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Band structure change in $Z > 50$ region: Doubly odd ^{120,122}Cs and ^{126,128}La

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$\Delta J = 1$ band structures were found in the doubly odd ^{120,122}Cs and ^{126,128}La nuclei via γ-ray spectroscopy following heavy-ion-induced reactions. The band characteristics for the $Z > 50$ transition region (nonstaggered spacings and positive $E2/M1$ mixing ratios), that are associated with the $g_{9/2}$ proton-hole intruder, were observed in ^{120}Cs, but changed to significant staggering and negative mixing ratios along with increased $E2$ crossover branching in the other three nuclei.

The $g_{9/2}$ proton-hole intruder state has been observed to induce systematic $\Delta J = 1$ collective bands in the odd-Sb, -I, and -Cs nuclei of the $Z > 50$ transition region.[1,2] Recent studies have shown that the stable collectivity associated with the $g_{9/2}$ proton hole persists along with a decoupled $h_{11/2}$ neutron as yrast $\Delta J = 1$ bands in the doubly odd $^{112-120}$Sb (Ref. 3) and $^{116-122}$I (Ref. 4) nuclei. The empirical characteristics of these $\Delta J = 1$ bands observed both in the odd and doubly odd nuclei are smoothly increasing band spacings (nonstaggered) and positive $E2/M1$ mixing ratios for the $\Delta J = 1$ transitions. To date, the theoretical interpretations for this collectivity are not unique.[5-8]

To further explore the additional sensitivity to the collectivity provided by the combined odd valence proton and neutron, studies of the doubly odd-^{120,122}Cs and -^{126,128}La nuclei were undertaken. An extended mapping of the collective properties can yield valuable information about the development of the potential energy surfaces. A $\Delta J = 1$ bandlike structure was observed in each of these four nuclei. The band in ^{120}Cs followed the characteristics of those previously observed[3,4] in the doubly odd-Sb and -I nuclei. Surprisingly for ^{122}Cs and ^{126,128}La, an abrupt change in the nature of the band structure was observed; the $\Delta J = 1$ band spacings became staggered in energy and the sign of the $E2/M1$ mixing ratios became negative, along with increased $E2$ crossover branching. This change in the $\Delta J = 1$ band characteristics, which suggests either an alteration of the core shape or different particle configurations, is the focus of this paper.

Prior to this study, no level scheme information was available for ^{120,122}Cs or ^{126,128}La, except for β-decay studies which suggest low-lying high-spin isomers.[9,10] In ^{122}Cs, β-decay measurements identified three isomeric states with half lives of 21 sec (ground state), 4.2 min, and 0.36 sec; a spin parity of $J^\pi = 1^+$ was assigned to the ground state.[10] To populate the high-spin states of these neutron deficient, doubly odd nuclei, the following reactions with isotopically enriched self-supporting targets were used: ^{112}Sn(^{12}C, $p3n$)^{120}Cs at a lab energy of 86 MeV, ^{109}Ag(^{18}O, $5n$)^{122}Cs at 96 MeV, ^{112}Sn(^{16}O,pn)^{126}La and ^{103}Rh(^{27}Al,$p3n$)^{126}La at 72 and 137 MeV, respectively, and ^{116}Sn(^{14}N, $2n$)^{128}La at 60 MeV. The heavy-ion beams were provided by the Stony Brook FN tandem and, in several cases, the superconducting LINAC. For the purpose of this investigation, in-beam measurements of γ-ray excitation functions, γ-γ-t coincidences, and γ-ray angular distributions were performed with Ge detectors. Based on excitation function measurements and comparisons with fusion-evaporation reaction calculations, optimal bombarding energies for the different reactions were chosen. Preliminary reports of this work have been made.[11]

Identification of specific residual nuclei was obtained from the γ-ray excitation functions. In the study of ^{126}La, the two excitation functions, ^{16}O + ^{112}Sn and ^{27}Al + ^{103}Rh, aided by different background γ rays, facilitated the identification of the nucleus. (Earlier preliminary measurements[12] had not separated the ^{126,128}La γ-ray cascades from those in competing channels with ^{125,127}La residual nuclei, respectively.) The γ-γ-t coincidence information allowed the extraction of the γ-ray cascades associated with the yrast $\Delta J = 1$ band in each nucleus. The data include coincidence information for the low-spin states, which is usually complicated for the doubly odd nuclei and not necessarily connected to the high-spin cascade. A sum-gate coincidence spectrum for the band structure in ^{122}Cs is shown in Fig. 1. Gated γ-ray spectra for all of these nuclei are presented[13] in the Ph.D. thesis of Quader. Typical high-spin γ spectra for the $\Delta J = 1$ bands in the lighter doubly odd nuclei of this region are shown in Ref. 4. The angular distribution measurements provided information on the γ-ray intensities and transition multipolarities.

