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Letter

Band structures of the ^{123}Cs nucleus

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Abstract. Band structures of the ^{123}Cs nucleus have been investigated using the ^{100}Mo(^{28}Si, p4n) reaction at a beam energy of 130 MeV. The previously observed rotational bands based on $\pi h_{11/2}$, $\pi g_{7/2}$ and $\pi g_{9/2}$ orbitals have been extended. The excitation energies of these bands have been established with the help of interband transitions and those connecting to the low-energy levels established from the β^+/EC decay of ^{123}Ba ($T_{1/2} = 2.7$ m). The bandhead of the $\pi g_{9/2}$ band at the 328.1 keV ($I^\pi = 9/2^+$) is proposed to be isomeric following arguments based on the intensity balance of the feeding and de-exciting γ transitions. New multiquasiparticle bands based on $\pi h_{11/2} \otimes \nu h_{11/2} \otimes \nu g_{7/2}$, $\pi g_{7/2} \otimes \pi(h_{11/2})^2$ and $\pi g_{7/2} \otimes \pi(h_{11/2})^2 \otimes \nu(h_{11/2})^2$ configurations have been identified.

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

The $_{55}$Cs nuclei lie in the transitional region ranging from the primarily vibrational $_{50}$Sn nuclei to the well-deformed $_{57}$La and $_{58}$Ce nuclei. Investigations in the odd-Z nuclei in this region, particularly the $_{53}$I isotopes, resulted in multiplicity of shapes and richness of the nuclear-structure phenomena. For the $_{55}$Cs nuclei, the proton Fermi surface lies in vicinity of the $h_{11/2}$ subshell and the active proton orbitals are $g_{7/2}$, $d_{5/2}$, the $g_{9/2}$ extruder and the unique parity $h_{11/2}$ intruder. The neutron Fermi surface lies in the $h_{11/2}$ subshell. The number of valence nucleons outside the spherical $_{50}$Sn$_{64}$ core is sufficient to induce quadrupole nuclear deformation that is generally soft with respect to the triaxiality parameter (γ). For odd-Z nuclei, the shape at low rotational frequencies is mainly influenced by the valence quasiproton. At higher frequencies, additional rotationally aligned $\nu(h_{11/2})^2$ quasiparticles are expected to polarize the γ soft core depending upon the position of the neutron Fermi surface in the $h_{11/2}$ subshell. The triaxial deformation of the core has been established through the interpretation of crossing frequencies and staggering behaviour [1,2] and recently observed chiral twin bands in doubly odd nuclei [3]. Collectively rotating prolate and oblate nuclear shapes for the $\pi h_{11/2}$ and $\pi g_{7/2}$ configurations have been found to coexist in ^{119,121}I [4,5] and ^{127}Cs nuclei [6]. Interesting features such as smooth and abrupt band termination have been observed in various Sb, Te, I, Xe and La isotopes [7,8]. The [404]9/2$^+$ proton orbital arising from the $g_{9/2}$ subshell plays a prominent role in the stabilization of large deformation in the neutron-deficient isotopes. Additional interest in this mass region arises from the recently observed strongly coupled $\Delta I = 1$ rotational sequences with configurations involving three different quasiparticles at an excitation energy of ~ 2 MeV in odd-A $^{117-125}$I [4,5,9] and ^{121,125,127}Cs [10,11,6] nuclei.

The purpose of the present in-beam gamma spectroscopic investigation is to explore structural features of the ^{123}Cs nucleus. The low-lying states of ^{123}Cs following the β^+/EC decay of ^{123}Ba have been well established recently by Gizon and coworkers [12]. The high-spin structures of this nucleus have previously been studied by Hughes *et al.* [13] and Liden *et al.* [10] using the nuclear fusion-evaporation reactions. Band structures based on the $\pi h_{11/2}$, $\pi g_{7/2}$ and $\pi g_{9/2}$ orbitals were reported with uncertain bandhead energies for the latter two.

