PHYSICAL REVIEW C VOLUME 27, NUMBER 6 JUNE 1983

Rapid Communications

Proton-hole induced bands in odd-odd ^{118,120}Sb

S. Vajda, W. F. Piel, Jr., M. A. Quader, W. A. Watson III, F. C. Yang,* and D. B. Fossan
Department of Physics, State University of New York, Stony Brook, New York 11794

(Received 23 March 1983)

Negative parity $\Delta J = 1$ bands were observed in ^{118,120}Sb with (^{7}Li, $3n\gamma$) and (^{11}B, $3n\gamma$) reactions. Bandhead and level spacing properties are consistent with the $g_{9/2}$ proton-hole collectivity and a decoupled $h_{11/2}$ neutron. These bands decay to the low-lying $(\pi d_{5/2}, \nu h_{11/2})8^-$ isomers via several high-spin states, one of which, $7^{(+)}$ in ^{118}Sb, had a measured $t_{1/2} = 22.4 \pm 0.5$ ns. Comparisons to $\pi g_{9/2}{}^{-1}$ $\Delta J = 1$ bands in odd-mass Sb nuclides are made.

[NUCLEAR REACTIONS ^{114,116}Cd(^{7}Li, $3n$)^{118,120}Sb, ^{110}Pd(^{11}B, $3n$)^{118}Sb; measured γ-γ-t coinc. (E, γ, t); deduced level schemes in ^{118,120}Sb, γ multipolarities, J^π, $T_{1/2}$. Enriched targets, Ge detectors.]

The low-lying level schemes of odd-mass Sb ($Z = 51$) nuclei, with one proton outside the $Z = 50$ closed proton shell, are expected to be described simply in terms of the available single-particle states. An experimental study[1] has shown, however, that coexisting at low energies with the single-particle states are $\frac{9}{2}^+$ proton-hole (2p-1h) states upon which $\Delta J = 1$ collective bands are found. This collective feature, which lies lowest near the middle of the 50–82 neutron shell, surprisingly dominates the lower part of the yrast level spectra for the odd-Sb nuclides. Similar $\frac{9}{2}^+$ proton-hole $\Delta J = 1$ bands have been observed systematically over the $Z > 50$ transition region including the odd-mass I ($Z = 53$), Cs ($Z = 55$), and La ($Z - 57$) nuclei.[2] Theoretical interpretations[3] of this stable feature, which have involved proton-hole quadrupole-core interactions with the cores being treated phenomenologically as deformed rotors or anharmonic vibrators, have shown some success, but are not unique. More microscopic theoretical approaches are currently being examined.[4] To study further the nature of the core collectivity in transition nuclei, there has been recent interest in odd-odd nuclei; the combined coupling of the odd-proton and odd-neutron orbitals to the collective core may provide more unique information. Several theoretical predictions for the collectivity in odd-odd nuclei have been made in terms of deformed rotor cores and either "conflicting" or "peaceful" coupling (opposite or similar decoupled—strongly-coupled orbitals).[5] Recently, calculations involving a proton-neutron vibrational-core coupling have also been made for odd-odd transition nuclei.[6]

In the $Z > 50$ transition region, the $h_{11/2}$ neutron orbital combined with the $g_{9/2}$ proton hole that induces the collectivity in the odd-proton nuclei would be the relevant odd-odd configuration which is near yrast. The pure high-spin properties of this negative parity $[\pi g_{9/2}{}^{-1}, \nu h_{11/2}]$ configuration can be experimentally extracted despite the complexity of the odd-odd nuclei; the lowest state of the multiplet is expected to be $J^\pi = 7^-$ or 8^-. In a recent experiment, van Nes *et al.* have observed $\Delta J = 1$ bands based on these 8^- states in the odd-odd ^{114,116}Sb nuclei via the $(\alpha, 3n\gamma)$ reaction.[7] Their band spacings were similar to the $\frac{9}{2}^+$ $\Delta J = 1$ bands of the neighboring odd Sb nuclei, suggesting that the $h_{11/2}$ neutron is a spectator. To explore the extent and persistence of this dominant $g_{9/2}$ proton-hole collectivity and the systematics for the odd-odd Sb isotopes, the ^{116,118,120}Sb nuclei were studied with the (^{7}Li, $3n\gamma$) and (^{11}B, $3n\gamma$) reactions. New $\Delta J = 1$ collective bands were found in ^{118,120}Sb and the band[7] in ^{116}Sb was confirmed. These band structures which are built on the $[\pi g_{9/2}{}^{-1}, \nu h_{11/2}]$ configuration, are the focus of this Communication; the complete level schemes of ^{118,120}Sb will be reported in a later paper. Preliminary reports of this work have been made.[8] The current experiments which have extended the odd-odd band properties from ^{114}Sb ($N = 63$) through ^{120}Sb

