Eur. Phys. J. A **11**, 5–8 (2001)

THE EUROPEAN PHYSICAL JOURNAL A

Short Note

Rotational bands in the doubly odd ^{130}Cs nucleus

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Received: 20 February 2001 / Revised version: 3 May 2001
Communicated by D. Schwalm

Abstract. The band structures built on the 5^- isomeric state ($T_{1/2} = 3.46$ m) in the doubly odd ^{130}Cs nucleus have been established up to $I = 24\hbar$ via the ^{124}Sn(^{11}B, 5n)^{130}Cs reaction. The previously observed bands based on the $\pi h_{11/2} \otimes \nu h_{11/2}$, $\pi g_{7/2} \otimes \nu h_{11/2}$ and $\pi d_{5/2} \otimes \nu h_{11/2}$ configurations and a positive-parity side band with multiple connections to the $\alpha = 0$ signature partner of the yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ band have been extended to higher spins. A new band based on the $\pi h_{11/2} \otimes \nu g_{7/2}$ configuration is observed. The yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ band exhibits anomalous signature splitting whose magnitude decreases up to spin 15 and then increases without restoring the normal signature splitting.

PACS. 21.10.Re Collective levels – 23.20.Lv γ transitions and level energies – 21.60.-n Nuclear-structure models and methods – 27.60.+j $90 \leq A \leq 149$

Nuclei in the $A \sim 130$ mass region are known to be γ-soft and their shapes are strongly influenced by the quasiparticles in the high-j orbitals. The doubly odd nuclei in this mass region are particularly interesting to investigate because of the bands built on the low-$\Omega h_{11/2}$ proton and the high-$\Omega h_{11/2}$ neutron orbitals having different shape-driving effects. Rotational bands built on the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration are known in many doubly odd isotopes of the nuclei ranging from $_{55}$Cs to $_{63}$Eu [1–3]. One of the most striking features has been the anomalous signature splitting and signature inversion in these bands. This phenomenon in the doubly odd nuclei in this mass region has been studied in the framework of the particle-triaxaial-rotor model [4]. However, the lack of spin assignments on the experimental basis makes the comparison ambiguous. Recently, Liu *et al.* [1,2] have studied the excitation energy systematics of the $\pi h_{11/2} \otimes \nu h_{11/2}$ band in the doubly odd $^{118\text{-}132}$Cs, $^{124\text{-}134}$La, $^{130\text{-}136}$Pr, $^{134\text{-}138}$Pm and ^{138}Eu nuclei and assigned spin values to the lowest observed states by taking the ^{128}La [5] and ^{130}Cs [6] as reference, where the spin assignments were available through experimental spectroscopic information. It has been noticed that only the low-lying states are known for the $\pi h_{11/2} \otimes \nu h_{11/2}$ band in the heavier doubly odd nuclei in this mass region and more experimental information on the high-spin states is required for better understanding of the above-mentioned features. In the present work, we have investigated high-spin states in the doubly odd ^{130}Cs nucleus. Previous investigations of excited states in ^{130}Cs resulted in systematic understanding of the low-lying states up to $I^\pi = 14^+$. Weiss and co-workers [7] identified a 5^- isomeric state ($T_{1/2} = 3.46$ m) at 163 keV and established its decay pattern to the 1^+ ground state. In-beam conversion electron and γ-ray spectroscopic investigations by Sala *et al.* [6] established first few states of the bands based on the $\pi h_{11/2} \otimes \nu h_{11/2}$, $\pi g_{7/2} \otimes \nu h_{11/2}$ and $\pi d_{5/2} \otimes \nu h_{11/2}$ configurations, which decay on to the 5^- isomeric state. At the time when this note was sent for publication, a paper by Starosta *et al.* [8], reporting the side bands having linking transitions feeding to the states of the yrast band built on the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration, was published.