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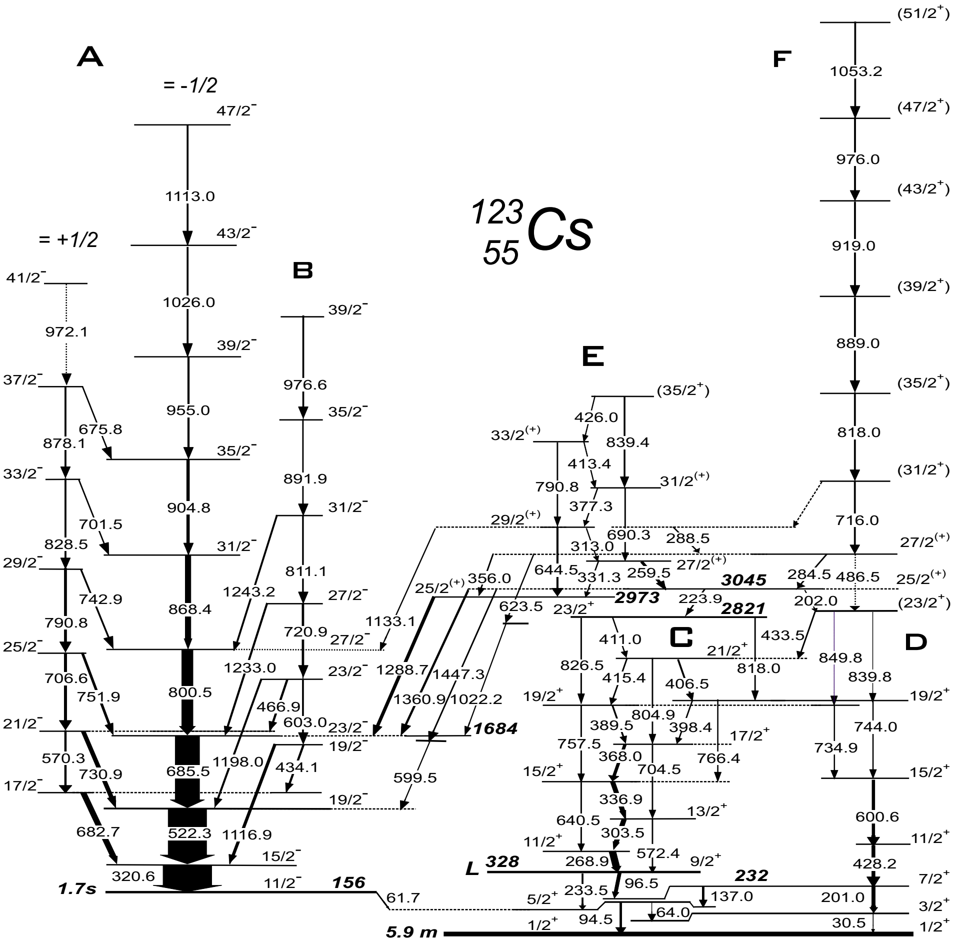

Fig. 1. The level scheme of ^{123}Cs established from the present work. The bold numbers represent the level energy in keV. The isomeric levels have been shown as thick lines.

Excited states in the ^{123}Cs nucleus were populated utilizing the ^{100}Mo(^{28}Si, p4n) reaction at a beam energy of 130 MeV. The ^{28}Si beam was provided by the 15 UD pelletron accelerator at Nuclear Science Centre (NSC), New Delhi. The target consisted of 3 mg/cm^2 of ^{100}Mo foil rolled onto a Pb backing of 15 mg/cm^2. The γ-γ coincidence data were obtained using INGA spectrometer consisting of 8 Compton-suppressed Clover detectors [14]. These detectors were mounted in two groups making angles of ±81° and ±141° with the beam direction and tilted at ±18° with respect to the horizontal plane. The coincidence data were taken using acquisition electronics with resolving time of $2\tau = 200$ ns. A total of 5×10^8 events were collected with condition of firing of at least two Clover detectors in coincidence. About 14% of the total cross-section constituted the p4n reaction channel leading to ^{123}Cs. Other significantly populated nuclides were ^{124}Cs (12%), ^{123}Ba (8%), ^{124}Ba (25%), ^{120}Xe (5%) and ^{121}Xe (10%). The coincidence events were sorted into different E_γ-E_γ matrices using INGASORT, which were used for building the level scheme of ^{123}Cs. An angular correlation analysis based on the DCO method [15] was used for characterizing the dipole/quadrupole nature of the γ transitions. The partial level scheme of ^{123}Cs established from the present work is displayed in fig. 1 and has been arranged into bands labelled as A, B, C, D, E and F. The placement of the gamma transitions in the level scheme is based upon their intensities, energy sums and coincidence relationships. The added γ-ray coincidence spectrum with gates on the low-lying 201, 269 and 304 keV transitions is shown in fig. 2.

