PHYSICAL REVIEW C VOLUME 31, NUMBER 2 FEBRUARY 1985

Collective structures in the odd-Z transitional nuclei ^{115,117}I and ^{121,123}Sb

W. F. Piel, Jr., P. Chowdhury,* U. Garg,† M. A. Quader, P. M. Stwertka,‡ S. Vajda,§ and D. B. Fossan
Department of Physics, State University of New York, Stony Brook, New York 11794
(Received 24 August 1984)

Collective properties of odd-Z ^{115,117}I and ^{121,123}Sb nuclei have been investigated via ^{106}Cd(^{12}C,p2n)^{115}I, ^{106}Cd(^{14}N,2pn)^{117}I, ^{112}Sn(^{12}C,αp2n)^{117}I, and ^{120,122}Sn(^{7}Li,α2n)^{121,123}Sb reactions, using in-beam γ excitation, γ-γ coincidence, γ-$W(\theta)$ and pulsed-beam-γ measurements. The two collective features common to the $Z>50$ transition region were observed; the first, the occurrence of $\Delta J=1$ bands built on low-lying $\frac{9}{2}^+$ states, was found in all four nuclei, and the second, $\Delta J=2$ bands built on $\frac{11}{2}^-$ states, was seen in ^{115,117}I. The $\frac{9}{2}^+$ and $\frac{11}{2}^-$ band heads involve a $1g_{9/2}$ proton hole and a $1h_{11/2}$ quasiproton, respectively. The systematics of these band structures in the $Z>50$ transition region, which have been extended in this study, are presented and discussed in terms of collective interpretations.

I. INTRODUCTION

Spectroscopic studies of the high-spin states of odd-A nuclei above the $Z=50$ closed shell have provided a wealth of experimental information regarding the nature of collectivity in this region. The coexistence of states with different degrees of collectivity in these transitional nuclei has generated considerable interest. A common collective feature observed is the systematic occurrence of $\Delta J=1$ bands built on $\frac{9}{2}^+$ proton-hole intruder states in $^{113-119}$Sb ($Z=51$),[1] $^{117-127}$I ($Z=53$),[2,3] and $^{119-125}$Cs ($Z=55$) (Ref. 4) nuclei, where the band head involves a $1g_{9/2}$ proton excited across the $Z=50$ closed shell. For each Z, the excitation energies of the band heads, as a function of the neutron number N, exhibit a minima near the middle of the 50–82 neutron shell. The unexpectedly low $\frac{9}{2}^+$ excitation energies (950 keV in ^{121}Sb; 307 keV in ^{119}I; and the ground state in ^{119}Cs), compared to $\sim$3–4 MeV for a spherical system, have been primarily attributed to collective effects, which are expected to be largest near the middle of the neutron shell. The $\Delta J=1$ band spacings also achieve minima near the middle of the neutron shell, and decrease with increasing Z.

The present measurements of high-spin states in odd-Z nuclei are an attempt to extend the mapping of the collective properties of the $Z>50$ transitional nuclei[5] over as large a (Z,N) region as possible. A complete mapping of this kind is of considerable theoretical importance. The nuclei ^{115,117}I and ^{121,123}Sb were studied in this perspective, in order to follow the systematics of the $\frac{9}{2}^+$ bands across the minima towards increasing N for the Sb and towards decreasing N for the I isotopes. No previous experimental information was available for ^{115}I. Except for the earlier ^{117}I study,[3] only limited low-spin information was available for the other nuclei.[6]

In addition to the $\frac{9}{2}^+$ $\Delta J=1$ bands, $\Delta J=2$ bands built on $\frac{11}{2}^-$ states, a second collective feature, were observed in the ^{115,117}I nuclei. These $\Delta J=2$ bands conform to the systematics of the $1h_{11/2}$ quasiproton bands observed in higher mass odd-I nuclei[3] and the odd-Cs nuclei.[4] The $\Delta J=2$ band spacings for the low mass odd-I nuclei show a large decrease compared to the ground-band spacings of the Te cores.

The detailed results for the ^{115,117}I and ^{121,123}Sb studies will be compared with the systematic properties of band structure observed in odd-Z nuclei for the entire $Z>50$ transition region. A summary of the collective interpretations will be given.

II. EXPERIMENTAL PROCEDURE

High-spin states of the odd-A nuclei studied in this work were populated via ^{106}Cd(^{12}C,p2n)^{115}I, ^{106}Cd(^{14}N,2pn)^{117}I, ^{112}Sn(^{12}C,αp2n)^{117}I, and ^{120,122}Sn(^{7}Li,α2n)^{121,123}Sb reactions. Isotopically enriched self-supporting targets were bombarded with heavy-ion beams provided by the Stony Brook FN tandem accelerator; the superconducting booster was also used for ^{12}C+^{112}Sn. The reaction and target information is summarized in Table I. For the purpose of this study, γ-ray excitation, γ-γ coincidence, γ-ray angular distribution, and pulsed-beam-γ measurements were performed. The γ rays produced in the deexcitation of the residual nuclei were detected with coaxial Ge(Li) detectors (10–12 % efficiency and $\sim$2.1 keV FWHM resolution at 1.33 MeV). A Ge planar detector was also used in the ^{115}I study for the detection of low-energy γ rays. On the basis of extensive excitation function measurements performed in the $Z>50$ region, and comparisons with fusion-evaporation

TABLE I. Reaction information for the residual nuclei.

Nucleus	Reaction	Beam energy (MeV)	Target thickness (mg/cm^2)
^{115}I	^{106}Cd(^{12}C,p2n)^{115}I	58 and 63	3.5
^{117}I	^{106}Cd(^{14}N,2pn)^{117}I	62	3.5
^{117}I	^{112}Sn(^{12}C,αp2n)^{117}I	86	3.9
^{121}Sb	^{120}Sn(^{7}Li,α2n)^{121}Sb	27	9.9
^{123}Sb	^{122}Sn(^{7}Li,α2n)^{123}Sb	27	$\sim$10

reaction calculations, bombarding energies were chosen for individual reactions to optimize the relative yields of the nuclei of interest. The γ rays were identified with the various residual nuclei via γ-γ coincidence measurements. The angular distributions provided the γ-ray intensity (I_γ) and anisotropy [$W(\theta)$] information. Level schemes for the various residual nuclei were constructed on the basis of the above-mentioned experimental information, with the J^π information extracted from the I_γ and $W(\theta)$ results. The data acquisition techniques and analysis procedures have been described previously.[1-4]

III. EXPERIMENTAL DETAILS AND RESULTS

The results for the individual nuclei are described separately in the following, together with the experimental details and problems unique to each nucleus studied.

