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Rotational structures in the ^{125}Cs nucleus

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Abstract. The collective band structures of the ^{125}Cs nucleus have been investigated by in-beam γ-ray spectroscopic techniques following the ^{110}Pd (^{19}F, 4n) reaction at 75 MeV. The previously known level scheme, with rotational bands built on $\pi g_{7/2}$, $\pi g_{9/2}$ and $\pi h_{11/2}$ orbitals, has been extended and evolves into bands involving rotationally aligned $\nu(h_{11/2})^2$ and $\pi(h_{11/2})^2$ quasiparticles. A strongly coupled band has been reassigned a high-K $\pi h_{11/2}\otimes\nu g_{7/2}\otimes\nu h_{11/2}$ three-quasiparticle configuration and a new side band likely to be its chiral partner has been identified. Configurations assigned to various bands are discussed in the framework of Principal/Tilted Axis Cranking (PAC/TAC) model calculations.

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The $_{55}$Cs isotopes lying in the transitional region above the $Z = 50$ and below the $N = 82$ shell closures are predicted to possess relatively flat potential-energy surfaces with respect to the quadrupole shape asymmetry parameter (γ) [1]. The triaxial deformation in this mass region has been evidenced by interpretation of observed crossing frequencies, staggering behaviour and $\Delta I = 1$ doublet bands, which have been explained as the manifestation of chirality [2]. Chiral bands have been observed in various odd-A [3] and odd-odd nuclei [4] with multiquasiparticle configurations that have substantial angular momentum components along the three principal axes. Another important feature is the magnetic dipole bands generated through the shears mechanism and have also been reported in the odd-A ^{131}Cs [5] and doubly odd ^{132}Cs isotopes [4]. Among the $_{55}$Cs isotopes, band-terminating states have been recently observed in ^{123}Cs at $I \sim 30\hbar$ [6]. The present in-beam gamma spectroscopic investigations are planned to probe for the above-mentioned structural features in the ^{125}Cs nucleus.

The excited states in the ^{125}Cs nucleus were populated using the ^{110}Pd (^{19}F, 4n) fusion-evaporation reaction at $E_{lab} = 75$ MeV. The ^{19}F ion beam was delivered by the 15 UD pelletron accelerator at the Inter-University Accelerator Centre (IUAC), New Delhi. The target consisted of a self-supporting 1 mg/cm^2 thick ^{110}Pd foil. The emitted γ-rays were detected using the Gamma Detector Array (GDA) comprising of 11 Compton-suppressed Ge detectors, one unsuppressed clover detector and a 14-element BGO multiplicity filter. The Ge detectors were mounted in three groups of four each making angles of 45°, 99° and 153° with the beam direction and having an inclination of ±23° with the horizontal plane. A total of 500 million coincidence events were collected in the experiment. Nuclides with major population in the reaction were ^{124}Cs ($\sim$ 25%), ^{125}Cs ($\sim$ 50%) and ^{124}Xe($\sim$ 10%). In the off-line analysis, the recorded coincidence data were sorted into 4k×4k E_γ-E_γ matrices. RADWARE graphical-analysis package [7] was used to establish coincidence and intensity relationships for various gamma transitions. The dipole/quadrupole nature of the γ-ray transitions was inferred from angular-correlation analysis based on the DCO method, which helped in level-spin assignments. The level scheme of ^{125}Cs is shown in fig. 1 with the band structures labeled 1-8.

