New Deformed States near the $Z=50$ Closed Shell: $^{117}_{51}Sb_{66}$

D. R. LaFosse, D. B. Fossan, J. R. Hughes, Y. Liang, P. Vaska, M. P. Waring, and J.-y. Zhang[(a)]
Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794
(Received 14 May 1992)

Three decoupled ($\Delta I=2$) rotational bands have been observed to rise out of irregular spherical excitations in $^{117}_{51}$Sb at moderate spin. These bands are interpreted as resulting from low-lying $\pi g_{7/2}$, $\pi d_{5/2}$, and $\pi h_{11/2}$ valence orbitals outside the $Z=50$ closed shell coupled to the deformed $[(\pi g_{7/2})^2 \otimes (\pi g_{9/2})^{-2}]$ ^{116}Sn core state at the $N=66$ midshell. The valence orbitals do not significantly influence either the spherical or the deformed core shape; the latter is regulated by the β at which the $\pi g_{7/2}$ and the intruder $\pi g_{9/2}$ levels cross. Two strongly coupled ($\Delta I=1$) bands involving $[(\pi g_{7/2})^2 \otimes (\pi g_{9/2})^{-1}]$ were also observed.

PACS numbers: 21.10.Re, 23.20.Lv, 27.60.+j

The manner in which nuclei near closed shells develop collective excitations is fascinating in that the degrees of freedom are usually severely limited to single-particle motion of the valence particles. The $_{51}$Sb nuclei are particularly interesting in this regard, being just beyond the closed $Z=50$ proton shell. The low-lying single-proton orbitals, $\pi g_{7/2}$, $\pi d_{5/2}$, and $\pi h_{11/2}$, coupled to the spherical $_{50}$Sn core states, namely, the 0_1^+ ground state, stiff vibrational 2^+ and 4^+ states ($E_{2^+} \approx 1.2$ MeV), and two-neutron negative-parity states, represent a major part of the Sb level structure. These coupled Sb states show no rotational-like bands, implying that these valence protons do not induce significant deviations from the spherical shapes. Collective features, however, have been observed previously in the odd-A Sb isotopes [1], which involve deformed two-particle–one-hole (2p1h) configurations of the β-upsloping $\pi g_{9/2}$ orbital intruding from below the $Z=50$ proton shell. These high-K $\frac{9}{2}^+$ states $[(\pi g_{7/2})^2 \otimes (\pi g_{9/2})^{-1}]$ of modest prolate deformation are manifest as strongly coupled ($\Delta I=1$) rotational bands, the bandheads of which achieve a minimum energy near the middle of the $N=50$–82 neutron shell. Subsequently, related deformed 2p2h 0_2^+ states $[(\pi g_{7/2})^2 \otimes (\pi g_{9/2})^{-2}]$ were discovered via related rotational bands in the even-A Sn isotopes [2], with the lowest bandhead energy occurring in ^{116}Sn at $N=66$, the middle of the neutron shell. Systematic structures involving such intruder orbitals have been theoretically examined [3]. An investigation in the Sb isotopes for collective excitations at modest spins, involving these 2p2h Sn core states and the $Z=51$ low-K valence proton orbitals with different deformation-driving properties, would probe the nature of the onset of collectivity near closed shells. The recent observation in ^{113}Sb by Janzen *et al.* [4] of the yrast band to high spin and excitation energy with an enhanced deformation, resulting from multiparticle alignment contributions, adds considerable interest to this investigation. For the present purpose, the $N=66$ ^{117}Sb nucleus was studied at moderate angular momentum. In addition to the 2p1h collectivity, three decoupled $\Delta I=2$ rotational bands associated with the above-mentioned low-K valence proton orbitals coupled to the deformed 0_2^+ core state were found in ^{117}Sb rising out of the chaotic spherical (single-particle) excitations. These results suggest that this $Z=51$ nucleus has a full complement of deformed collective excitations involving the 2p2h deformed core along with the above-mentioned spherical excitation mode. The observed band properties are sensitive to the detailed nature of the collective mode near the $Z=50$ closed shell.