High-spin states in the ^{130}Cs nucleus were populated via the ^{124}Sn(^{11}B, 5n) reaction at the beam energies of 61 and 64 MeV. The ^{11}B beam was delivered by the 15 UD pelletron accelerator at Nuclear Science Centre (NSC), New Delhi. The target consisted of a 3 mg/cm^2 foil of isotopically enriched ^{124}Sn backed with 20 mg/cm^2 of Pb. The emitted γ rays were detected using the Gamma Detector Array (GDA), which consisted of 12 Compton-suppressed Ge detectors and a 14-element BGO multiplicity filter. The Ge detectors were mounted in two groups making angles of 45°, 99° and 153° with the beam

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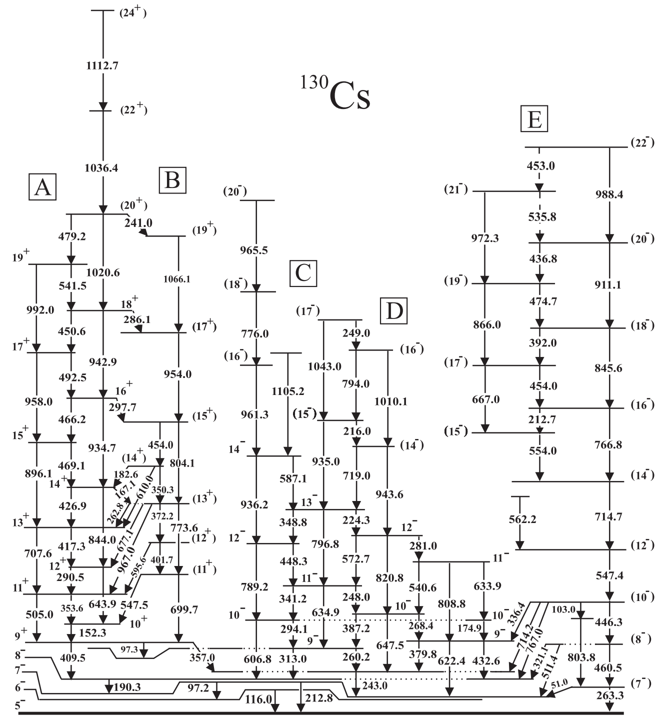

Fig. 1. The level scheme of ^{130}Cs established from the present work.

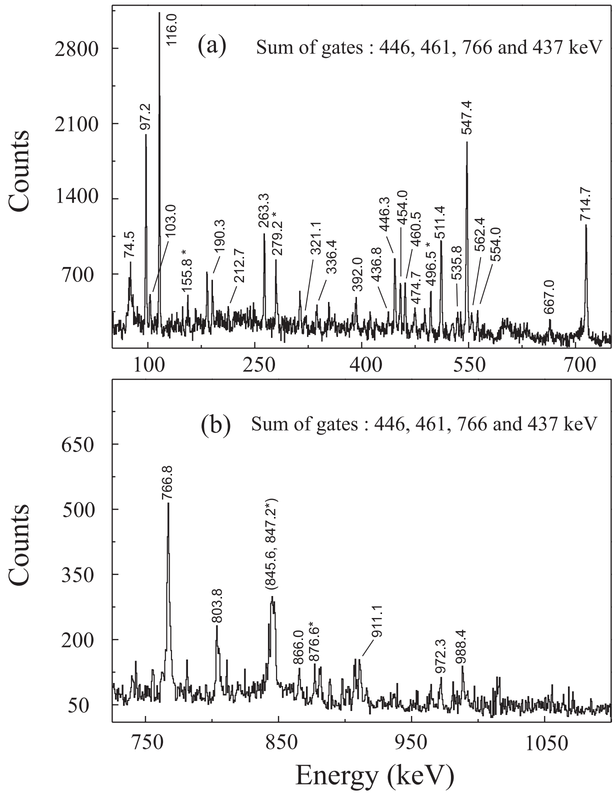

Fig. 2. The added gamma-ray coincidence spectra of ^{130}Cs with gates on the 446, 461, 766 and 437 keV transitions of the band E. The unlabelled peaks and those marked (*) are contaminations.

direction and tilted at $\pm 23°$ with respect to the horizontal plane. A total of 130 million Ge-Ge coincidence events with hardware multiplicity condition $K \geq 2$ were recorded in the LIST mode. The data after sorting into $4k \times 4k$ E_γ-E_γ matrices was used i) to establish coincidence and intensity relationships for various gamma transitions, and ii) to perform the directional correlation (DCO) analysis for gamma transitions in order to determine their multipolarities. The placement of the gamma transitions in the level scheme is based upon their intensities, energy sums and coincidence relationships.