($N=69$) map out a comparison of the collective influence of the $g_{9/2}$ proton hole in the odd and odd-odd Sb nuclei.

Previous to the van Nes *et al.*[7] study of ^{114,116}Sb, experimental information in odd-odd Sb nuclei involved medium- or low-spin states populated via light-ion reactions or radioactivity.[9] Very recently, Duffait *et al.*[10] reported additional work in the ^{114,116}Sb nuclei with the (^{7}Li, 3nγ) reaction. In many of the odd-odd Sb nuclei, low-lying 8^- isomers have been identified; their structure has been defined by magnetic moment measurements to be the $[\pi d_{5/2}, \nu h_{11/2}]8^-$ configuration.[11]

To investigate the collective properties of the odd-odd Sb nuclei, several experiments were performed via (HI,$xn\gamma$) reactions at the Stony Brook FN Tandem Laboratory. These measurements, involving various gamma-ray spectroscopic techniques with Ge detectors, included excitation functions, γ-γ-t coincidences, angular distributions, and pulsed beam γ timing. The excitation functions indicated an optimal bombarding energy of 29 MeV for the (^{7}Li, 3n) population of ^{118,120}Sb. Subsequent ^{7}Li experiments were performed at this energy with isotopically enriched 5 mg/cm^2 ^{112,114,116}Cd foils as targets. The ^{118}Sb nucleus was also studied via the ^{110}Pd(^{11}B, 3n) reaction with a 51 MeV ^{11}B beam. The γ-γ-t coincidence results were used to establish the γ-ray cascades and level schemes; gated spectra are presented in Figs. 1(a) and 1(b) for the ^{120}Sb and ^{118}Sb bands, respectively. To obtain information on γ-ray intensities, transition multipolarities, and spin assignments, angular distribution measurements were carried out at five angles between 90° and 150°. Lifetime results and delayed γ transitions were extracted from the pulsed beam measurements.

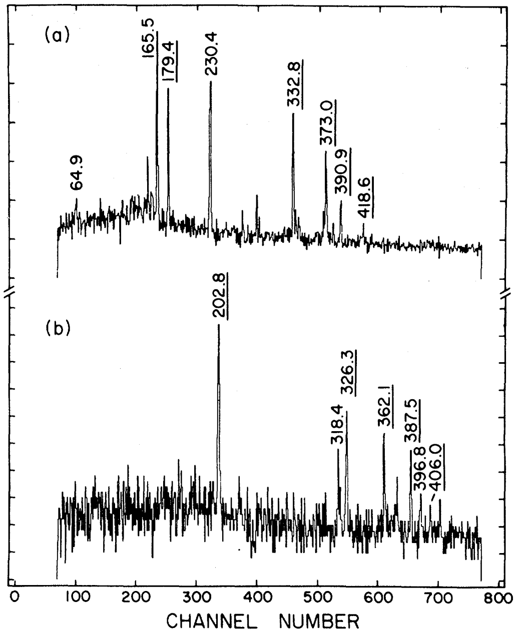

FIG. 1. Sum of γ-ray spectra gated by the $\Delta J=1$ band transitions for (a) ^{120}Sb and (b) ^{118}Sb. The sum spectrum in (a) was obtained from the ^{116}Cd(^{7}Li, 3n)^{120}Sb reaction and that in (b) from the ^{110}Pd(^{11}B, 3n)^{118}Sb reaction. Similar results were obtained for ^{118}Sb from the ^{114}Cd(^{7}Li, 3n)^{118}Sb reaction, which populated the band with somewhat greater relative strength. The underlined energies (in keV) represent the $\Delta J=1$ band transitions.