High-spin states in ^{117}Sb were populated via the ^{110}Pd(^{11}B,$4n$)^{117}Sb reaction with a beam energy of 45 MeV. The target consisted of 2.9 mg/cm^2 of enriched ^{110}Pd backed with 100 mg/cm^2 of lead, which stopped the recoiling nuclei and the beam. Gamma rays were detected using an array of five Compton-suppressed Ge detectors plus a multiplicity filter of fourteen closely packed bismuth germanate (BGO) crystals subtending 80% of 4π. A hardware trigger of two or more BGO crystals was required for each valid coincident γ-γ event in order to reduce low-multiplicity background. 6.2×10^7 events were collected in this experiment. These coincidence events were then sorted off-line into a symmetrized 2000×2000 E_γ-E_γ matrix, which was used to construct the level scheme of ^{117}Sb. The data were also sorted into an average directional correlation (DCO) matrix; detectors close to 90° were sorted against the forward and backward detectors. Extracted DCO ratios provide information on the transition multipolarities. Figure 1 shows the ^{117}Sb level scheme deduced from the present experiment, along with a partial level scheme of ^{116}Sn [2], which is used later for comparison and interpretation. Placement of the transitions in the level scheme was determined through coincidence and intensity relationships. The spin and parity (I^π) information was extracted from DCO ratios and from observed decay patterns to known states. A previous ^{117}Sb study [1] had identified and determined I^π assignments for a number of the low-lying levels.

The extracted γ-ray decay sequences in ^{117}Sb show two distinguishable groups of levels; one group is irregular, appearing to involve single valence protons coupled to the spherical core states, and the other group is systematic and bandlike, presumably involving a coupling to the deformed ^{116}Sn core states. The observed collective bands

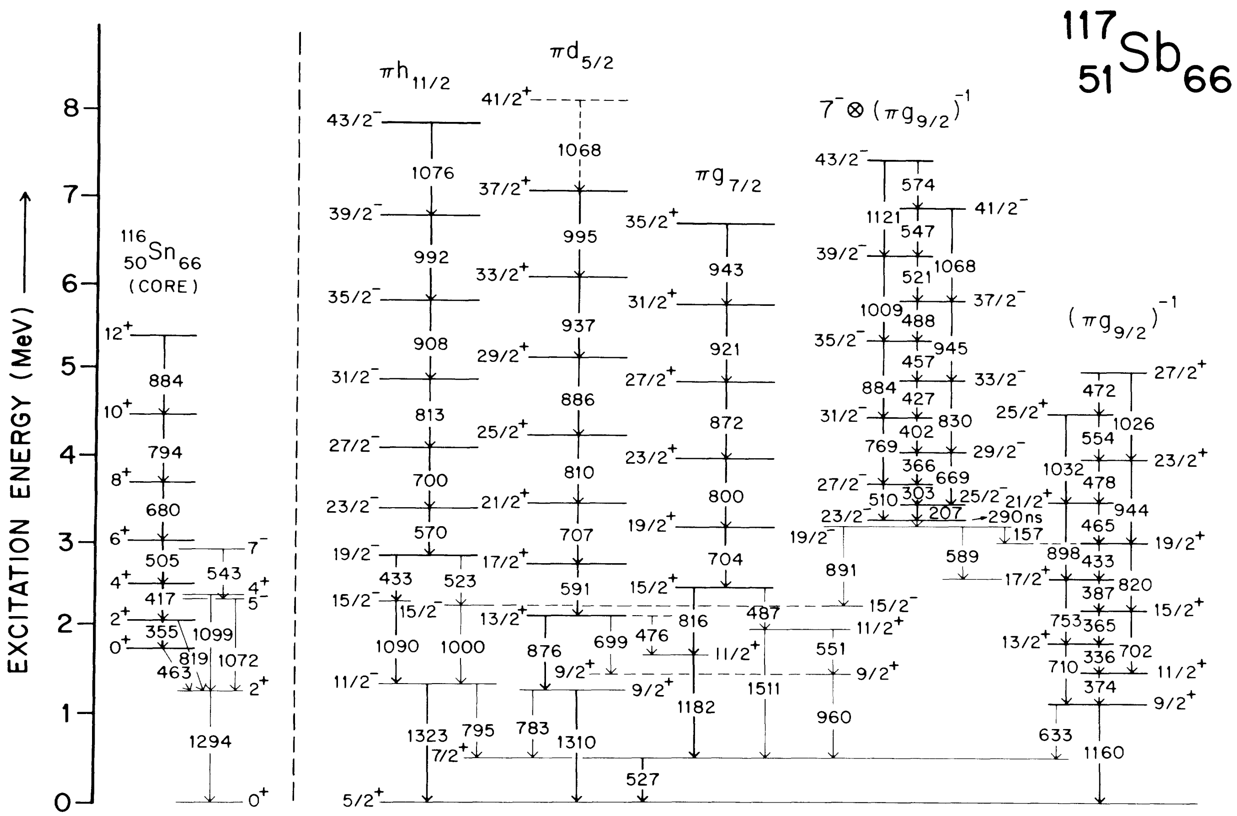

FIG. 1. Partial level scheme of ^{117}Sb, including several ^{116}Sn core levels for comparison. The three decoupled ($\Delta I=2$) bands in ^{117}Sb are labeled with the appropriate valence proton orbital.