A. ^{115}I

The investigation of the highly neutron deficient ^{115}I nucleus involved several complications. A viable reaction was ^{106}Cd(^{12}C,p2n)^{115}I, although the p2n channel has significant competition from the 2pn and αn channels which lead to the ^{115}Te and ^{113}Te residual nuclei, respectively. Furthermore, no level-scheme information was available on ^{115}I, making definite γ-ray assignments to the nucleus difficult. Coincidence measurements were made at both 58 and 63 MeV with two Ge(Li) coaxial detectors and with a coaxial-planar combination for low-energy γ rays. To clarify the situation, γ rays from the above-mentioned competing channels were eliminated by studies of ^{113,115}Te via ^{104,106}Pd(^{12}C,3n) reactions, both of which preclude the population of ^{115}I. Utilizing the γ-excitation study, which separated the two- and three-particle exit channels, an identification of ^{115}I γ rays could be made. Summed γ-γ coincidence spectra for gates set on the two dominant cascades in ^{115}I are shown in Fig. 1. Table II lists the angular distribution results, and the resulting level scheme for ^{115}I is presented in Fig. 2. The assumed $\frac{5}{2}^+$ ground-state assignment is consistent with the four ground-state transitions and known systematic properties of the odd-I nuclei. The preliminary results reported earlier[5] for ^{115}I, which were obtained at 58 MeV, included contaminant coincident γ rays from the unexpectedly strong, but unstudied, 2n and np channels. The subsequent coincidence measurements at 63 MeV allowed the identification of the p2n channel γ rays and the associated residual nucleus ^{115}I.

Two band structures were observed in ^{115}I. The first is the $\Delta J=1$ band from $J^\pi=\frac{9}{2}^+$ to $(\frac{25}{2}^+)$, shown on the

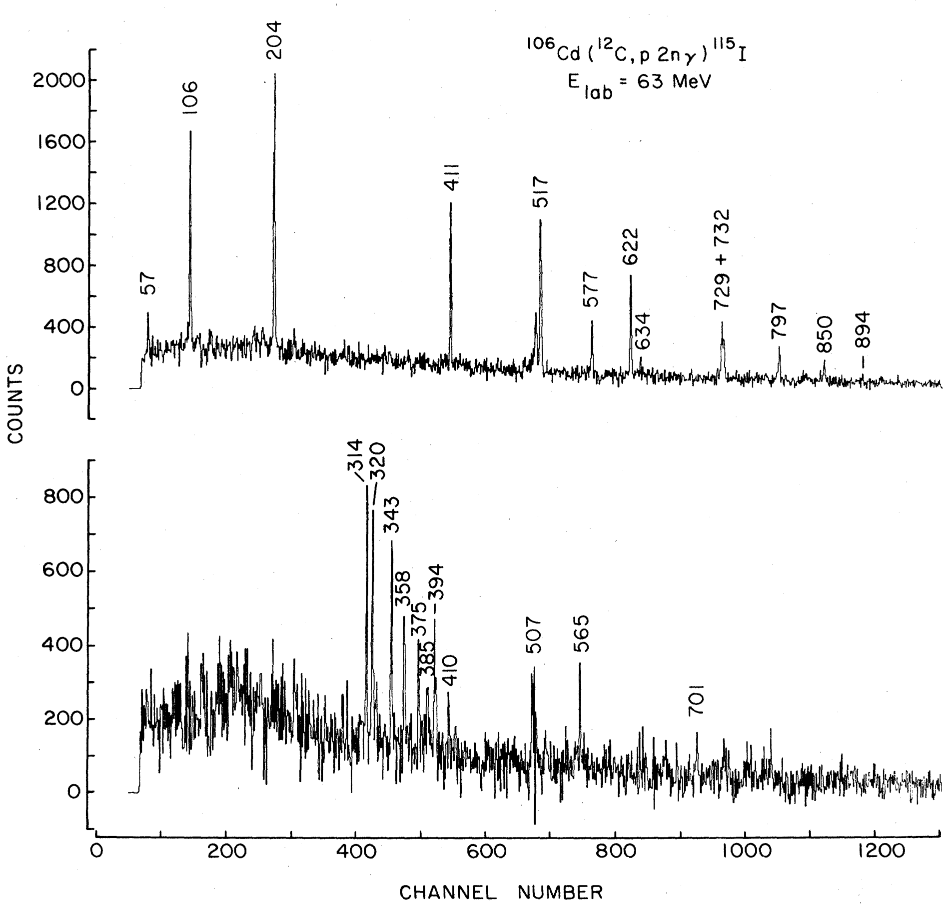

FIG. 1. Summed spectra of background-subtracted γ-γ coincidence gates for the transitions in the $\frac{9}{2}^+$ $\Delta J=1$ band (bottom) and in the $\frac{11}{2}^-$ $\Delta J=2$ band (top) of ^{115}I. The transition energies are labeled in keV.

TABLE II. Transitions in ^{115}I produced by 63 MeV ^{12}C+^{106}Cd. The relative intensities have been adjusted for the Ge(Li) detector efficiency, and the A_2/A_0 and A_4/A_0 values have been corrected for the finite solid angle of the detector. The E_γ uncertainties are ±0.3 keV.

E_γ (keV)	I_{rel}	A_2/A_0	A_4/A_0	Assignment	$\delta(E2/M1)$
410.7	<104	$+0.290\pm0.019$	-0.054 ± 0.028	$\frac{15}{2}^- \to \frac{11}{2}^-$	
517.0	$\equiv100.0\pm1.0$	$+0.247\pm0.013$	-0.028 ± 0.020	$\frac{19}{2}^- \to \frac{15}{2}^-$	
621.8	86.7 ± 1.2	$+0.284\pm0.018$	$+0.018\pm0.027$	$\frac{23}{2}^- \to \frac{19}{2}^-$	
728.6	37.2 ± 1.2	$+0.21\pm0.05$	$-0.00\ \pm0.07$	$\frac{27}{2}^- \to \frac{23}{2}^-$	
796.9	24.5 ± 1.2	$+0.25\pm0.07$	$-0.04\ \pm0.10$	$\frac{31}{2}^- \to \frac{27}{2}^-$	
850.1	16.6 ± 1.2	$+0.37\ \pm0.10$	$-0.04\ \pm0.14$	$\frac{35}{2}^- \to \frac{31}{2}^-$	
893.9	10.2 ± 0.9	$-0.09\ \pm0.12$	$-0.02\ \pm0.18$	$(\frac{39}{2}^- \to \frac{35}{2}^-)$	
313.5	35.2 ± 0.8	-0.024 ± 0.030	$+0.004\pm0.047$	$\frac{11}{2}^+ \to \frac{9}{2}^+$	$+0.13\pm0.04$
320.2	26.4 ± 0.8	$+0.004\pm0.037$	-0.042 ± 0.057	$\frac{13}{2}^+ \to \frac{11}{2}^+$	$+0.16\pm0.05$
342.6	17.6 ± 0.6	$-0.02\ \pm0.05$	$+0.07\ \pm0.08$	$\frac{15}{2}^+ \to \frac{13}{2}^+$	$\lvert\delta\rvert\geq0.08$
357.9	19.1 ± 0.6	$-0.08\ \pm0.05$	$+0.07\ \pm0.07$	$\frac{17}{2}^+ \to \frac{15}{2}^+$	$\lvert\delta\rvert\geq0.02$
374.6	24.7 ± 0.8	-0.089 ± 0.037	-0.022 ± 0.057	$\frac{19}{2}^+ \to \frac{17}{2}^+$	$+0.07\pm0.05$
385.2	4.2 ± 0.6	$+0.11\ \pm0.20$	$+0.08\ \pm0.31$	$(\frac{21}{2}^+ \to \frac{19}{2}^+)$	
393.5	≈10			$(\frac{23}{2}^+ \to \frac{21}{2}^+)$	
409.8	≈10			$(\frac{25}{2}^+ \to \frac{23}{2}^+)$	
56.7	≈80			$\frac{7}{2}^+ \to \frac{5}{2}^+$	
105.8	46.3 ± 0.6	-0.181 ± 0.016	$+0.034\pm0.024$	$\frac{11}{2}^- \to \frac{9}{2}^+$	
203.7	69.2 ± 0.8	$-0.31\ \pm0.04$	$+0.01\ \pm0.05$	$\frac{11}{2}^- \to \frac{9}{2}^+$	
507.4	≈15			$\frac{9}{2}^+ \to \frac{7}{2}^+$	
564.7	24.6 ± 1.2	$+0.26\ \pm0.07$	$+0.03\ \pm0.10$	$\frac{9}{2}^+ \to \frac{5}{2}^+$	
576.9	59.0 ± 1.4	$-0.65\ \pm0.04$	$+0.18\ \pm0.06$	$\frac{9}{2}^+ \to \frac{7}{2}^+$	-1.2 ± 0.7
633.5	≈15			$\frac{9}{2}^+ \to \frac{5}{2}^+$	
701.3	13.0 ± 0.8	$+0.25\ \pm0.09$	$+0.23\ \pm0.14$	$\frac{17}{2}^+ \to \frac{13}{2}^+$	
731.8	37.3 ± 1.2	$+0.24\ \pm0.05$	$+0.12\ \pm0.07$	$\frac{9}{2}^+ \to \frac{5}{2}^+$	