From the present data, a number of γ-ray transitions were identified in ^{120}Cs, including the cascade of $\Delta J = 1$ γ-ray transitions forming a high-spin band, as shown in Fig. 2. The level spacings of the band increase with spin and show no significant staggering. The angular distribution results of the $\Delta J = 1$ γ rays are consistent with positive $E2/M1$ mixing ratios. Thus, the characteristics of this band are similar

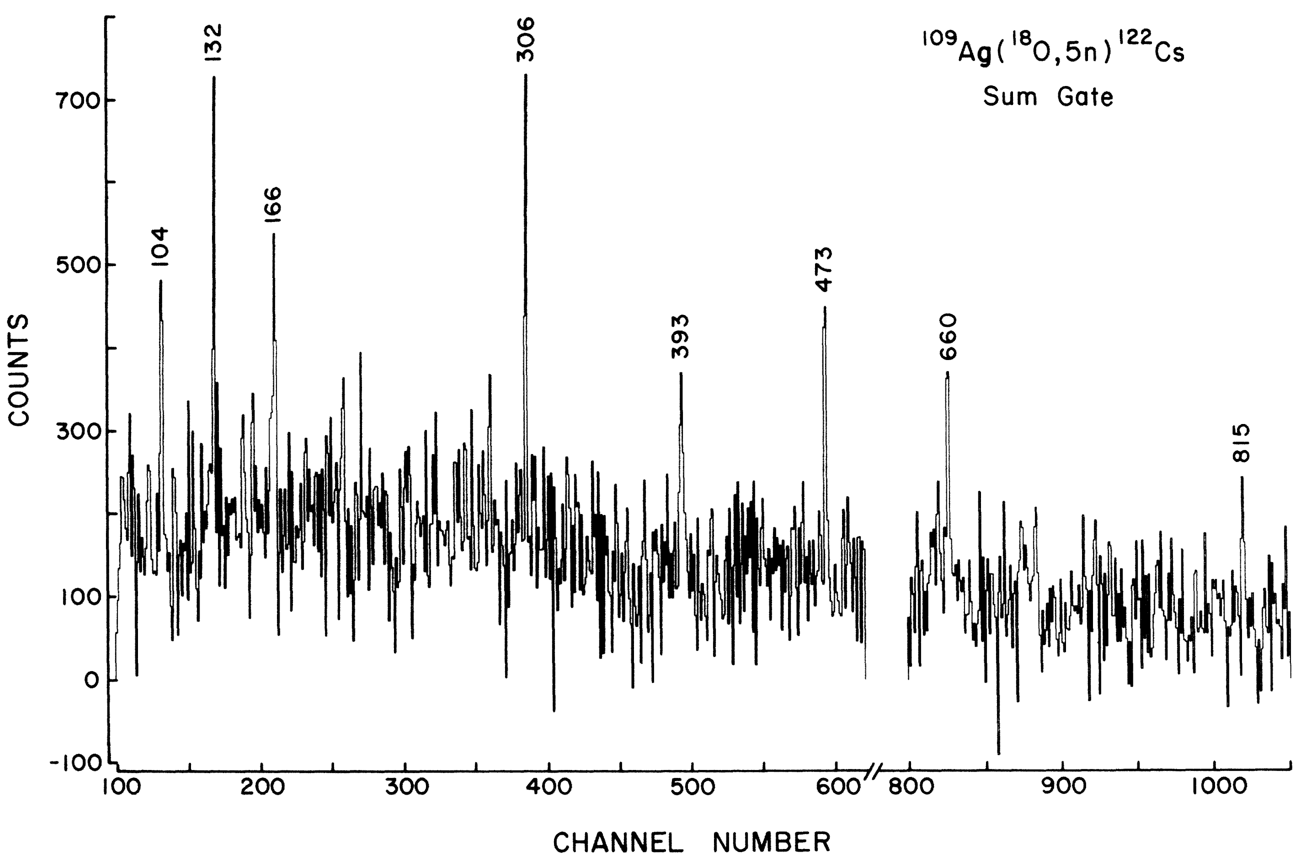

FIG. 1. Summed spectrum of background-subtracted γ-γ coincidence gates set on the stronger γ-ray transitions in ^{122}Cs.

