partially known band [9] has been extended up to spin 15 $\hbar$ with the addition of some more parallel transitions and the negative parity has been tentatively assigned.

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Additional Remark: While this manuscript was under revision, a paper [17] identifying the new band head of chiral partner bands, a result identical to ours, was published.

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