The ground state ($T_{1/2} = 5.9$ m) of ^{123}Cs has been assigned $I^\pi = 1/2^+$ [16]. An excited isomeric state ($T_{1/2} = 1.7$ s) with $I^\pi = 11/2^-$ has also been identified [10]. In the present work, the earlier observed bands based on the $\pi h_{11/2}$ (band A), $\pi g_{9/2}$ (band C) and $\pi g_{7/2}$ (band D) orbitals and the γ vibrational band (band B) [10,13] have been seen along with two newly identified bands labelled as E and F. The earlier observed level scheme has been extended with the addition of 40 new transitions. The 30.5 and 61.7 keV transitions in the decay of isomeric levels were not seen in the present experiment and their placements have been adopted from the β^+/EC decay study of ^{123}Ba [12]. There is an indication of linking transitions from levels of band F to those of band E, which could not

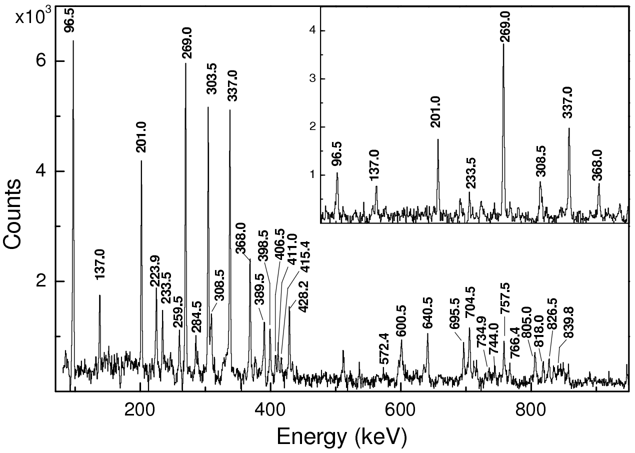

Fig. 2. The added γ-ray coincidence spectrum with gates on the 201, 269 and 304 keV transitions. The inset displays the spectrum with gate on the 304 keV transition.

be confirmed as most of the gated spectra for these bands were contaminated by other reaction channels.

The levels at 2973 keV (band E) and 3045 keV (band F) were assigned spin 25/2 $^{(+)}$ on the basis of high-energy 1288.7 and 1360.9 keV dipole transitions taken to be $E1$, which feed the $23/2^-$ level of band A. The $25/2^{(+)}$ level at 3045 keV further decays to the $23/2^+$ levels of bands C and D through low-energy 223.9 and 202.0 keV dipole transitions, respectively, taken to be $M1$. The dipole nature of the 1133.1 keV transition and the observation of linking transitions to various low-lying negative-parity states further support the spin assignments. The angular correlation analysis for most of the transitions in band F was not possible due to contamination and weak intensity.