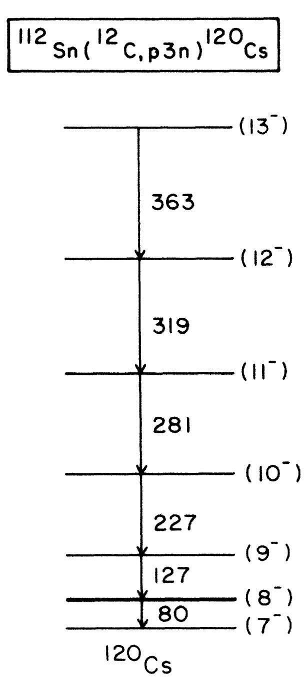

FIG. 2. Level scheme observed for the high-spin $\Delta J=1$ band in ^{120}Cs. The band spacings increase smoothly (nonstaggered) with spin.

to those of the $\Delta J=1$ bands as observed[3,4] in $^{112-120}Sb$ and $^{116-122}I$. A direct J^π assignment to the bandhead is not possible from the present results as none of the band members decays to known states by observable γ-ray transitions. The β decay[9] of ^{120}Cs, which populates the ^{120}Xe ground band up to the 6^+ state, implies a high-spin isomer. Based on the systematics[3,4] of the band properties in the doubly odd-Sb and -I nuclei, a J^π of 8^- is suggested for the ^{120}Cs bandhead.

The observed $\Delta J=1$ band in ^{120}Cs is believed to be associated with the $[\pi g_{9/2}^{-1}, \nu h_{11/2}]$ configuration. β-decay studies[14] underway for ^{120}Cs, which are consistent with the suggested bandhead spin, include on-line nuclear-orientation g-factor measurements; similar measurements[14,15] for $^{118,120}I$ documented the $[\pi g_{9/2}^{-1}, \nu h_{11/2}]$ configuration and confirmed the spin assignments of the $\Delta J=1$ bands. The similarities in the ^{120}Cs band spacings, except the lowest $(9^- \rightarrow 8^-)$, and those of the $\frac{9}{2}^+$ $\Delta J=1$ band in ^{119}Cs suggest that the collectivity associated with the $g_{9/2}$ proton hole is largely unaffected by the $h_{11/2}$ neutron. This feature was observed in all of the doubly odd-Sb and -I nuclei.[3,4] The lowest ^{120}Cs transition $9^- \rightarrow 8^-$ of the $\Delta J=1$ cascade is smaller relative to the corresponding transition $(\frac{11}{2}^+ \rightarrow \frac{9}{2}^+)$ in ^{119}Cs. Similar energy shifts of the 8^- and 9^- band members, which were also observed in the doubly odd-Sb and -I nuclei, may result partially from the increasing alignment of the $h_{11/2}$ neutron, which achieves angular momentum in a more energy efficient manner than the collective mechanism manifest in the $\pi g_{9/2}^{-1}$ ^{119}Cs band. The

^{120}Cs band, thus, fits nicely into the extended $^{112-120}$Sb and $^{116-122}$I systematics.