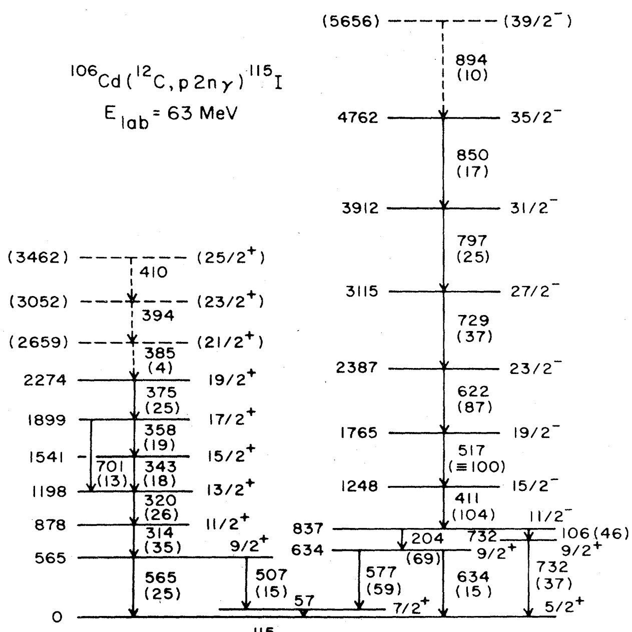

FIG. 2. Level scheme deduced for the ^{115}I nuclide. All energies are in keV.

left-hand side of Fig. 2. $E2$ crossover transitions corroborated the ordering of the $\Delta J=1$ transitions. This band agrees with the systematics of the $\Delta J=1$ bands built on low-lying $\frac{9}{2}^+$ states observed in the odd-A $^{117-127}$I nuclei,[3] in band spacings, positive $E2$-$M1$ mixing ratios, and in the excitation energy of the band head. The second is a $\Delta J=2$ band from $J^\pi=\frac{11}{2}^-$ to $(\frac{39}{2}^-)$ shown on the right-hand side, which also conforms to the systematics of the $\Delta J=2$ bands built on the $\frac{11}{2}^-$ states.

B. ^{117}I

The nucleus ^{117}I was populated via ^{106}Cd(^{14}N,2pn) and ^{112}Sn(^{12}C,αp2n) reactions. These two reactions were employed instead of the (^{12}C,p2n) reaction that was used for the ^{115}I study because enriched ^{108}Cd, which is of low natural abundance, was not available for a target. Previous studies of this nucleus[3] had been carried out in this laboratory via a ^{114}Sn(^{6}Li,3n) reaction which had populated a $\Delta J=1$ band built on a $\frac{9}{2}^+$ state up to the $\frac{17}{2}^+$ state, and a $\Delta J=2$ band built on the $\frac{11}{2}^-$ state up to the $\frac{19}{2}^-$ state. The use of the heavier beams in the present study enabled the observation of these bands to higher spins. The $\frac{11}{2}^-$ band was seen up to the $(\frac{35}{2}^-)$ state, and

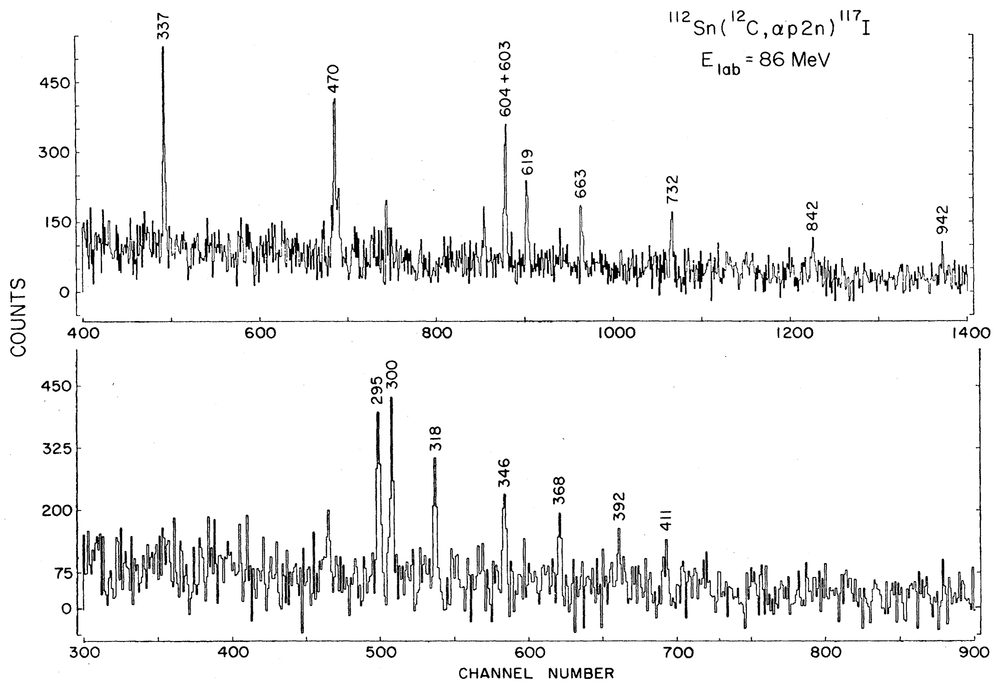

FIG. 3. Summed spectra of background-subtracted γ-γ coincidence gates for the transitions in the $\frac{9}{2}^+$ $\Delta J=1$ band (bottom) and in the $\frac{11}{2}^-$ $\Delta J=2$ band (top) of ^{117}I. The transition energies for each band are labeled in keV.

the $\frac{9}{2}^+$ band to the $(\frac{21}{2}^+)$ state, with three previously unobserved crossover transitions. Summed γ-γ coincidence spectra for gates set on the two dominant cascades in ^{117}I are shown in Fig. 3. All the transitions of the previous study were corroborated. The resultant level scheme for ^{117}I is shown in Fig. 4.