The bandhead energies of the $\pi g_{9/2}$ (band C) and $\pi g_{7/2}$ (band D) bands have been determined on the basis of observed linking transitions to the low-energy level scheme from the β^+/EC decay of ^{123}Ba ($T_{1/2}$ = 2.7 m) [12] and the intensity balance from the present coincidence data. It is worth mentioning that the internal conversion-corrected intensity of the 96.5 keV ($M1$) transition is balanced by that of the 137.0 ($M1$) and 201.0 ($E2$) keV transitions in the gated spectra of higher-lying transitions (time window chosen for the present sorted coincidence data $\sim$ 100 ns). This implies that the 232 keV level is certainly not an isomer with $T_{1/2}$ of the order of 100 ns. However, a loss of about 50% gamma transition intensity has been observed at the 328 keV ($9/2^+$) state in the gated spectra of higher-lying 303.5 (fig. 2) and 336.9 keV transitions. This could be explained by a lifetime of few tens of nanoseconds for this level. Based upon this observation it is suggested that the 328 keV level ($9/2^+$) is isomeric and is the bandhead for the $\pi g_{9/2}$ band. It is likely that the decay curves obtained for the 201 and 137 keV gamma rays by Gizon *et al* [12] using the in-beam recoil catcher measurements were due to the 328 keV isomeric state rather than the one proposed close

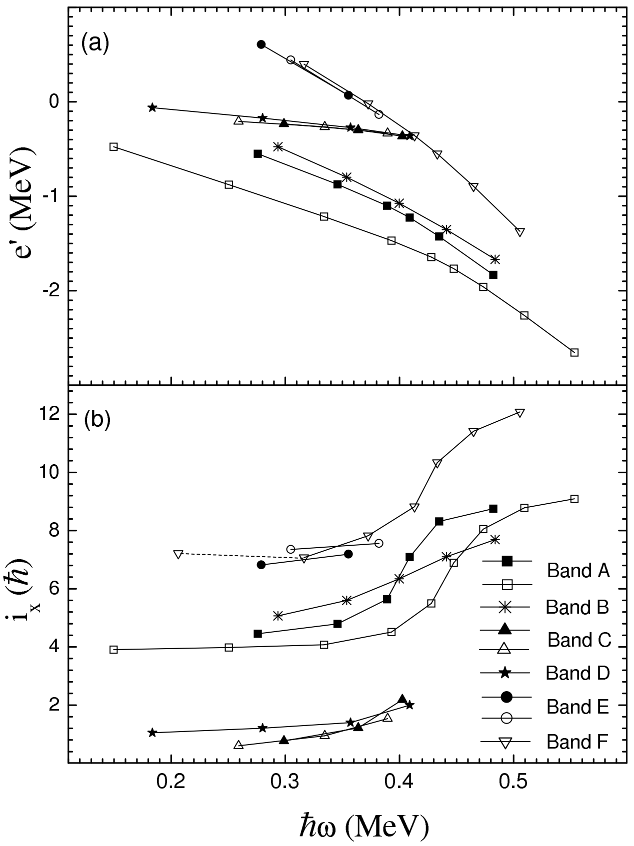

Fig. 3. Experimental Routhian (a) and alignment (b) plots for the bands observed in ^{123}Cs using $J_0 = 17.0$ MeV$^{-1}\hbar^2$ and $J_1 = 25.8$ MeV$^{-3}\hbar^4$ as reference core parameters.

to the 232 keV level ($T_{1/2}$ = 114 ns) with uncertain excitation energy. It may be added that the 96.5 and 233.5 keV transitions depopulating the 328 keV level were not observed in the earlier in-beam experiments [10,13] and the investigations related to their decay curves were not mentioned in [12]. The isomeric 328.1 keV level is assigned $9/2^+$ rather than the earlier proposed ($5/2^+$, $7/2^+$) spin value [12].