A partial level scheme of ^{130}Cs based on the 5^- isomeric state ($T_{1/2} = 3.46$ m), established from the present experiment, is shown in fig. 1. It consists of five signature-splitted bands labelled as A, B, C, D and E. The level scheme has been substantially extended with the addition of about 70 transitions. All features reported by Sala *et al.* [6] are confirmed. The earlier observed bands based on the $\pi h_{11/2} \otimes \nu h_{11/2}$ (band A) and its side band partners (band B), $\pi g_{7/2} \otimes \nu h_{11/2}$ (band C) and $\pi d_{5/2} \otimes \nu h_{11/2}$ (band D) configurations have been extended to the higher spins $24\hbar$, $19\hbar$, $20\hbar$ and $17\hbar$, respectively. Band labelled E has been observed for the first time. The spectrum given in fig. 2 shows the various transitions of this band along with the connecting transitions to the earlier known levels [6].

Band A is the most intensely populated and is yrast at low spins. This band, extended to higher spins in the present level scheme, fits well in the excitation energy systematics of the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in both the isotopic ($Z = 55$) and the isotonic ($N = 75$) chains of nuclei (fig. 3) and hence, supports the recently suggested spin values for the $^{118\text{-}132}$Cs isotopes [2]. Band A shows anomalous signature splitting with the Routhian for the odd-spin signature ($\alpha = -1$) lying above that of the even-spin signature ($\alpha = 0$) with a small signature splitting, $\Delta e' \sim 50$ keV (fig. 4 (a)). The $E2$ transitions in the even-spin signature partner are stronger as compared to those in the odd-spin signature partner. An upbend is observed in this band at $\hbar\omega = 0.47$ MeV (fig. 4 (b)). Since both the odd-proton and odd-neutron occupy the lowest available $h_{11/2}$ orbital, the low-frequency breaking of the first pair of $h_{11/2}$ particles is blocked. Therefore, the observed upbend can be due to the alignment of the second and third $h_{11/2}$ proton or neutron quasiparticles. The ratios of the reduced intraband transition probabilities, $B(M1; I \rightarrow I-1)/B(E2; I \rightarrow I-2)$, for this band has an average value $\sim 6(\mu_n/eb)^2$ and exhibits an abrupt decrease to $\sim 1(\mu_n/eb)^2$ at the 16^+ state. To elaborate the systematic of the energy staggering in the $^{118\text{-}132}$Cs isotopes, the staggering plots for the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands are given in fig. 5. The low-spin signature of this band is inverted for all the isotopes and the inversion spin ($I_{\text{inv.}}$) increases with increasing neutron number for the ^{118,120,124,126}Cs isotopes. In ^{122}Cs, inversion is likely to occur at spin 17.5. In ^{128}Cs, inversion is not observed even up to spin 20. Interestingly, in ^{130}Cs, the magnitude of signature splitting is found to decrease up to $I = 15$ and then increases without restoring the normal signature splitting. In ^{132}Cs,

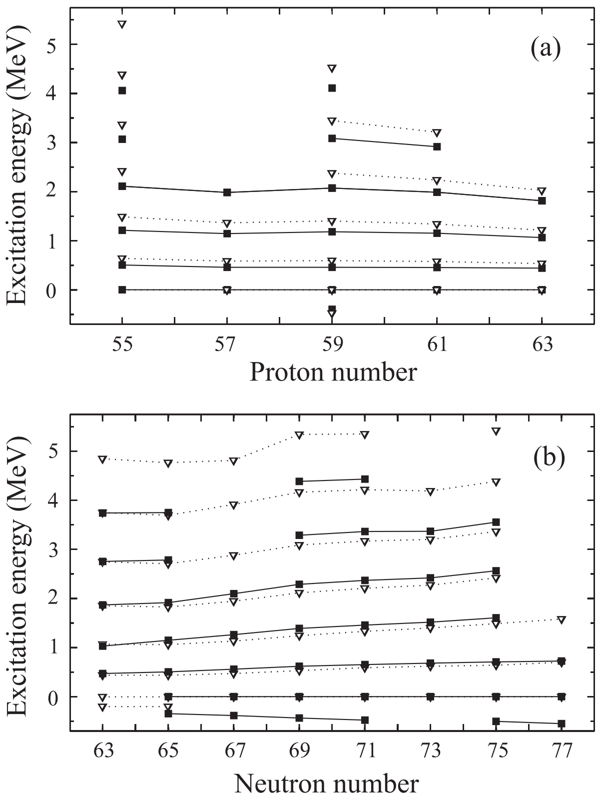

Fig. 3. Excitation energy systematics of the $\pi h_{11/2} \otimes \nu h_{11/2}$ band in (a) the doubly odd $^{118\text{-}130}$Cs isotopes, and (b) the doubly odd $N = 75$ isotones. The states at $I = 10$ and 11 are used as reference energy for the $\alpha = 0$ (triangle) and $\alpha = -1$ (square) signatures, respectively.