from the latter group decay out through the lower levels of the spherical group of states, namely, those from the three valence protons coupled to the 0_1^+ and 2_1^+ ^{116}Sn core levels. Since the collective bands are the focus of this study, in addition to the band members only these $(j\otimes 0_1^+)$ and $(j\otimes 2_1^+)$ spherical states are shown in Fig. 1; these include the $\frac{5}{2}{}_1^+$ ground state and the $\frac{9}{2}{}_1^+$ state from the valence $\pi d_{5/2}$ orbital, the $\frac{7}{2}{}_1^+$ and the $\frac{11}{2}{}_1^+$ states from the $\pi g_{7/2}$ orbital, and the $\frac{11}{2}{}_1^-$ and the $\frac{15}{2}{}_1^-$ states from the $\pi h_{11/2}$ orbital. This I^π and structure information can be used together with the decay patterns to help identify the configurations of the observed collective bands. Some 32 levels of a spherical (single-particle) nature were identified in ^{117}Sb, and over 100 transitions connecting them were found.

The fascinating new feature observed for ^{117}Sb in the present experiment is the three decoupled ($\Delta I=2$) rotational bands rising out of the irregular spherical states as shown in Fig. 1. Each of these decoupled bands has its own unique decay pattern through the above-mentioned spherical states. Using the DCO ratios and previous I^π information, the decay out of the observed bands involves predominantly stretched $E2$ transitions, which yields the I^π assignments given in Fig. 1. With this knowledge, the three observed bands appear to be directly related to the coupling of the deformed ^{116}Sn core shown in the left in Fig. 1 to the low-K members of the three valence orbitals labeled at the top of each $\Delta I=2$ band. Figure 2 displays a coincident γ-ray gate that documents the band labeled

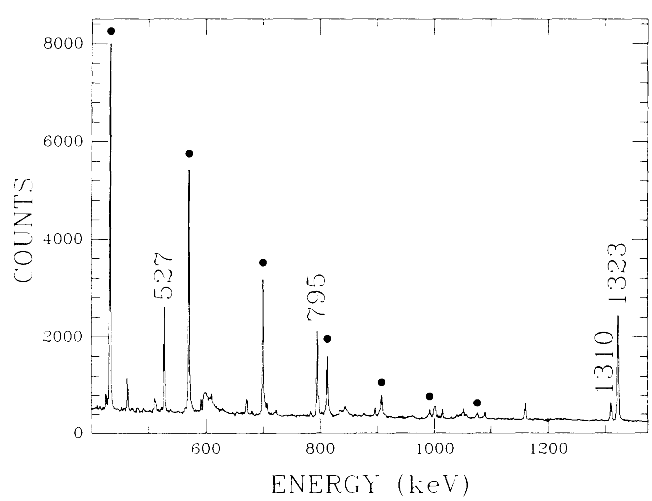

FIG. 2. Coincidence γ-ray gate on the 1090-keV transition showing the decoupled band labeled $\pi h_{11/2}$. The solid circles indicate the in-band transitions.

$\pi h_{11/2}$. Since the deformed structure in the ^{116}Sn core is prolate, the orbitals available to the $Z=51$ valence proton at the beginning of the shell have $K=\frac{1}{2}$ projections. This would result in the observed $\Delta I=2$ bands of only one signature with the other signature being split to higher excitation energies.

On the basis of the spins, the three decoupled bands in ^{117}Sb begin to branch out at the levels corresponding to the ^{116}Sn 4^+ band member, decaying to both the spherical and the deformed version of the $(j\otimes 2^+)$ states. This is similar to the manner in which the deformed band in ^{116}Sn decays out into its low-lying spherical (vibrational) states. Thus, the $\frac{19}{2}^-$ member of the $\pi h_{11/2}$ band decays to two $\frac{15}{2}^-$ states, the $\frac{13}{2}^+$ member of the $\pi d_{5/2}$ band decays to two $\frac{9}{2}^+$ states, and the $\frac{15}{2}^+$ member of the $\pi g_{7/2}$ band decays to two $\frac{11}{2}^+$ states. It appears that the ^{117}Sb coupled states of the same I^π corresponding to the spherical and deformed 2^+ and 4^+ ^{116}Sn levels are admixed, which causes these decay patterns. The lowest ^{117}Sb band members corresponding to the deformed ^{116}Sn 0_2^+ bandhead, which would not be yrast, are not observed.