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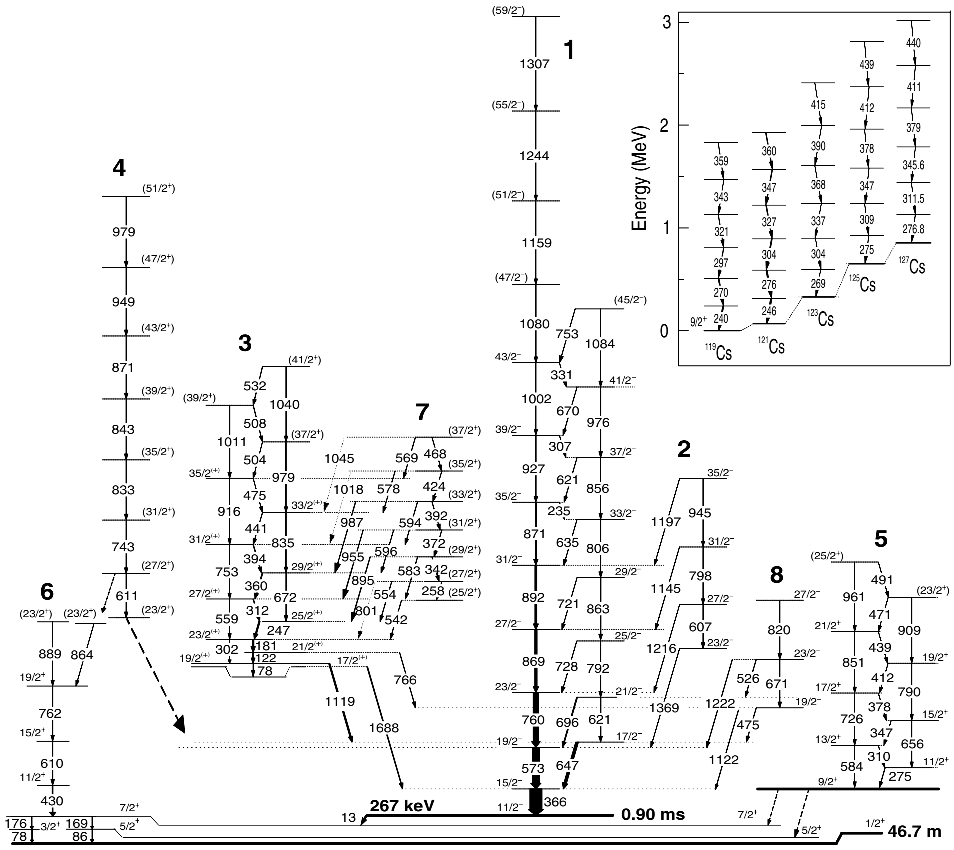

Fig. 1. The level scheme of ^{125}Cs established from the present work. The inset shows the excitation energy systematics of the $\pi g_{9/2}$ band in the $^{119-127}$Cs isotopes. The isomeric levels have been shown as thick lines.

The spin and parity of the ground state ($t_{1/2} = 46.7\,$m) have been assigned $I^\pi = 1/2^+$ by Arlt *et al.* [8] from the EC decay of ^{125}Ba. The earlier-known level schemes [9, 10] established through in-beam spectroscopy following fusion-evaporation reactions have been substantially extended up to $I = 59/2\hbar$ with the addition of about 40 transitions. The present level scheme preserves major features of the previous level schemes [9,10], which revealed rotational structures based on the $\pi h_{11/2}$ (band 1), the $\pi h_{11/2} \otimes \gamma$ vibrational band (band 2), $\pi g_{9/2}$ (band 5) and $\pi g_{7/2}$ (band 6) orbitals, a coupled band 3 that was assigned the $\pi g_{7/2} \otimes \nu h_{11/2} \otimes \nu g_{7/2}$ configuration and band 8. The negative-parity band 1 built on an $I^\pi = 11/2^-$ isomeric state ($t_{1/2} = 0.90$ (3) ms, excitation energy = 267 keV) is most intensely populated. The decay of this isomer has been adopted from the studies by Suguwara *et al.* [11]. Band 3 comprises strong dipole transitions along with weak $E2$ crossover transitions. It decays into the states of band 1 through high-energy dipole 1688, 1119 and 766 keV transitions. The present DCO analysis also confirms the previously established [10] dipole nature of these transitions. Several new states de-exciting to both the signatures of the coupled band 3 form a new side band 7. This band is composed of a regular sequence of low-energy transitions (likely to be $M1$) which are weak compared to the interband transitions to band 3. The γ-γ coincidence spectrum for these bands is shown in fig. 2. A newly observed sequence of transitions (likely to be $E2$) is shown as band 4 in fig. 1 The decay of this band is fragmented, mostly connecting to the low-lying states with

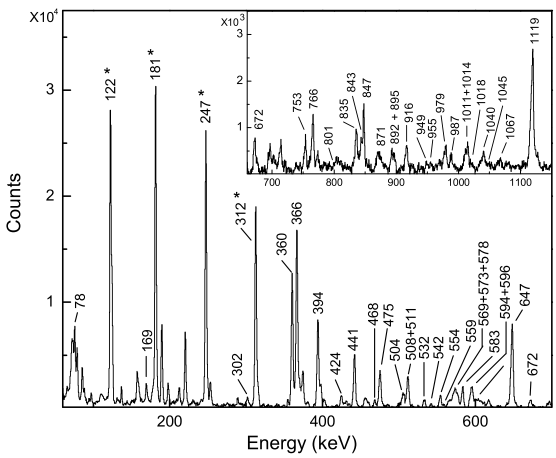

Fig. 2. The added γ-ray coincidence spectrum with gates on the transitions (indicated by *) of band 3. The unmarked peaks correspond to contaminations mainly from ^{124}Cs.