The $\Delta J = 1$ band structures observed in ^{122}Cs and ^{126,128}La are shown in Fig. 3. The strong $E2$ crossover transitions, which corroborate the $\Delta J = 1$ γ rays, are more intense for these three nuclei by factors of up to 10 relative to the $\Delta J = 1$ transitions when compared to the above mentioned systematics $[B(M1)/B(E2) \approx 1.4$ compared to 12 (nm)^2/e^2(barn)$^2]$. Although the bands were weakly populated, which limited the number of identified band members, the $\Delta J = 1$ transitions in all three nuclei exhibit staggered energies. The staggering parameter[16] $S[S = (e_1 + e_3 - 2e_2)/(e_1 + e_3 + 2e_2)$, where e_1, e_2, and e_3 are the three lowest $\Delta J = 1$ transition energies of the band] is 0.36 in ^{122}Cs, 0.14 in ^{126}La, and 0.12 in ^{128}La. ($S = 0$ implies no staggering.) The $\Delta J = 1$ transitions in all three bands showed strong anisotropies (large negative A_2 values) which implies negative $E2/M1$ mixing ratios ($\delta \approx -0.4$). These features represent an abrupt change from the non-staggered spacings and positive $E2/M1$ mixing ratios ($\delta \approx +0.2$) that characterize the $\Delta J = 1$ bands in the doubly odd-$^{112-120}$Sb, -$^{116-122}$I, and -^{120}Cs nuclei.

The $\Delta J = 1$ band in ^{128}La has been confirmed and extended by Nolan *et al.*[17,18] via the ^{115}In(^{16}O,$3n$)^{128}La reaction. This group had been studying ^{127,129}La with their sensitive array of Compton suppressed Ge spectrometers (TESSA II).[19] As a by-product of their ^{115}In(^{16}O,$4n$)^{127}La measurements, the γ rays from the ^{128}La $\Delta J = 1$ band, which we

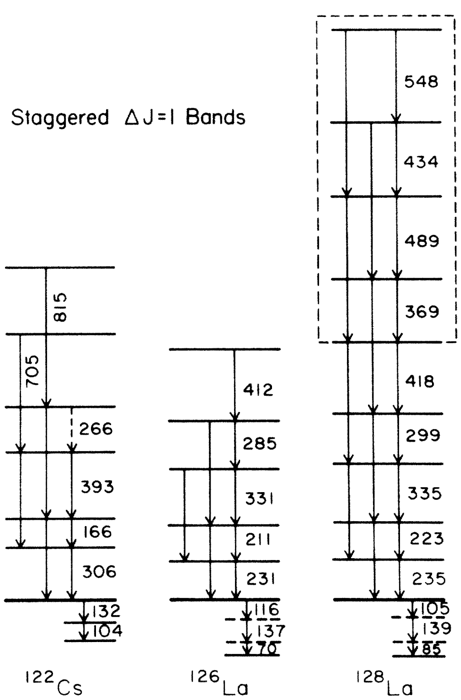

FIG. 3. Level schemes observed for the $\Delta J = 1$ band structures in ^{122}Cs, ^{126}La, and ^{128}La. The energy staggering can be seen by comparing the second band spacings with the first and third spacings. The portion of the ^{128}La band enclosed by the dashed box shows additional γ rays extracted by Nolan *et al.* (Refs. 17 and 18) using the sensitivity of TESSA II. For a $[\nu g_{7/2}^{-1}, \pi h_{11/2}]$ configuration, the J^π assignment for the bandheads (thick horizontal lines) is expected to be 6^- or 7^-.

had observed, appeared in their data from the simultaneous population of the $3n$ channel.[17] With the additional sensitivity of TESSA II, coincidence gates on these γ rays revealed four additional $\Delta J = 1$ transitions and several more $E2$ crossovers to the band in ^{128}La. Their results, shown in Fig. 3, are in agreement with the changed $\Delta J = 1$ band features as discussed above. Subsequently, Nolan *et al.*[18] found a similar band in ^{130}La.

The relative ordering of the three low-energy transitions below the bandhead is not definite in ^{126,128}La because of similar intensities and no observed side feeding. These γ-ray transitions and the two in ^{122}Cs below the bandhead were dipole in character from the angular distributions. No definite spin information concerning the bandheads can be extracted from the data, although β-decay populations in daughter nuclei suggest[9] that states of reasonably high spin exist at low energies in these three nuclei.

The staggered energy spacings and negative $E2/M1$ mixing ratios, as well as the relative strength of the $E2$ crossovers that characterize the changed $\Delta J = 1$ bands for ^{122}Cs and ^{126,128}La, require an explanation in terms of the underlying nuclear structure. The $\Delta J = 1$ bands induced by the $g_{9/2}$ proton-hole intruder in the $Z > 50$ region consistently exhibit increasing energy spacings and positive mixing ratios, as observed in odd-proton nuclei[1,2] and the doubly odd-Sb and -I isotopes[3,4] as well as ^{120}Cs.