The band spacings for the $\pi h_{11/2}$ and $\pi d_{5/2}$ band members above the corresponding 6^+ core member are similar to those in the ^{116}Sn core deformed band, implying similar moments of inertia. Although the odd valence particle coupled to the 2p2h core is expected to reduce the pairing slightly, this similarity suggests that the β-driving strength of these downsloping valence orbitals individually is not sufficient to significantly alter the nuclear shape of the 2p2h deformed core, implying considerable shape stability. The deformation of the proton particle-hole configuration appears to be regulated by the deformation at which the $\pi g_{7/2}$ and $\pi g_{9/2}$ levels cross, as displayed in Fig. 3. Although the $\pi d_{5/2}$ orbital is lowest at $\beta=0$, the $K=\frac{1}{2}$ members of the $\pi d_{5/2}$ and $\pi g_{7/2}$ orbitals interact and admix as β increases, such that by

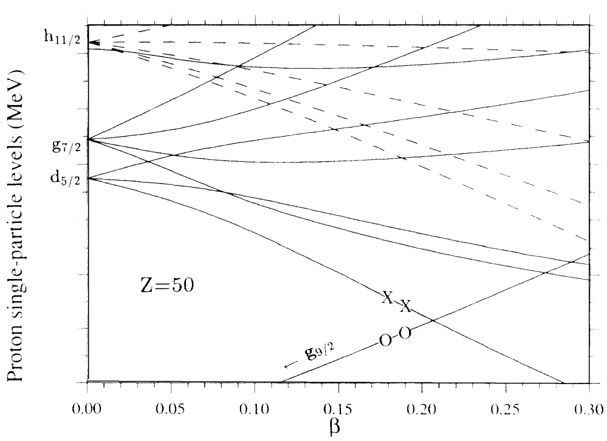

FIG. 3. A Woods-Saxon level scheme as a function of deformation β for proton orbitals near $Z=50$. A 2p2h configuration with $\beta<0.2$ (as shown) drives to the crossing, but at $\beta>0.2$, the reverse driving occurs.

$\beta=0.2$, the lowest orbital is predominantly $\pi g_{7/2}$. [For simplicity, $\pi g_{7/2}$ is used rather than an admixed $\pi g_{7/2}(d_{5/2})$ notation.] At β values less than that at the crossing, the particle orbitals $(\pi g_{7/2})^2$ are downsloping with β while the hole orbitals $(\pi g_{9/2})^{-2}$ are upsloping with β; thus both the particles and the holes β-drive to the crossing deformation. At β values larger than that at the crossing, the roles of the particles and the holes are exchanged and the reverse is true, namely, both drive back to the crossing value. This would explain the reduced influence of the odd valence proton on the nuclear shape. The ^{117}Sb band spacings corresponding to the 6^+-4^+ core spacing, however, are smaller than that in ^{116}Sn, which indicates an energy perturbation of the band members corresponding to the 4^+ core member because of admixing of the nearly degenerate spherical and deformed $(j\otimes 4^+)$ states.

The $\pi g_{7/2}$ band is interesting in that the band spacings are larger than those in the corresponding deformed ^{116}Sn band, which could imply a reduction in the relative moment of inertia. Since the configuration of the deformed band in ^{116}Sn is believed to be predominantly $[(\pi g_{7/2})^2\otimes(\pi g_{9/2})^{-2}]$, a $\pi g_{7/2}$ valence orbital in ^{117}Sb would require that K increase to $\frac{3}{2}$ because of the Pauli principle, which with less alignment would yield larger band spacings. Alternatively, a $K=\frac{1}{2}$ $\pi g_{7/2}$ valence orbital would block this deformed core configuration, forcing a core change to perhaps include the nearly degenerate $\pi d_{5/2}$ orbital, namely, an orthogonal $[(\pi d_{5/2})^2 \otimes(\pi g_{9/2})^{-2}]$ admixture, and a different optimal deformation.

Dynamic moments of inertia extracted from the in-band transition energies of the decoupled bands associated with the $\pi d_{5/2}$ and the $\pi g_{7/2}$ valence orbitals show clear evidence for Coriolis pair alignment at $\hbar\omega\approx 0.45$ MeV. This is most likely caused by the alignment of a $\nu h_{11/2}$ pair, which is predicted at this frequency by cranked shell-model calculations. The moment of inertia of the $\pi h_{11/2}$ decoupled band shows a gradual increase, but no clear evidence of an alignment.