The γ-ray cascades extracted from the present data revealed new $\Delta J=1$ band structures in ^{118,120}Sb, which are shown in Fig. 2 along with the previously observed bands[7,10] in ^{114,116}Sb for comparison. The $\Delta J=1$ intraband transitions are of a $M1/E2$ mixed character (positive mixing ratios), which are corroborated by several weak $E2$ crossover transitions. The band spacings increase with spin and show no significant staggering. In all of these odd-odd Sb nuclei, the corresponding band spacings are remarkably similar differing by less than 8% but showing a definite increase with neutron number. The J^π of the bandheads, which are determined from the decay transitions, are 8^- in ^{118,120}Sb as in ^{114,116}Sb. Their energies relative to the $[\pi d_{5/2}, \nu h_{11/2}]8^-$ isomers gradually decrease with increasing neutron number from just above 1 MeV in ^{114}Sb to slightly below 1 MeV in ^{120}Sb. A common feature is a high energy transition connecting the 9^- band members with the low-lying 8^- isomers, which are strong in ^{114,118}Sb but somewhat weaker in ^{116,120}Sb. In ^{116,118}Sb, the bands partially decay through $7^{(+)}$ isomers; the present experiment yields a half-life of $t_{1/2}=22.4+0.5$ ns for the $7^{(+)}$ isomer in ^{118}Sb while Duffait *et al.*[10] obtained $t_{1/2}=10.3$ ns for the ^{116}Sb 7^+ isomer, showing $E1$ strengths $\sim 10^{-6}$ W.u. (Weisskopf unit).

The systematic collective band structures observed in the odd-odd Sb nuclei are believed to result from the collectivity associated with the $g_{9/2}$ proton hole via the $[\pi g_{9/2}{}^{-1}, \nu h_{11/2}]$ configuration. Calculations[6] based on a spherical core with residual interactions between the proton hole and the neutron particle suggest that the $J^\pi=7^-$ and 8^- configuration states are the lowest in energy being nearly degenerate, while the 9^- and 10^- configuration states are predicted[6] to be 250 anad 700 keV higher, respectively. Similar estimates result from a deformation core picture[5] (conflicting case) with a strongly coupled proton hole and a decoupled neutron particle (nearly perpendicular orbits). The observed bandheads are the 8^- states, although the 7^- state in ^{118}Sb was found, by a strong $8^- \rightarrow 7^-$ dipole transition, to be 37 keV below the bandhead. This is similar to the situation in ^{116}Sb.[7,10] The near degeneracy of the 7^- state will, of course, influence the band. The 9^- and 10^- band members are also expected to contain admixtures from the $[\pi g_{9/2}{}^{-1}, \nu h_{11/2}]9^-$, 10^- configuration states (particle alignment with total J) and thereby show