The negative-parity band (labelled A) is the most intensely populated and remains yrast till the excitation energy of 7.35 MeV observed in the present experiment. It is based on the unique parity $h_{11/2}$ proton orbital and both the favoured ($\alpha = -1/2$) and unfavoured ($\alpha = +1/2$) signatures are observed. The $\Delta I = 1$ transitions from the unfavoured signature states to the favoured ones have been observed. Band A shows large initial alignment ($\sim 4\hbar$) and signature splitting ($e' \sim 400$ keV at $\hbar\omega = 0.30$ MeV) exhibiting a trend significantly decreasing with frequency (fig. 3). The low-Ω $h_{11/2}$ [550]$1/2^-$ orbital, which is near the proton Fermi surface, accounts for the observed large initial alignment and large signature splitting. The signature partners with $\alpha = -1/2$ ($+1/2$) exhibit upbends at a rotational frequency of $\hbar\omega \sim 0.43$ MeV, each with a corresponding alignment gain of $\sim 4.5\hbar$ (fig. 3(b)). On the basis of blocking arguments, these upbends are due to the rotational alignment of a pair of $h_{11/2}$ neutrons. The first proton crossing is observed at ~ 0.37 MeV in the even-even ^{124}Ba nucleus [17] and the second proton crossing is calculated to occur around 0.65 MeV [10]. The signature splitting in the yrast band remains large ($\Delta e' \sim 200$ keV) after the alignment indicating that the nuclear shape remains close to prolate. The systematic of the neutron crossing in the yrast band in the odd-A $^{119-131}$Cs isotopes has been discussed by Hughes *et al.* [11]. The nature of the shape-driving force of the $\nu(h_{11/2})^2$ alignment on the core in ^{123}Cs was obtained by the cranked shell model (CSM) calculations of the single-quasineutron Routhian at $\hbar\omega = 250$ keV as a function of γ (fig. 9 of [11]) and $\gamma = -25°$ is favoured by the aligning neutrons. Staggering between the favoured and unfavoured $\pi h_{11/2}$ bands in ^{123}Cs which depends on γ is similar to that observed in the ^{125,127,129}Cs nuclei, the $17/2^-$ and $21/2^-$ levels are above the $19/2^-$ and $23/2^-$ levels, respectively, and for the $25/2^-$ and higher spins the unfavoured states lie below the next favoured states [2]. Band B is the γ vibrational band built on the favoured signature partner of the $h_{11/2}$ band and is a feature common to nuclei in this mass region [4,6,11,13,18]. Each of these states lies ~ 1 MeV above the corresponding yrast rotational state, and decays to the yrast state via $E2$ transition. In addition, $I \rightarrow I-1$ ($M1$) transitions are also observed from the γ vibrational states to the unfavoured signature component of the $\pi h_{11/2}$ band.

The strongly coupled band C has been assigned a $g_{9/2}$ proton hole configuration. The $[404]9/2^+$ component of the $\pi g_{9/2}$ orbital, which originates from below the $Z = 50$ shell closure, becomes energetically favourable at a prolate deformation of $\epsilon_2 \sim 0.25$. This high-Ω value is responsible for the near to zero signature splitting for this band. In addition, the $\Delta I = 1$ transitions linking states of opposite signatures are relatively strong compared to the $E2$ crossover transitions ($B(M1)/B(E2) \sim 3$ $(\mu_N/\mathrm{eb})^2$). The large $B(M1)/B(E2)$ values result from the large positive g-factor ~ 1.27 [18] and high-K value. Similar band structures have systematically been observed throughout the light odd-A $^{117-127}$Cs nuclei [19,10,13,11,6]. The 328 keV bandhead excitation energy in ^{123}Cs fits well in the parabola-like curve as a function of N with minima dropping phenomenally to become ground state in ^{119}Cs$_{64}$ [10]. The other positive-parity band labelled D, built on the $7/2^+$ state, has been assigned the $\pi g_{7/2}$ configuration. For the position of the proton Fermi surface, the $\pi g_{7/2}$, $\Omega = 3/2$ orbital is expected to give rise to a decoupled band and as a result only the favoured $\alpha = -1/2$ signature partner is observed. Similar bands have also been observed in the ^{125,127}Cs isotopes [11,6]. This band has interlinking dipole and quadrupole transitions with the high-Ω $\pi g_{9/2}$ $[404]9/2^+$ band.