As mentioned in the introduction, a previous ^{117}Sb study [1] had identified a $\Delta I=1$ strongly coupled band; this band, which has been extended to $I^\pi=\frac{27}{2}^+$ in the present experiment, is shown on the right in Fig. 1 and is labeled $(\pi g_{9/2})^{-1}$. With essentially no signature splitting, this band is consistent with the $K=\frac{9}{2}$ hole orbital resulting from the 2p1h configuration $(\pi g_{7/2})^2 \otimes(\pi g_{9/2})^{-1}$. The $B(M1)/B(E2)$ branching ratios and the positive mixing ratios δ extracted for the in-band transitions are consistent with the empirical $(\pi g_{9/2})^{-1}$ g factor and a prolate deformation. The observed moments of inertia for the three-quasiproton configuration are also consistent with the deformation of the $\pi g_{7/2}$-$\pi g_{9/2}$ level crossing.

A second, similar $\Delta I=1$ band in ^{117}Sb has been found in the present experiment as shown in Fig. 1 under the label $7^- \otimes (\pi g_{9/2})^{-1}$. The band spacings and lack of signature splitting as well as the $B(M1)/B(E2)$ branching ratios extracted for this band are similar to those of the $(\pi g_{9/2})^{-1}$ band. This strongly coupled band is built on the 290-ns isomer previously observed by Ionescu-Bujor *et al.* [5]. Following perturbed angular distribution measurements, they assigned the $[(\nu h_{11/2}, \nu d_{3/2})_{7^-} \otimes (\pi g_{9/2})^{-1}]_{23/2^-}$ configuration to this isomer based on the extracted g factor [5]; additional measurements also showed this isomer to have a significant positive quadrupole moment, namely, a prolate deformation [6]. These results suggest that the coupling of the ^{116}Sn spherical $(\nu h_{11/2}, \nu d_{3/2})_{7^-}$ state does not significantly alter the shape of the $(\pi g_{7/2})^2 \otimes (\pi g_{9/2})^{-1}$ structure. The $\frac{23}{2}^-$ bandhead decays to a close-lying $\frac{19}{2}^-$ state, which is believed to be predominantly the spherical $7^- \otimes \pi d_{5/2}$ configuration.

In summary, the ^{117}Sb nucleus, with one proton beyond the $Z=50$ closed proton shell and at the $N=66$ neutron midshell, reveals two separate but rather complete modes of excitation involving the valence protons coupled to the spherical and to the deformed ^{116}Sn core states. The deformed mode includes three $\Delta I=2$ bands resulting from the $g_{7/2}$, $d_{5/2}$, and $h_{11/2}$ valence proton orbitals coupled to the 2p2h deformed core band, and 2p1h $\Delta I=1$ bands from the $g_{9/2}$ proton hole. The $Z=51$ valence proton does not show significant shape-driving effects on either the spherical or the deformed cores. The $\pi g_{7/2}$-$\pi g_{9/2}$ level crossing at $\beta \approx 0.2$ appears to stabilize the proton particle-hole deformed core configurations, despite the additional valence proton and the associated small pairing change. Thus, the intruding $\pi g_{9/2}$ orbital at prolate deformations has an influential role in the deformed excitation mode of the Sb nuclei at the neutron midshell for both the three- and the five-quasiproton configurations.

This work was supported in part by the National Science Foundation. One of us (J.-y.Z.) would like to acknowledge NSF Grant No. INT-9001476, and thank Dr. Paul Semmes for discussions.

[a]Current address: University of Tennessee, Knoxville, TN 37996.

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

[2] J. Bron, W. H. A. Hesselink, A. Van Poelgeest, J. J. A. Zalmstra, M. J. Uitzinger, and H. Verheul, Nucl. Phys. **A318**, 335 (1979).

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

[4] V. P. Janzen *et al.*, in Proceedings of the Workshop and Symposium on Future Directions in Nuclear Physics with 4π Detection Systems of the New Generation, Strasbourg, March 1991 (to be published); V. P. Janzen *et al.* (to be published).

[5] M. Ionescu-Bujor, A. Iordachescu, G. Pascovici, and C. Stan-Sion, Nucl. Phys. **A466**, 317 (1987).

[6] M. Ionescu-Bujor, A. Iordachescu, G. Pascovici, and V. Sabaiduc, Phys. Lett. B **200**, 259 (1988).