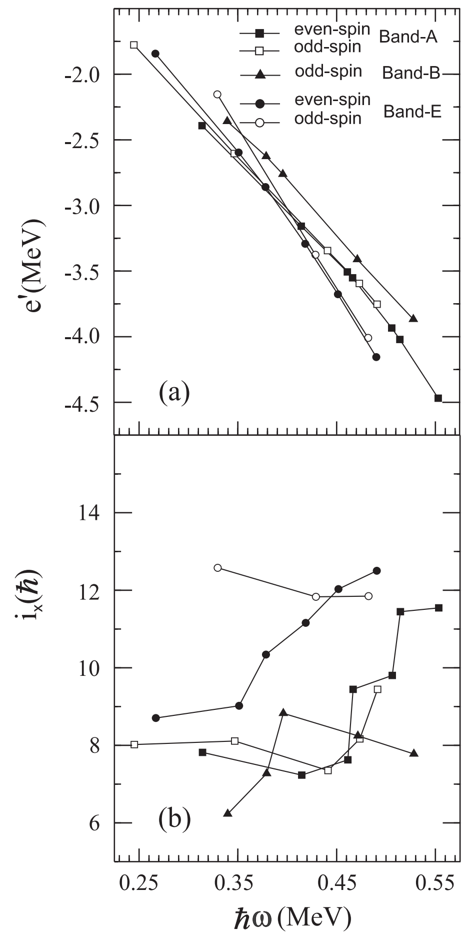

Fig. 4. Experimental (a) Routhians and (b) alignment plots for the bands labelled A, B and E using $J_0 = 5.8$ MeV$^{-1}\hbar^2$ and $J_1 = 50.8$ MeV$^{-3}\hbar^4$ as reference core parameters.

inversion is seen at a lower spin 13.5. A systematic calculation of signature splitting of the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in $A \sim 130$ mass region was performed by Tajima [4] using the particle-triaxial-rotor model with the inclusion of p-n interaction of Semmes and Ragnarsson [9]. It predicted inverted low-spin signature splitting with the ($I_{\text{inv.}}$) values to be 14.5, 16.0, 19.0 and 20.5 in the ^{120,124,126,128}Cs isotopes, respectively, and > 21, 18.5 and 15.0 in the $N = 75$ isotones, ^{132}La, ^{134}Pr and ^{136}Pm, respectively. Both the trends predict a higher value of $I_{\text{inv.}}$ for the ^{130}Cs nucleus.

Several new states comprising a positive-parity side band labelled B and having multiple connections to the even-spin signature partner ($\alpha = 0$) of the $\pi h_{11/2} \otimes \nu h_{11/2}$ band are observed in the present work (fig. 1). Tentative spin assignments for the states of the side band were done in view of the connecting transitions to various states of the yrast band and the multipolarity of the 167.1, 401.7, 454.0, 595.6 and 610.0 keV transitions to be mainly dipole and that of the 773.6 keV transition to be quadrupole as inferred from the measured DCO ratios. Recently, Starosta *et al.* [8] have reported similar side bands having linking transitions feeding to the states of the yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ band in the odd-odd $_{55}$Cs, $_{57}$La and $_{61}$Pm $N = 75$ isotones of ^{134}Pr, where such bands have been earlier reported by Petrache *et al.* [10]. In ^{124}Cs, similar set of bands have been observed by Gizon *et al.* [11]. Starosta *et al.* [8] have reported this side band in ^{130}Cs up to spin 15^+ with the 609, 677 and 595 keV transitions feeding to the states of the yrast band. In the present work, a number of cross-linking transitions between the states of the bands A and B have been observed. The relatively strong linking transitions with the band A suggest that the band B may be based on the configuration involving the unfavoured signature ($\alpha = +1/2$) of the $\pi h_{11/2}$ orbital. The Routhian for the band B lies ~ 250 keV above and parallel to that of the band A (fig. 4 (a)). The predicted signature splitting between the proton states is ~ 0.8 MeV in the frequency region where the band B is observed [11]. The observed difference between the Routhians of the two bands is less than the predicted value. The possiblity of this band resulting from coupling of the γ-phonon to the yrast band [10] is also less convincing because in this region the γ vibration energies are ≥ 0.60 MeV. Starosta *et al.* [8] and Dimitrov *et al.* [12] have interpreted these bands in the doubly odd $N = 75$ isotones using the microscopic tilted axis cranking (TAC) calculations. A planar solutions of 3D tilted axis cranking calculations for triaxial shapes define the left- and right-handed chiral systems out of the three angular momenta provided by the valence particles