The positive-parity band F has a decoupled structure. This band also shows a large initial alignment $\sim 7.5\hbar$ (fig. 3(b)) indicating it to be based on a three-quasiparticle configuration. The band exhibits an upbend at a rotational frequency of $\hbar\omega \sim 0.42$ MeV with an alignment gain of $4.5\hbar$. This trend is similar to the one corresponding to the alignment of the $\nu(h_{11/2})^2$ quasiparticles in the $\pi h_{11/2}$ band. So, the highest portion of band F is a five-quasiparticle structure involving $(\nu h_{11/2})^2$. On the basis of blocking arguments, the involvement of the $\nu h_{11/2}$ quasiparticle in the configuration of band F before the $\nu(h_{11/2})^2$ alignment can be ruled out. The large value of the initial alignment $\sim 7.5\hbar$ can be accounted only by the $\pi(h_{11/2})^2$ alignment as the $\pi g_{7/2}$ and $\pi g_{9/2}$ bands exhibit a $\sim 1\hbar$ alignment. The first $\pi(h_{11/2})^2$ alignment is not blocked in the $\pi g_{9/2}$ or $\pi g_{7/2}$ bands. In the neighbouring isotone ^{124}Ba [17], the $\pi(h_{11/2})^2$ alignment is observed at 0.37 MeV, similar to that observed in the $\pi g_{9/2}$ band of ^{123,125}La [20,18]. An alignment gain of $\sim 8\hbar$ was observed for the $\pi(h_{11/2})^2$ alignment in the $\pi g_{7/2}$ band in ^{125}La. Further, the decoupled nature of the band favours the involvement of $\pi g_{7/2}$. So, $\pi g_{7/2} \otimes \pi(h_{11/2})^2$ is the likely configuration for band F.

The new positive-parity band labelled E has a strongly coupled structure with the $\Delta I = 1$ transitions linking states of opposite signatures, which are relatively strong compared to the $E2$ crossover transitions ($B(M1)/B(E2) \sim 2$ $(\mu_N/\mathrm{eb})^2$). It lacks signature splitting ($\Delta e' \sim 0$) and exhibits a large initial alignment $\sim 7\hbar$ (fig. 3) suggesting it to be a three-quasiparticle band. The coupled nature of this band indicates the involvement of the $\pi g_{9/2}$ quasiparticle. The $\pi g_{9/2} \otimes \pi(h_{11/2})^2$ is a possible configuration accounting for a large initial alignment. However, the calculations using a geometrical model developed by Dönau and Frauendorf [21] give $B(M1)/B(E2)$ values < 0.5 [10] for the $\pi g_{9/2} \otimes \pi(h_{11/2})^2$ configuration over the observed spin range. The possiblity of a $\pi g_{9/2} \otimes \nu(h_{11/2})^2$ configuration involving a $\nu(h_{11/2})^2$ pair with an alignment gain of $\sim 4\hbar$ is unlikely. Also band E is not a regular extension of the $\pi g_{9/2}$ band (band C) as observed for the $\pi g_{9/2} \otimes \nu(h_{11/2})^2$ band in ^{119}I [5]. The other possible configuration accounting for a $\sim 7\hbar$ alignment is $\pi h_{11/2} \otimes \nu h_{11/2} \otimes \nu g_{7/2}/d_{5/2}$. A similar band de-exciting through many dipole transitions to the $\pi h_{11/2}$ band in ^{119}I [5] has been assigned the $\pi h_{11/2} \otimes \nu h_{11/2} \otimes \nu d_{5/2}$ configuration. However, the $\pi h_{11/2} \otimes \nu h_{11/2} \otimes \nu g_{7/2}$ configuration is preferred for band E as the $B(M1)/B(E2) \sim 2$ $(\mu_N/\mathrm{eb})^2$ calculated using the geometrical model [21] agree with the observed values. The calculated values for the $\pi h_{11/2} \otimes \nu h_{11/2} \otimes \nu d_{5/2}$ configuration are ~ 4 $(\mu_N/\mathrm{eb})^2$.

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