Angular distribution results for the (^{12}C,αp2n) reaction, which agree with those from the earlier study,[3] showed the cascade γ rays in the $\Delta J=2$ $\frac{11}{2}^-$ band to have positive

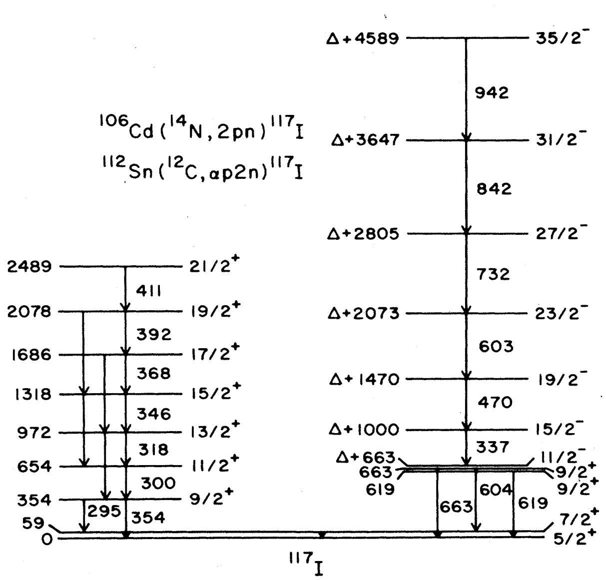

FIG. 4. Level scheme deduced for the ^{117}I nuclide from the present results and those of Ref. 3. All energies are in keV.

A_2/A_0 values consistent with stretched $E2$ transitions. The A_2/A_0 values for the $\Delta J=1$ $\frac{9}{2}^+$ in-band transitions were small and negative, implying the characteristic positive $E2$-$M1$ mixing ratios; these $\Delta J=1$ transitions are corroborated by $E2$ crossovers. The $\frac{9}{2}^+ \to \frac{7}{2}^+$ 295-keV transition from the band head had an $A_2/A_0=-0.14\pm0.06$, which is consistent with an $M1$ of less admixture. In the previous study,[3] the $\frac{9}{2}^+$ band head was measured to have a half-life of $t_{1/2}=12.1\pm0.7$ ns.

The 663-keV transition in ^{117}I did not have any delayed components ($t_{1/2}>10$ ns), implying that it does not decay directly from the $\frac{11}{2}^-$ band head; an $\frac{11}{2}^- \to \frac{5}{2}^+$ $E3$ transition would require an unreasonable enhancement of $>2\times10^3$ W.u. The $A_2/A_0=+0.16\pm0.09$ extracted for the 663-keV γ ray is consistent with a stretched $E2$ transition and the modest alignment for this reaction. This suggests an unobserved $E1$ transition (Δ) between the $\frac{11}{2}^-$ band head and the 663-keV $\frac{9}{2}^+$ level as indicated in Fig. 4. The existence of two $\frac{9}{2}^+$ states being fed by the $\frac{11}{2}^-$ band head occurs also in ^{115}I as well as the other light odd-I nuclei.[3]

C. ^{121}Sb

A ^{120}Sn(^{7}Li,α2n) reaction was used to study ^{121}Sb. The reaction mechanism most probably involves the breakup of the ^{7}Li ions into α particles and tritons, followed by a (t,2n) fusion-evaporation reaction. The population of high angular momentum states by a projectile as light as a triton suggests that the breakup occurs near the periphery of the nucleus and involves large impact parameters.[7] The angular distribution results are listed in Table III, while Figs. 5 and 6 show γ-γ coincidence spectra and the result-

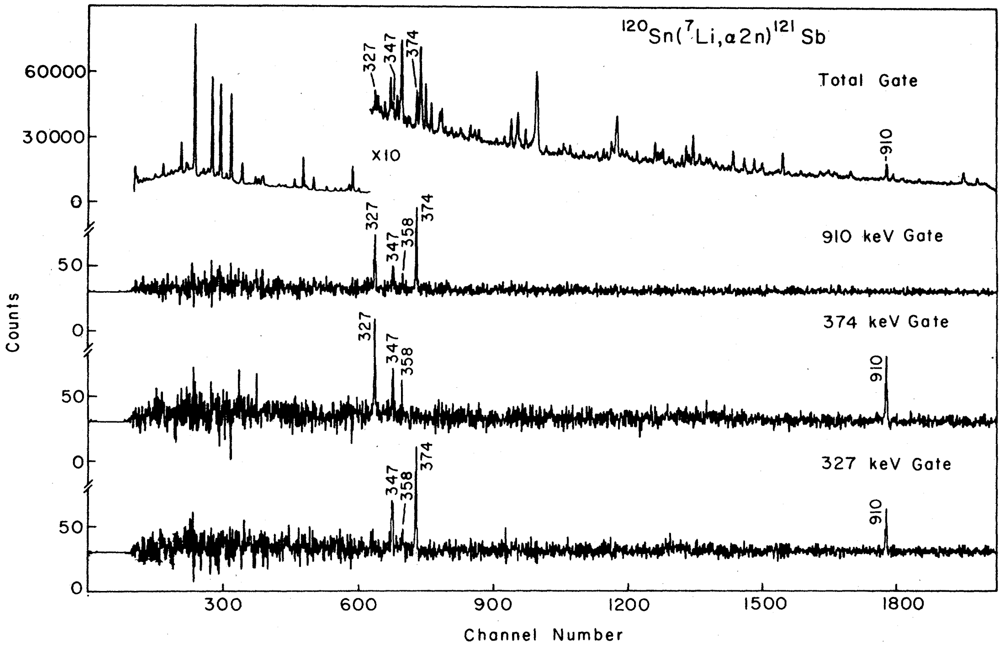

FIG. 5. Background-subtracted γ-γ coincidence spectra for the three gates in ^{121}Sb (bottom). The total γ-γ gates spectrum is shown at the top.

ing level scheme for ^{121}Sb. A $\Delta J=1$ band, with γ-ray energies (from the bottom) of 374, 327, 347, and 358 keV, was observed in coincidence with a 910 keV transition, which is the γ ray depopulating the known $\frac{9}{2}^+$ state[6] at 947 keV. Although the singles angular distribution measurement did not allow a complete isolation of the 358-keV γ-ray photopeak, it appeared to be consistent with the expected $\Delta J=1$ nature of the transition. The 37-keV $\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$ transition[6] was not observed in the present measurement. The energy spacings of the band follow the systematics of the $\frac{9}{2}^+$ bands observed in the lower odd-A Sb nuclei.