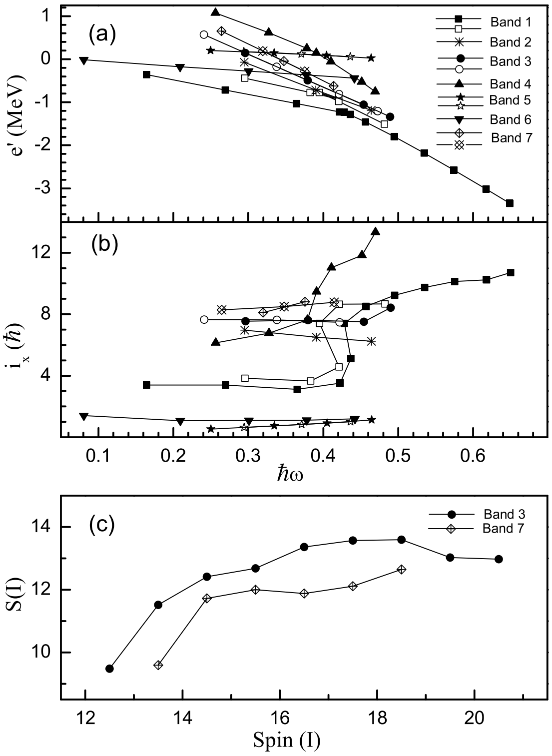

Fig. 3. Experimental plots for Routhian (a) and alignment (b) for bands 1–8, and staggering $S(I)$ for bands 3 and 7 (c).

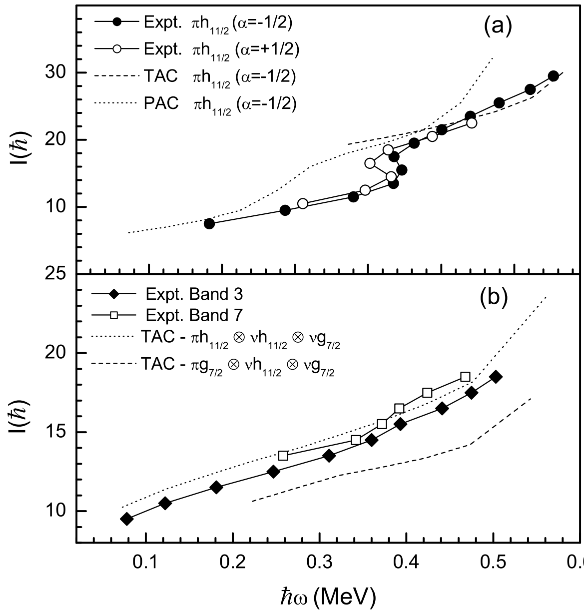

Fig. 4. The experimental spin (I) *vs.* rotational frequency ($\hbar\omega$) and those predicted using TAC/PAC model calculations for band 1 (a) and band 3 (b).

both the parities, and could not be established. On the basis of a partially identified decay pattern and the similarity to a band observed in ^{123}Cs (band 4 fig. 1 of [12]), the lowest observed state of the band is expected to have an excitation energy of ~ 3 MeV and $I^\pi = (23/2^+)$. In the previous works [9,10], the $\pi g_{9/2}$ band (band 5) is shown to decay to the $11/2^-$ isomeric state through 275 keV ($9/2^+ \to 11/2^-$) and 584 keV ($11/2^+ \to 11/2^-$) transitions without any spectroscopic measurements, which are indeed difficult due to weak population. The systematics of the $\pi g_{9/2}$ band in $^{119-127}$Cs [5,12,13] shown in inset of fig. 1 suggests that i) the 275 keV transition may be assigned as $11/2^+ \to 9/2^+$ and the 584 keV crossover transition as $13/2^+ \to 9/2^+$, and ii) the $9/2^+$ bandhead is expected to be a long-lived isomer that decays into the $7/2^+$ and $5/2^+$ states rather than the $11/2^-$ isomer. The energy for the $9/2^+$ bandhead is expected to be ~ 600 keV from the excitation energy parabola for the $_{55}$Cs isotopes. The $\pi g_{9/2}$ bandhead excitation energies in the $_{51}$Sb and $_{53}$I also exhibit a parabola-like trend as a function of neutron number [13].