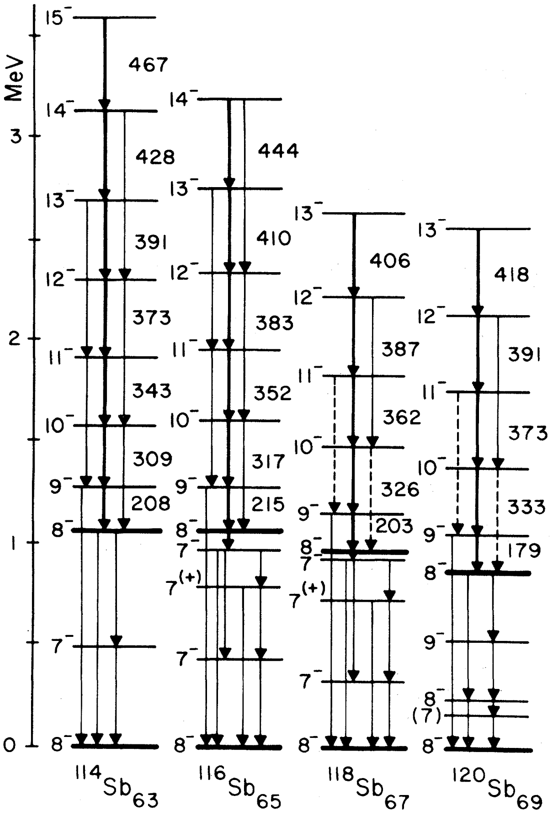

FIG. 2. Decay schemes for the $\Delta J = 1$ bands in ^{114,116,118,120}Sb. The results for ^{118,120}Sb are from the current work and those for ^{114,116}Sb are from Refs. 7 and 10. The energy scales are all normalized to the energies of the $[\pi d_{5/2}, \nu h_{11/2}]8^-$ isomers (thick lines at the zero of the energy scale). The $[\pi g_{9/2}{}^{-1}, \nu h_{11/2}]8^-$ bandheads are also indicated by thick lines.

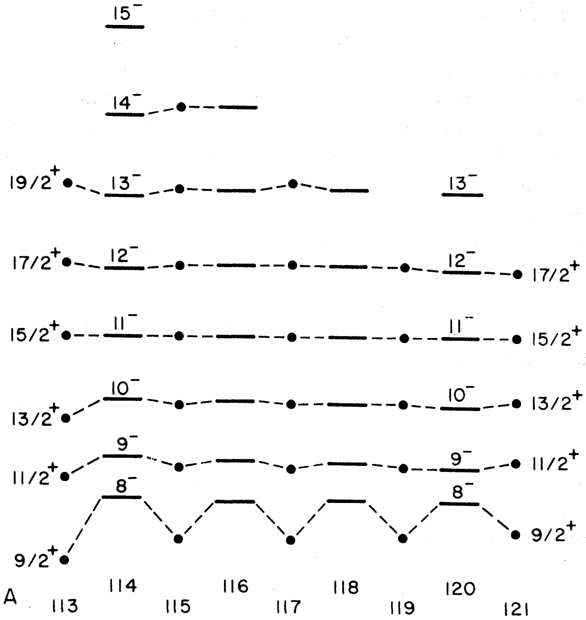

FIG. 3. Comparison of the $\Delta J = 1$ bands in the odd-odd Sb isotopes with those (filled circles) associated with the $g_{9/2}$ proton-hole states in the odd Sb isotopes from Ref. 1. The energy scales are normalized to a constant energy for the corresponding 11^- and $\frac{15}{2}^+$ band members.

possible energy shifts from a single collective-band picture. In addition, possible admixtures in the 8^- and 9^- band members can arise from the $[\pi g_{7/2}, \nu h_{11/2}]$ configuration which has energies between the bandhead and the 8^- isomer, on the basis of the odd-Sb level schemes. Such admixtures cause energy shifts and are perhaps responsible for the transitions from the 9^- band members to the 8^- isomers.

The most interesting feature of the collective bands observed in the odd-odd Sb nuclei is their precise reproduction of the spacing of the $g_{9/2}{}^{-1}$ proton hole bands in the neighboring odd-Sb nuclei. A detailed comparison of these band spacings is given in Fig. 3 from $N = 62$ through $N = 70$. The 11^- band members of the odd-odd Sb nuclei are normalized in energy to the $\frac{15}{2}^+$ odd-Sb band members as they are the lowest odd-odd band members which are expected to be free of significant admixtures. With the exception of the 8^- and 9^- band members, which show energy shifts due to the admixtures discussed above, the remaining band spacings in the odd-odd Sb nuclei agree with the corresponding odd Sb spacings to within ~ 5%. The odd-odd spacings are generally smaller by this amount. Large but systematic energy shifts are observed in the 8^- bandheads and to a lesser extent in the 9^- band members. The staggering observed in the odd-Sb band spacings, which is mainly a squeezing of the $j+1$ and $j+2$ levels $(\frac{11}{2}^+ - \frac{13}{2}^+)$, has been washed out in the odd-odd Sb bands. The remarkable similarities between the odd-odd Sb bands, that result from the $[\pi g_{9/2}{}^{-1}, \nu h_{11/2}]$ configuration, and the odd-Sb bands, from the $g_{9/2}{}^{-1}$ proton-hole states, suggest that the collectivity associated with the $g_{9/2}{}^{-1}$ proton hole is largely unaffected by the $h_{11/2}$ neutron particle. The slight reduction in the odd-odd spacings implies that the $h_{11/2}$ neutron enhances the collectivity a small amount. Thus, the $h_{11/2}$ neutron is essentially a spectator to the dominant $g_{9/2}$ proton-hole collectivity.