D. ^{123}Sb

As in the case of ^{121}Sb, a (^{7}Li,α2n) reaction was used to populate ^{123}Sb. The degree of difficulty in populating and detecting the $\frac{9}{2}^+$ bands in the Sb nuclei via yrast spectroscopy increases sharply with N for nuclei away from the middle of the 50—82 neutron shell. This is due to the steep rise in the excitation energy of the $\frac{9}{2}^+$ state [947 keV in ^{121}Sb ($N=70$), to 1337 keV in ^{123}Sb ($N=72$), to 1850 keV in ^{125}Sb ($N=74$)], as determined from $l=4$ pickup in transfer reaction studies.[6] In addition, the (^{7}Li,α2n) reaction cross section is relatively small. In order to increase the γ-γ coincidence detection efficiency for high energy γ rays, three Ge(Li) detectors were employed instead of the usual two. Two of them (placed at 60° and 120° to the beam direction) were gain matched and

TABLE III. Angular distribution results for ^{121}Sb.

E_γ[a] (keV)	$I_{\rm rel}$	A_2/A_0	A_4/A_0[b]	Assignment
326.9	34	-0.17 ± 0.06		$\frac{13}{2}^+ \rightarrow \frac{11}{2}^+$
347.1	25	-0.23 ± 0.12		$\frac{15}{2}^+ \rightarrow \frac{13}{2}^+$
374.0	67	-0.03 ± 0.03		$\frac{11}{2}^+ \rightarrow \frac{9}{2}^+$
909.5	100	-0.38 ± 0.03	0.07 ± 0.06	$\frac{9}{2}^+ \rightarrow \frac{7}{2}^+$

[a]Energy uncertainties are ±0.3 keV.
[b]The A_4/A_0 values are consistent with 0.0 where not quoted.

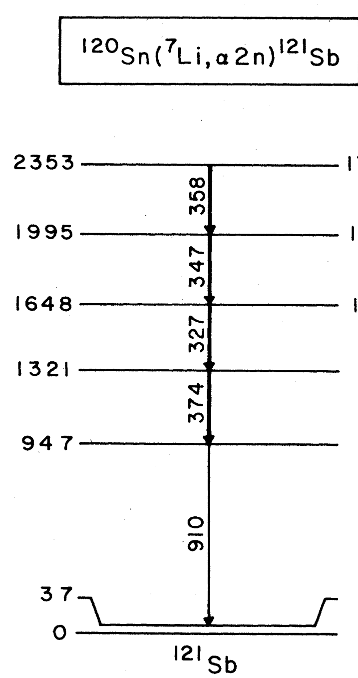

FIG. 6. Level scheme deduced for the ^{121}Sb nuclide. All energies are in keV.

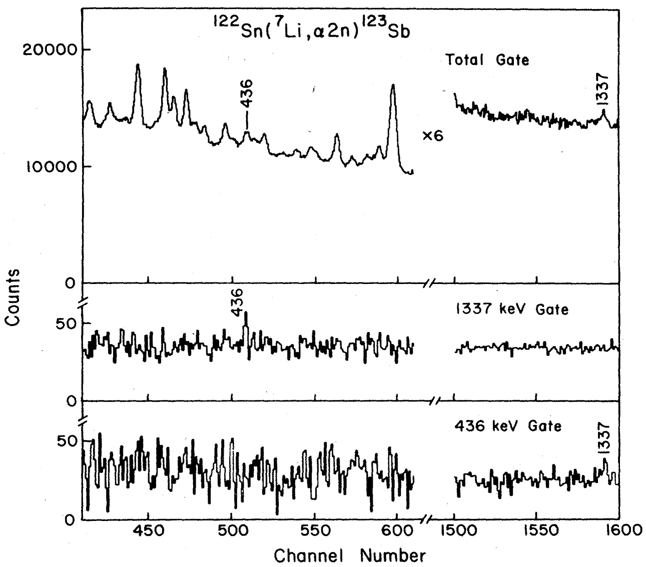

FIG. 7. Background-subtracted γ-γ coincidence spectra for two gates in ^{123}Sb (bottom). The total γ-γ gated spectrum is shown at the top.

multiplexed together to operate as a single system with increased detection efficiency for, in particular, the 1337-keV decay transition of the $\frac{9}{2}^+$ state. The third Ge(Li), placed at 90°, was primarily for detection of the band transitions in coincidence with the 1337-keV γ ray. The γ-γ coincidence spectra for ^{123}Sb are shown in Fig. 7. The γ-ray gates from both halves of the coincidence system have been summed, in order to utilize all the available statistics for discerning weak coincidences. A 436-keV γ ray was observed in coincidence with the 1337-keV transition. The 1337-keV γ ray exhibits an A_2 coefficient of -0.31 ± 0.20. A small peak-to-background ratio for the 436-keV γ ray made precise angular distribution measurements difficult; however, the ratio of intensities of 90° and 150° clearly show a dipole characteristic. This 436-keV γ ray is evidently the lowest member of the $\frac{9}{2}^+$ $\Delta J=1$ band.

IV. DISCUSSION

Two common collective features were observed in the odd-proton nuclei, ^{115,117}I and ^{121,123}Sb, that were studied in the present work. The first, the occurrence of $\Delta J=1$ bands built on low-lying $\frac{9}{2}^+$ states, was observed in all four nuclei. The second feature, $\Delta J=2$ bands built on $\frac{11}{2}^-$ states, was seen in ^{115,117}I.

The systematics of the $\frac{9}{2}^+$ $\Delta J=1$ bands observed in the odd-proton Sb ($Z=51$), I ($Z=53$), and Cs ($Z=55$) nuclei are shown in Fig. 8. The results for $^{113-119}$Sb, $^{119-127}$I, and $^{119-125}$Cs have been taken from Refs. 1–4, respectively. The excitation energies of the $\frac{9}{2}^+$ band heads in the Sb, I, and Cs isotopes exhibit a minimum, with respect to neutron number N, near the middle of the 50–82 neutron shell. The surprisingly low excitation energies of the $\frac{9}{2}^+$ band heads, which would occur at $\sim$3–4 MeV for a spherical system, suggest the influence of collective ef-