The change in the sign of the mixing ratio $\delta(E2/M1)$ for the in-band $\Delta J = 1$ transitions provides some insight into possible explanations for these effects. The sign of $\delta(E2/M1)$ depends on the intrinsic g factor and on the quadrupole shape Q_0 of the core.[20] Thus, the abrupt change of $\delta(E2/M1)$ from positive to negative, in the ^{122}Cs and ^{126,128}La nuclei, might be related to either an intrinsic configuration change with the appropriate alteration of the g factor or to a core shape change from prolate to oblate. The presence of low-lying $g_{7/2}$ neutron-hole states and related $\Delta J = 1$ bands with large negative mixing ratios in the neighboring odd-Xe and -Ba isotopes[21] favors the intrinsic configuration change; in addition, no drastic shape changes in the cores are indicated by the decoupled bands that exist in these odd nuclei. The corresponding g factor changes along with any increase in $E2$ collectivity would also help explain the relative strength of the $E2$ crossovers to the $\Delta J = 1$ $M1$ transitions. A possible common configuration basis for these yrast $\Delta J = 1$ bands in ^{122}Cs and ^{126,128}La is $[\nu g_{7/2}^{-1}, \pi h_{11/2}]$, since the $\pi h_{11/2}$ orbital is also at low excitation energies in the odd-proton nuclei. The lowest member of this configuration is expected to be $J^\pi = 6^-$ or 7^- from the coupling of the near perpendicular orbitals of the strongly coupled $g_{7/2}$ neutron hole and the decoupled $h_{11/2}$ proton. Although the available β-decay information is consistent with the existence of states with these J^π values, no definite spin assignments to the bandheads have been made.

The reason for the change to staggered energy levels in the $\Delta J = 1$ bands of ^{122}Cs and ^{126,128}La with the suggested $[\nu g_{7/2}^{-1}, \pi h_{11/2}]$ configuration is an open question. The related $\Delta J = 1$ bands, induced by the $g_{7/2}$ neutron hole in the odd-Xe and -Ba isotopes, are not staggered in energy.[21] For the $\Delta J = 1$ bands of doubly odd nuclei in the $Z < 82$ transition region, staggering has been given two different interpretations. Yadav *et al.*[5] have interpreted the staggering as due to the residual interaction between the two odd particles. They obtained reasonable fits to staggered bands in the framework of a triaxial deformed rotor model using a surface delta interaction for the residual interaction. According to Kreiner *et al.*,[6] the staggering effect is due to the Coriolis interaction in their quasiparticle plus rotor model. Chen *et al.*[7] have calculated the rotational bands in ^{130}La in the cranked shell model (CSM). In this model, the energy staggering between the alternate spins in rotational bands is a manifestation of the energy splitting between the two signature quantum numbers. The signature splitting of the aligned orbitals is a probe of a triaxial shape of the core. Their calculation gave no signature splitting for the predicted negative parity $[\nu g_{7/2}^{-1}, \pi h_{11/2}]$ band in ^{130}La. The experimental signature splitting $[(e_I+e_{I+2})/2-e_{I+1}]$ is about 150 keV in ^{122}Cs and 50 keV in ^{126,128}La. Nolan *et al.* observed[18] a signature splitting < 10 keV in ^{130}La. The nonstaggered $\Delta J=1$ bands in the doubly odd-Sb isotopes have been theoretically fit[8] by coupling vibrational phonons or an appropriate collective core to the quasiparticles; the $\Delta J=1$ bands associated with the $[\pi g_{9/2}^{-1}, \nu h_{11/2}]$ configuration in the doubly odd-Sb and -I isotopes and in ^{120}Cs appear to be consistent in their lack of staggering.

In conclusion, the stable collectivity induced by the $g_{9/2}$ proton hole in the $Z>50$ region appears to persist in ^{120}Cs as characterized by a $\Delta J=1$ band of the $[\pi g_{9/2}^{-1}, \nu h_{11/2}]$ configuration. Abrupt changes in the $\Delta J=1$ bands observed for the ^{122}Cs and ^{126,128}La nuclei most probably result from the different yrast $[\nu g_{7/2}^{-1}, \pi h_{11/2}]$ configuration. Further experimental and theoretical work is necessary to understand the details of these changes.

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