The level scheme of ^{125}Cs shows properties typical of a collectively rotating deformed nucleus. Observed bands have been analyzed in the framework of either the Principal Axis Cranking (PAC) model calculations or the hybrid version of the Tilted Axis Cranking (TAC) model [14]. The pairing parameters are chosen as 80% of the odd-even mass difference, *i.e.*, $\Delta_\pi = 1.0906$ MeV and $\Delta_\nu = 0.758$ MeV. The total energy is minimized by using Nilsson-Strutinsky method. Both the favoured ($\alpha = -1/2$) and unfavoured ($\alpha = +1/2$) signatures for the yrast $\pi h_{11/2}$ band (band 1) exhibit almost constant initial alignment $\sim 4\hbar$ (fig. 3(b)) and large signature splitting ($\Delta e' \sim 360$ keV at $\hbar\omega = 0.30$ MeV). The signature partners with $\alpha = -1/2$ ($+1/2$) exhibit upbends at a rotational frequency of $\hbar\omega \sim 0.43$ (0.41) MeV, each with a corresponding alignment gain of $\sim 6\hbar$. On the basis of blocking arguments, these upbends are attributed to rotational alignment of a pair of $h_{11/2}$ neutrons that have oblate driving tendency. It may be noted that the signature splitting remains large ($\Delta e' \sim 180$ keV) after the alignment and the transitions from the favoured to unfavoured signature could also be observed. For this band, we have performed i) PAC model calculations in a self-consistent manner with a single-particle configuration $\pi h_{11/2}$ and ii) TAC calculations using the three-quasiparticle $\pi h_{11/2} \otimes (\nu h_{11/2})^2$ configuration. The self-consistent minimized energy locates the deformation parameters at $\epsilon_2 = 0.20$, $\epsilon_4 = 0.0$, $\gamma = 0°$ before the alignment; and $\epsilon_2 = 0.20$, $\epsilon_4 = 0.0$, $\gamma = 58°$ (nearly oblate) with an average tilt angle $\theta \sim 20°$ after the alignment. The calculations show good agreement with the experimental plot of spin (I) *vs.* rotational frequency ($\hbar\omega$) (fig. 4(a)). The TAC calculations result in $B(M1)/B(E2)$ ratios with values dropping from ~ 17 $(\mu_N/\text{eb})^2$ at $\hbar\omega = 0.37$ MeV to $\sim 7(\mu_N/\text{eb})^2$ at 0.67 MeV for the $\pi h_{11/2} \otimes (\nu h_{11/2})^2$ configuration. The experimental average value ~ 5 $(\mu_N/\text{eb})^2$ at $\hbar\omega \sim 0.45$ MeV compares well with the calculated ones. Also, the calculated $B(M1)$ values show a mild decreasing trend, viz, $B(M1) = 3.4$ μ_N^2 at 0.37 MeV and 2.2 μ_N^2

at 0.67 MeV, which support the magnetic-rotation character. Similar behaviour after the neutron pair alignment has also been observed in the $\pi h_{11/2}$ band of ^{127,131}Cs [5].