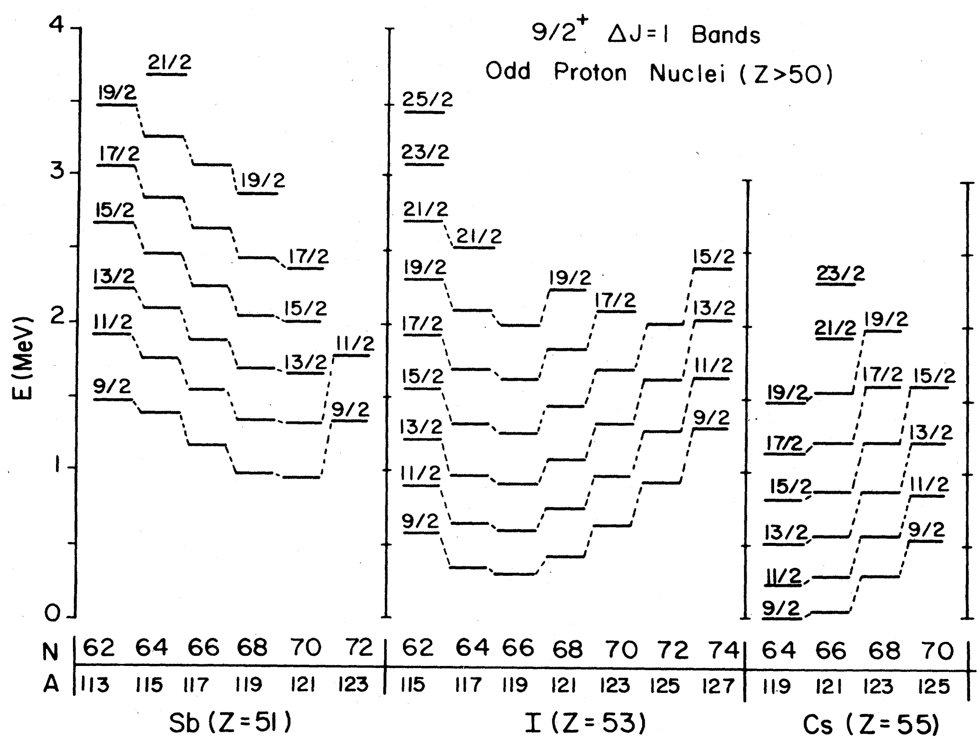

FIG. 8. Systematic properties of the $\Delta J=1$ bands built on the $\frac{9}{2}^+$ proton-hole states in the Sb, I, and Cs nuclei as a function of neutron number N (present work and Refs. 1–4). The $\pi g_{9/2}$ band head energies and the band spacings achieve minima near the middle of the $N=50$–82 neutron shell.

fects, which are expected to be largest nearer the middle of the neutron shell. It is to be noted, however, that these excitation energies are measured relative to the ground states of the particular nuclei, and would only reflect collective effects of the $\frac{9}{2}^+$ state relative to those of the ground states. For nuclei near the $Z=50$ closed shell, e.g., the Sb and I isotopes, the ground states are essentially noncollective.

The band spacings for these $\frac{9}{2}^+$ $\Delta J=1$ bands in this region also achieve minima near the middle of the neutron shell.[1–4] Although the $\frac{9}{2}^+$ band head energy has increased to 565 keV in ^{115}I, the band spacings increase only slightly at the bottom of the band compared to ^{117}I. The spacings in ^{121}Sb exhibit an overall decrease from those in ^{119}Sb, but increase again with the band head energy for ^{123}Sb. A regular decrease in the band spacings is observed for increasing Z, as seen in Fig. 8. A collective structure common to all the odd-proton nuclei in the transition region is documented by the similarity of the $\Delta J=1$ bands.

These $\Delta J=1$ bands have been described in terms of a $1g_{9/2}$ quasiproton hole coupled to a deformed rotor or to a vibrator. A strongly coupled deformed (prolate) rotor interpretation[8] for these bands has been found to reproduce the band spacings, the $E2$-$M1$ mixing ratios, the direct-to-crossover intensity ratios, and the $\frac{9}{2}^+$ band head energies rather well.[1–4] These bands have also been interpreted in terms of a vibrational core-plus-quasiparticle approach, which contains several equivalent features.[9] However, the low energies of the $\frac{9}{2}^+$ states are not easily explained in the latter model without involving a large number of phonons. These two theoretical approaches to the collectivity of the $Z>50$ transition have been recently reviewed.[10]

The surprisingly low energies of the $\frac{9}{2}^+$ band heads have been explained in terms of Nilsson proton-hole orbitals available at prolate deformations.[10,2] The $[404]\frac{9}{2}^+$ orbital has a steep positive slope for prolate deformations; thus, the state formed by exciting a proton out of this orbital would decrease in energy with increasing deformation, insofar as the potential energy of the core is fairly broad as a function of deformation. Minima in the total potential energy surface were obtained, for example, in ^{115,117}I, at a prolate deformation $\epsilon_2 \approx 0.12$. The resulting calculated band head energies are in fair agreement with experiment. Full band-mixing calculations, carried out at these equilibrium minima, achieved reasonably good fits to the band spacings.[10,2] At the higher spins, the experimental spacings are slightly smaller than the calculated spacings, suggesting an increased moment of inertia. Moments of inertia, estimated for a symmetric rotor and from the $\frac{9}{2}^+$ to $\frac{13}{2}^+$ spacings to avoid asymmetry staggering, are $2\mathscr{I}/\hbar^2=37.8$ MeV^{-1} for ^{115}I, and 34.2 MeV^{-1} for ^{121}Sb. These fits to the band spacings are achieved, however, only with significant band mixing. The $[413]\frac{7}{2}^+$ admixture into the dominant $[404]\frac{9}{2}^+$ configuration, for example, increases from $\sim 4\%$ at the $\frac{9}{2}^+$ band head to $\sim 16\%$ at the $\frac{21}{2}^+$ band member. The observed positive $E2$-$M1$ mixing ratios ($\delta \approx +0.15$) for the $\Delta J=1$ in-band transitions are consistent with the prolate deformation and the $[404]\frac{9}{2}^+$ orbital.[10] The vibrational core approach also achieves reasonable agreement with the band properties, although with rather broad phonon distributions. The equivalence between these two theoretical approaches in regard to the collective coexistence in the $Z>50$ transition region is discussed in detail in Ref. 10.

To explore the possibility of finding a better theoretical basis, the Meyer-ter-Vehn (MTV) model[11] has been used to make detailed calculations of the energy spacings of $\Delta J=1$ bands based on a $1g_{9/2}$ proton-hole coupled to an asymmetric rotor. The variables are the deformation parameter β, the asymmetry parameter γ, and the Fermi energy parameter λ_F. λ_F is defined such that for a hole spectrum, $\lambda_F=0$ corresponds to the Fermi level situated on the highest single-particle state of the j shell, $\lambda_F=1$ corresponds to the second highest, and other values are interpolated or extrapolated linearly from these points. The pairing potential was chosen to be $\Delta=(135/A)$ MeV. A reasonable variation of the Fermi level did not seem to have a significant effect on the results. Thus, λ_F was fixed at 0 for the calculations, which corresponds to the Fermi level being placed on the highest single-particle state of the $1g_{9/2}$ orbital. The deformation parameter β and the asymmetry parameter γ were varied to obtain the best overall fit to the experimental band spacings. For ^{121}Sb, the best fit was obtained with $\beta=0.31$ and $\gamma=20°$. The γ parameter is essential for reproducing the observed compression of the $\frac{13}{2}^+$-$\frac{11}{2}^+$ level spacing in the Sb $\frac{9}{2}^+$ bands. The levels in ^{115}I were well reproduced with $\beta=0.35$ and $\gamma=15°$. Although this approach yields good fits to the band spacings, the triaxial rotor model[11] does contain the additional asymmetry parameter.