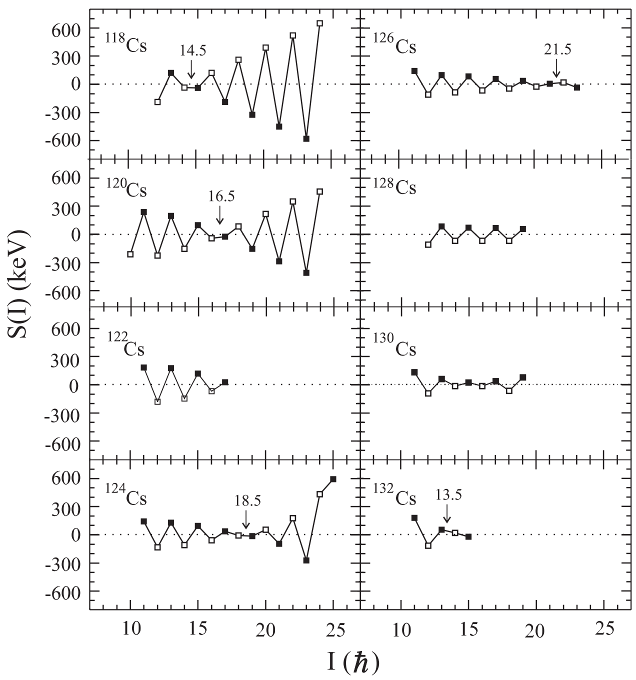

Fig. 5. Staggering plots $S(I) = E(I) - E(I-1) - [E(I+1) - E(I) + E(I-1) - E(I-2)]/2$ for the states of the $\pi h_{11/2} \otimes \nu h_{11/2}$ band in the doubly odd $^{118\text{-}132}$Cs isotopes. Solid and open symbols correspond to the $\alpha = -1$ and $\alpha = 0$ signature partner, respectively.

and the core rotation, which leads to spontaneous chiral symmetry breaking and the doublet bands. This interpretation as a collective chiral vibration appears to be more convincing, although small admixtures of the other above-mentioned alternatives are also possible.

The new band E with two signature components has been established up to $22\hbar$. This band is found to decay onto the earlier known negative-parity states with $I \leq 9\hbar$ through many pathways. In view of the connecting transitions to various low-lying negative-parity states and the multipolarity of the 336.4, 392.0, 454.0, 460.5, 474.7, 511.4 keV transitions to be dipole and the 446.3, 714.7 and 766.8 keV transitions to be quadrupole, as inferred from the DCO ratios, tentative spin assignments with negative parity were done for the states of this band. No connecting transition is found to the positive-parity states. The $E2$ transitions in the odd-spin signature partner are weaker than those in the even-spin signature partner and are seen at higher spins only. The even-spin partner shows band crossing at $\hbar\omega = 0.37$ MeV (fig. 4), which is likely to be due to the alignment of the $\nu h_{11/2}$ pair. The odd-spin signature partner shows large alignment. It is quite likely that the odd-spin signature partner is seen only after the alignment of the $\nu h_{11/2}$ pair. The Routhian for the odd-spin signature lies above that of the even-spin signature with a signature splitting, $\Delta e' \sim 80$ keV (fig. 4). This band also exhibits energy staggering and inversion is not seen. The average value for the $B(M1; I \to I-1)/B(E2; I \to I-2)$ ratios for this band is $\sim 4(\mu_n/eb)^2$. In view of its similarity with the band A, this band is likely to have the same proton partner *i.e.* $\pi h_{11/2}$, and the possible configuration for this band is $\pi h_{11/2} \otimes \nu g_{7/2}$. In that case, this band also shows anomalous signature splitting. The Routhian for the band E before the band crossing has slope similar to that of the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands (fig. 4 (a)). In the absence of the linking transitions to the positive-parity states, the possiblity of neutron partner for this band to be the $h_{9/2}$ or $f_{7/2}$ intruder orbital, which lead to positive-parity doubly decoupled band in the odd-odd nuclei, is unlikely [10].

We are thankful to the GDA scientific staff and pelletron accelerator crew at NSC. Financial assistance from NSC, UGC is duly acknowledged. Two of us AG and SC also acknowledge the financial support from INSA-DFG under Indo-German collaboration programme.

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