In summary, the coexistence of the stable collectivity that is associated with $g_{9/2}$ proton hole in the $Z > 50$ transition region has been shown to persist in the odd-odd Sb nuclei through the experimentally defined band properties of the $[\pi g_{9/2}{}^{-1}, \nu h_{11/2}]$ configuration. A detailed comparison of the odd and odd-odd Sb bands reveals the lack of any significant influence by the $h_{11/2}$ neutron on this dominant collectivity. The theoretical approach involving $[\pi g_{9/2}{}^{-1}, \nu h_{11/2}]$ orbitals (with residual interactions) coupled to a spherical vibrator can achieve reasonable fits to the $\Delta J = 1$ bands only with large broad phonon distributions in each band member.[6] This result which deviates from the typical particle-vibrator weak coupling calculation is somewhat unsatisfactory. The two-quasiparticle plus deformed rotor framework can also achieve negative parity $\Delta J = 1$ bands as semidecoupled (conflicting case) $[\pi g_{9/2}{}^{-1}, \nu h_{11/2}]$ orbitals with a prolate core and Coriolis distortions.[5] The combined odd-odd and odd band properties have not been calculated for the $Z > 50$ region in this model and any residual interaction effects have not been determined. The impressive systematics of the dominant $g_{9/2}$ proton-hole collectivity with the additional sensitivities of the odd-odd band properties will hopefully motivate a thorough theoretical investigation of the $Z > 50$ transition region aimed at defining a more unique understanding of the collective structure involved.

This work was supported in part by the National Science Foundation. One of us (F.C.Y.) acknowledges partial support of a Mrs. James Ying kui Ying Fellowship.

---

[*] Permanent address: Department of Nuclear Science, Fudan University, Shanghai, People's Republic of China.

[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. B. Fossan, in *Structure of Medium-heavy Nuclei—1979,* edited by "Demokritos" Tandem Accelerator Group, IOP Conf. Proc. No. 49 (IOP, Bristol and London, 1980).

[3] K. Heyde, M. Waroquier, H. Vincx, and P. Van Isacher, Phys. Lett. 64B, 135 (1976); P. Van Isacher, M. Waroquier, H. Vincx, and K. Heyde, Nucl. Phys. A292, 125 (1977).

[4] M. Gai, A. Arima, and D. Strottman, Phys. Lett. 106B, 6 (1981); F. Iachello and O. Scholten Phys. Rev. Lett. 43, 679 (1979).

[5] A. J. Kreiner, Z. Phys. A 288, 373 (1978); H. Toki, H. L. Yadav, and A. Faessler, *ibid.* 292, 79 (1979).

[6] J. van Maldeghem, J. Sau, and K. Heyde, Phys. Lett. 116B, 387 (1982).

[7] P. van Nes, W. H. A. Hesselink, W. H. Dickoff, J. J. van Ruyven, M. J. A. de Voigt, and H. Verheul, Nucl. Phys. A379, 35 (1982).

[8] W. F. Piel, Jr., M. A. Quader, S. Vajda, W. A. Watson III, F. C. Yang, and D. B. Fossan, in Proceedings of the Conference on High Angular Momentum Properties of Nuclei, Oak Ridge, Tennessee, 1982 (unpublished), Vol. I, p. 80; F. C. Yang *et al.,* Bull. Am. Phys. Soc. 27, 517 (1982); S. Vajda *et al., ibid.* 27, 517 (1982).

[9] *Tables of Isotopes,* 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978).

[10] R. Duffait, J. van Maldeghem, A. Charvet, J. Sau, K. Heyde, A. Emsallem, M. Meyer, R. Beraud, J. Treherne, and J. Genevey, Z. Phys. A 307, 259 (1982).

[11] P. T. Callaghan, M. Shott, and N. J. Stone, Nucl. Phys. A221, 1 (1974).