The $\Delta J=1$ band structures observed in the odd-proton nuclei of the $Z>50$ transition region are thus seen to be explained rather well within a rotational interpretation, involving the coupling of a quasiparticle (hole) to an axially symmetric or asymmetric rotor. The uniqueness of such an interpretation, however, still remains in question. As mentioned earlier, some of these band properties have also been described, with reasonable success, in terms of a particle-vibrator model, where the quasiparticle (hole) is coupled to anharmonic phonons of the core.[9]

Another interesting aspect of the $1g_{9/2}$ proton-hole properties is the collective structure relationship between the excitation of a $1g_{9/2}$ proton and a pair of $1g_{9/2}$ protons across the $Z=50$ closed shell. The $\Delta J=2$ bands observed on two-proton hole 0_2^+ states in the even-Sn ($Z=50$) nuclei[12] show characteristics of the $\Delta J=1$ $\frac{9}{2}^+$ bands in the odd-Sb ($Z=51$) nuclei, both in the moments of inertia extracted from the band spacings and in the N dependence of the band head excitation energies. A search for similar collective bands built on two-proton hole 0^+ states in even Te ($Z=52$) nuclei[13] has revealed $\Delta J=2$ structures which are possibly related to the $1g_{9/2}$ proton-hole bands in odd-I ($Z=53$) nuclei. No evidence for similar structures was found in the even-Xe ($Z=54$) nuclei.[13] The increased level density, from the increasing number of valence protons, is believed to result in the deterioration of the two-proton hole band strength.

The surprising stable collectivity associated with the $g_{9/2}$ proton-hole intruder state is also manifest in the doubly odd nuclei in this region. Recent measurements in the odd-odd $^{112-120}$Sb nuclides[14] and $^{116-122}$I nuclides[15] have revealed $\Delta J=1$ bands based on nearly perpendicular orbitals of the $[\pi g_{9/2}^{-1}, \nu h_{11/2}]$ configuration. The similarity of the band properties of the odd-odd nuclei with those of the neighboring odd nuclei implies a decoupled spectator role for the $h_{11/2}$ neutron relative to the $g_{9/2}$ proton-hole collectivity. The two valence quasiparticles contribute additional sensitivities to the nature of the core collectivity.

The second common collective feature, observed in ^{115,117}I and exhibited by the odd-proton nuclei in the $Z>50$ transition region, is the occurrence of $\Delta J=2$ bands built on $\frac{11}{2}^-$ states. The $\frac{11}{2}^-$ bands had been previously observed by Stephens *et al.* in a systematic study of odd-A La isotopes,[16] where the $\Delta J=2$ band spacings followed the spacings of the ground state bands in the even-even $^{A-1}$Ba core nuclei fairly well. These were interpreted as "decoupled" bands involving a $1h_{11/2}$ quasiproton and an axially symmetry prolate core; the Coriolis interaction at moderate deformations tends to align the particle angular momentum with that of the core, essentially decoupling the particle from the symmetry axis of the core. Consequently, the "favored" high-spin states ($\frac{11}{2}^-, \frac{15}{2}^-, \frac{19}{2}^-, \ldots,$) follow the $0^+, 2^+, 4^+, \ldots,$ level spacings of the core nuclei, while the other "unfavored" states lie considerably higher in energy and are only weakly populated,

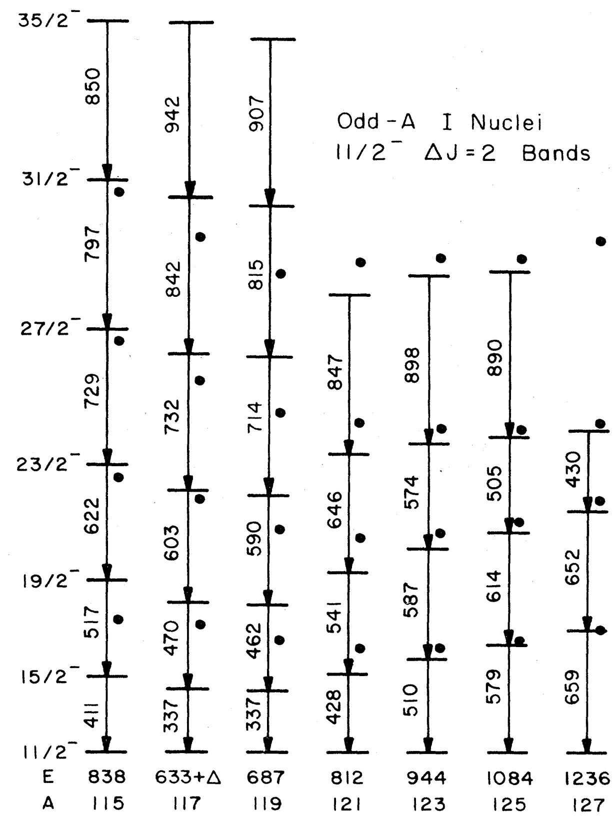

FIG. 9. Systematic $\Delta J=2$ bands built on the $\frac{11}{2}^-$ states in the odd-A I nuclei (present work and Refs. 2 and 3). The filled circles represent the ground-state bands in the corresponding $^{A-1}$Te core nuclei (Ref. 5). The γ-ray and band head energies are in keV.

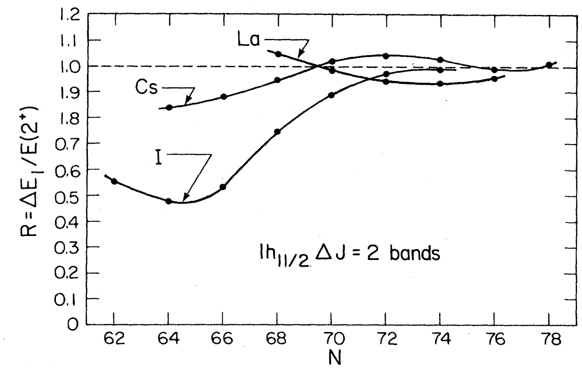

FIG. 10. Experimental R ratios of the $\frac{15}{2}^-$-$\frac{11}{2}^-$ $\Delta J=2$ band spacings to the 2^+-0^+ spacing of the ($A-1$) core nuclei for the odd-mass I, Cs, and La nuclei (present work and Refs. 2, 3, and 16). The curves simply connect the experimental ratios.

if at all, via the (HI,xn) reactions. Similar bands have been observed in odd-I nuclei[3] and odd-Cs nuclei,[4] built on $1h_{11/2}$, $2d_{5/2}$, and $1g_{7/2}$ quasiproton states. As in the case of the $\Delta J=1$ bands, a rotational interpretation is by no means unique for the $\Delta J=2$ bands observed in transitional nuclei. These band patterns can also be achieved by coupling a particle to anharmonic phonons of the core.[17] In fact, it is seen that one aspect of the $h_{11/2}$ $\Delta J=2$ band observed in the I nuclei does not have a natural explanation in the rotational interpretation, as described in the following.