Band 3 shows a large initial alignment $\sim 7\hbar$ that remains constant in the frequency range 0.30–0.45 MeV and shows near to zero signature splitting. The $\pi g_{7/2} \otimes \nu h_{11/2} \otimes \nu g_{7/2}$ configuration has been previously associated with this band [10]. Indeed, it favours a three-quasiparticle configuration with likely involvement of the $\nu h_{11/2}$ quasiparticle on the basis of blocking arguments. However, it is difficult to reconcile the earlier assigned configuration, where the added alignment of the three quasiparticles is $\sim 4\hbar$ that is well below the observed value $\sim 7\hbar$. It may be added that this band does not decay into the states of the $\pi g_{7/2}$ and $\pi(g_{9/2})$ bands, which makes the other possible configurations, viz, $\pi g_{7/2}/\pi(g_{9/2}) \otimes \nu(h_{11/2})^2$ unlikely. Band 3 feeds states of both the signatures of the $\pi h_{11/2}$ band. Further high-K $\nu h_{11/2} \otimes \nu g_{7/2}$ bands characterized by strong $\Delta I = 1$ transitions and lack of signature splitting have systematically been observed in the even-even $^{124-128}$Xe and $^{124-128}$Ba isotopes. In an odd-Z nucleus, this high-K two-quasineutron configuration would be coupled to the yrast odd $\pi h_{11/2}$ quasiproton, *i.e.*, the $\pi h_{11/2} \otimes \nu h_{11/2} \otimes \nu g_{7/2}$ configuration is favoured for band 3. Strongly coupled bands with configurations involving similar three different quasiparticles $\pi g_{7/2}/\pi h_{11/2} \otimes \nu h_{11/2} \otimes \nu g_{7/2}$ have been seen in the Cs and La isotopes [5,12], where the $\pi g_{7/2}$ or $\pi h_{11/2}$ orbital whichever is lower in energy is preferred in the configuration. We have carried out the TAC calculations for the $\pi g_{7/2}/\pi h_{11/2} \otimes \nu h_{11/2} \otimes \nu g_{7/2}$ configurations. The energy minimization fixes the deformation parameters at $\epsilon_2 = 0.202$, $\epsilon_4 = 0.0$, $\gamma = 0°$ (prolate shape) and an average tilt angle $\theta \sim 32°$ for the earlier assigned $\pi g_{7/2} \otimes \nu h_{11/2} \otimes \nu g_{7/2}$ configuration [10] and $\epsilon_2 = 0.202$, $\epsilon_4 = 0.0$, $\gamma = 4°$ (nearly prolate) with an average tilt angle $\theta = 60°$ for the $\pi h_{11/2} \otimes \nu h_{11/2} \otimes \nu g_{7/2}$ configuration. The observed bandhead spin and overall plot of spin, I, *vs.* the rotational frequency, $\hbar\omega$, is reproduced for the $\pi h_{11/2} \otimes \nu h_{11/2} \otimes \nu g_{7/2}$ configuration (fig. 4(b)). Further, the calculations show variation in the $B(M1)/B(E2)$ values ~ 16 $(\mu_N/\mathrm{eb})^2$ at $\hbar\omega = 0.07$ MeV to ~ 2 $(\mu_N/\mathrm{eb})^2$ at $\hbar\omega = 0.60$ MeV. These results compare reasonably well with the average observed value ~ 10 $(\mu_N/\mathrm{eb})^2$. The interband $\Delta I = 1$ and $\Delta I = 2$ transitions from levels of new band 7 to those of band 3 supports the same parity for these bands. The Routhians for band 7 lie about 250 keV above and parallel to that for band 3 (fig. 3(a)). These bands show a smooth variation of the staggering parameter defined as $S(I) = [E(I) - E(I-1)]/2I$ as a function of spin (fig. 3(c)). These observed characteristics are in adherence to the observed chiral bands in the region. In odd-A ^{125}Cs, configuration for the chiral bands is based on the yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration responsible for the chirality in odd-odd Cs isotopes coupled with a normal parity $g_{7/2}$ quasineutron, which acts as a spectator. Similar chiral bands have been observed in odd-Z, even-N ^{105}Rh nucleus [15], which involve a spectator $g_{7/2}$ quasineutron coupled to the yrast $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration yielding chiral band in the odd-odd ^{104,106}Rh isotopes. The measurement of transition probabilities and refined calculations would be very helpful to corroborate this suggestion.

The positive-parity band 4 exhibits large initial alignment $\sim 7\hbar$ (fig. 3(b)), which implies a three-quasiparticle configuration with likely involvement of the aligned $\pi(h_{11/2})^2$ or $\nu(h_{11/2})^2$ pair. The alignment plot for this band exhibits an upbend at $\hbar\omega \sim 0.40$ MeV with an alignment gain $\geq 6\hbar$. On the basis of blocking arguments, the $\pi g_{9/2}/\pi g_{7/2} \otimes \pi(h_{11/2})^2/\nu(h_{11/2})^2$ configurations are favourable for the lower observed part of band 4. This band is observed to be decoupled and does not feed the $\pi g_{9/2}$ band (band 5), which makes the configurations involving the $\pi g_{9/2}$ quasiparticle unlikely. TAC calculations favour the $\pi g_{7/2} \otimes \nu(h_{11/2})^2$ configuration with the deformation parameters $\epsilon_2 = 0.181$, $\epsilon_4 = 0.0$, $\gamma = 60°$ with an average tilt angle $\sim 40°$ (the oblate shape). The calculated excitation energy plot is in reasonable agreement with the expected experimental value. The PAC calculations for $\pi g_{7/2} \otimes \pi(h_{11/2})^2$ configuration result in the deformation parameters $\epsilon_2 = 0.195$, $\epsilon_4 = 0.0$ and $\gamma = 0°$ (the prolate shape). The calculated plot of I *vs.* $\hbar\omega$ shows a trend similar to the experimental one, however, the predicted bandhead excitation energy for this configuration is ~ 4 MeV higher than that for the $\pi g_{7/2} \otimes \nu(h_{11/2})^2$. The calculated $B(M1)/B(E2)$ ratios for both the configurations are small favouring a decoupled band. More experimental information for this band is indeed desirable for a conclusive configuration assignment.

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