The $\Delta J=2$ band, observed to be built on an $\frac{11}{2}^-$ state in ^{115,117}I, follows the systematics of $h_{11/2}$ quasiproton bands observed[3,4] in the higher odd-A I nuclei, as shown in Fig. 9. The level spacings are minimized for ^{119}I ($N=66$) and increase for lower-A isotopes. The different and intriguing aspect of the $1h_{11/2}$ bands in the odd-I nuclei is that the $\Delta J=2$ level spacings deviate significantly from the $^{A-1}$Te core spacings (filled circles[5]) with decreasing N. Figure 10 shows the ratios of the $\frac{15}{2}^-$-$\frac{11}{2}^-$ spacing to the 2^+-0^+ core spacing for this region. This deviation is not naturally understood within the particle-plus-rotor models, since the absence of similar deviations for the $\frac{5}{2}^+$ and $\frac{7}{2}^+$ bands in the same nuclei makes it difficult to invoke an increase in the deformation as A decreases. An explanation for these deviations has been offered[3,18] via a more microscopic collective model (generalized seniority scheme) using a second order perturbation expansion of the particle-core interaction, which involves linear and quadratic terms of the neutron number in an effective shell. The observed lack of deviation of the $\frac{5}{2}^+$ and $\frac{7}{2}^+$ bands then requires further explanation.

V. CONCLUSIONS

The nuclei ^{115,117}I and ^{121,123}Sb have been studied in the present work in order to extend the systematics of band structures observed in odd-Z nuclei of the $Z>50$ transition region. In all four of these nuclei, $\Delta J=1$ bands were observed to be built on the $1g_{9/2}$ proton-hole states. Energy levels of the $\frac{9}{2}^+$ $\Delta J=1$ bands are consistent with calculations using symmetric and triaxial rotors coupled to the $1g_{9/2}$ proton hole. In addition, $\Delta J=2$ bands were observed in ^{115,117}I on the $1h_{11/2}$ quasiproton states; the band spacings were reduced from those of the core, in variance with what is expected in the standard rotor model.

The band structure information obtained in the present study coupled with previous information from the odd, even-even, and odd-odd nuclei in this region, provide an extensive data array as a function of N,Z for testing various theoretical approaches to the collective phenomena. It is hoped that the extended systematics will impose additional constraints on the theoretical models, and thus contribute to the development of a unique description for the total set of experimental data in the $Z>50$ transition region.

Note added in proof. A recent paper [A. Kerek, T. Lönnroth, K. Honkanen, E. der Mateosian, and P. Thieberger, Z. Phys. A **317**, 169 (1984)] reported the observation of the $\Delta J=2$ band in ^{117}I up to the same spin as observed in the present experiment.

This work was supported in part by the National Science Foundation.

*Present address: Material Science Laboratory, Reactor Research Centre, Kalpakkam 603102, India.

†Present address: Physics Department, University of Notre Dame, Notre Dame, IN 46556.

‡Present address: Nuclear Structure Research Laboratory, University of Rochester, Rochester, NY 14627.

§Present address: Physics Department, Rutgers University, Piscataway, NJ 08854.

[1] A. K. Gaigalas, R. E. Shroy, G. Schatz, and D. B. Fossan, Phys. Rev. Lett. **35**, 555 (1975); R. E. Shroy, A. K. Gaigalas, G. Schatz, and D. B. Fossan, Phys. Rev. C **19**, 1324 (1979).

[2] D. M. Gordon, M. Gai, A. K. Gaigalas, R. E. Shroy, and D. B. Fossan, Phys. Lett. **67B**, 161 (1977); D. B. Fossan, M. Gai, A. K. Gaigalas, D. M. Gordon, R. E. Shroy, K. Heyde, N. Waroquier, H. Vincx, and P. Van Isacker, Phys. Rev. C **15**, 1732 (1977).

[3] R. E. Shroy, D. M. Gordon, M. Gai, D. B. Fossan, and A. K. Gaigalas, Phys. Rev. C **26**, 1089 (1982); M. Gai, D. M. Gordon, R. E. Shroy, D. B. Fossan, and A. K. Gaigalas, *ibid.* **26**, 1101 (1982).

[4] U. Garg, T. P. Sjoreen, and D. B. Fossan, Phys. Rev. C **19**, 207 (1979); **19**, 217 (1979).

[5] D. B. Fossan, in *Structure of Medium Heavy Nuclei, Rhodes, 1979,* Institute of Physics Conference Series No. 49 (Techno House, Bristol, 1980), p. 151.

[6] M. Conjeaud, S. Harar, M. Caballero, and N. Cindro, Nucl. Phys. **A215**, 383 (1973); H. R. Hooper, P. W. Green, H. E. Siefken, G. C. Neilson, W. J. McDonald, D. M. Sheppard, and W. K. Dawson, Phys. Rev. C **20**, 2041 (1979); *Table of Isotopes,* 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978).

[7] D. R. Zolnowski, H. Yamada, S. E. Cala, A. C. Kahler, and T. T. Sugihara, Phys. Rev. Lett. **41**, 92 (1978).

[8] K. Heyde, M. Waroquier, H. Vincx, and P. Van Isacker, Phys. Lett. **64B**, 135 (1976).

[9] P. van Isacker, M. Waroquier, H. Vincx, and K. Heyde, Nucl. Phys. **A292**, 125 (1977).

[10] K. Heyde, P. van Isacker, M. Waroquier, J. L. Wood, and R. A. Meyer, Phys. Rep. **102**, 291 (1983).

[11] J. Meyer-ter-Vehn, F. S. Stephens, and R. M. Diamond, Phys. Rev. Lett. **32**, 1383 (1974); J. Meyer-ter-Vehn, Nucl. Phys. **A249**, 111 (1975); **A249**, 141 (1975).

[12] J. Bron, W. H. A. Hesselink, A. van Poelgeest, J. J. A. Zalmstra, M. J. Uitzinger, H. Verheul, K. Heyde, M. Waroquier, H. Vincx, and P. van Isacker, Nucl. Phys. **A318**, 335 (1979).

[13] P. Chowdhury, W. F. Piel, Jr., and D. B. Fossan, Phys. Rev. C **25**, 813 (1982).

[14] S. Vajda, W. F. Piel, Jr., M. A. Quader, W. A. Watson III, F. C. Yang, and D. B. Fossan, Phys. Rev. C **27**, 2995 (1983).

[15] M. A. Quader, W. F. Piel, Jr., S. Vajda, W. A. Watson III, F. C. Yang, and D. B. Fossan, Phys. Rev. C **30**, 1772 (1984).

[16] F. S. Stephens, R. M. Diamond, J. R. Leigh, T. Kammuri, and K. Nakai, Phys. Rev. Lett. **29**, 438 (1972).

[17] U. Hagemann and F. Donau, Phys. Lett. **59B**, 321 (1975); G. Alaga and V. Paar, *ibid.* **61B**, 129 (1976).

[18] M. Gai, A. Arima, and D. Strottman, Phys. Lett. **106B**, 6 (1981).