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Identification of excited states in doubly odd ^{110}Sb: Smooth band termination

G. J. Lane,[1] D. B. Fossan,[1] I. Thorslund,[1] P. Vaska,[1] R. G. Allatt,[2] E. S. Paul,[2] L. Käubler,[3,4] H. Schnare,[4] I. M. Hibbert,[5] N. O'Brien,[5] R. Wadsworth,[5] W. Andrejtscheff,[6] J. de Graaf,[7] J. Simpson,[8] I. Y. Lee,[9] A. O. Macchiavelli,[9] D. J. Blumenthal,[10] C. N. Davids,[10] C. J. Lister,[10] D. Seweryniak,[10,11] A. V. Afanasjev,[12,13] and I. Ragnarsson[12]

[1]*Department of Physics, State University of New York at Stony Brook, New York 11794-3800*
[2]*Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, United Kingdom*
[3]*Institut für Kern- und Teilchenphysik, TU Dresden, Mommsenstrasse 13, D-01062 Dresden, Germany*
[4]*Institut für Kern- und Hadronenphysik, FZ Rossendorf, Postfach 510119, D-01314 Dresden, Germany*
[5]*Department of Physics, University of York, Heslington Y01 5DD, United Kingdom*
[6]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Tzarigrad Chaussee 72, BG-1784 Sofia, Bulgaria*
[7]*Department of Physics, University of Toronto, Ontario, Canada M55 1A7*
[8]*CCLRC, Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom*
[9]*Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[10]*Argonne National Laboratory, Argonne, Illinois 60439*
[11]*University of Maryland, College Park, Maryland 20742*
[12]*Department of Mathematical Physics, Lund Institute of Technology, Box 118, S-22100 Lund, Sweden*
[13]*Nuclear Research Center, Latvian Academy of Sciences, LV-2169, Salaspils, Miera str. 31, Latvia*

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Excited states in ^{110}Sb have been identified for the first time in a series of γ-spectroscopy experiments using both thin and backed targets, including neutron-fold and recoil-mass measurements to provide unambiguous channel identification. The three decoupled intruder bands observed in ^{110}Sb are based upon configurations involving 2p-2h excitations across the $Z=50$ shell gap and show the features of smooth band termination. The yrast intruder band, which has been connected to the low-spin levels, is tentatively identified up to its predicted termination at $I^{\pi}=45^{+}$. Excellent agreement with configuration-dependent cranked Nilsson-Strutinsky calculations is obtained for the high-spin states near termination. [S0556-2813(97)50105-1]

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The competition between single-particle and collective degrees of freedom is of central interest in the field of nuclear structure. In the $Z=50$ region, the coexistence between spherical and deformed shapes is well understood in terms of the preference for spherical shape at low-excitation energy, due to the proximity of the $Z=50$ shell gap, and the preference for a deformed shape at higher-excitation energies, when protons are promoted from the upsloping (with deformation) $g_{9/2}$ orbital into the downsloping $(d_{5/2}/g_{7/2})$ and $h_{11/2}$ orbitals. Such particle-hole excitations are known to result in collective rotational bands in the antimony [1] and tin [2] isotopes. In the $A\approx 110$ region such bands are particularly interesting, because, with the small number of valence particles outside the Z and $N=50$ closed shells, the total angular momentum for configurations with a few holes in the $\pi g_{9/2}$ subshell is limited to $\sim 30-50\hbar$. When a particular configuration giving rise to a collective band is followed to high spin, eventually the total angular momentum available from the spin alignment of the particles (and holes) outside the closed shells is exhausted and the band terminates [3,4]. As the particles gradually align, the nuclear shape is predicted [3,4] to change over many transitions from collective near prolate ($\gamma\approx 0°$) at low spin, to noncollective oblate ($\gamma=+60°$) at the band termination. The $A\approx 110$ region is rather unique in this respect, since specific configurations are found to be yrast over a large spin range and can be observed up to termination. Such smoothly terminating bands have been studied to near termination spins in ^{106,108,109}Sn [5–7], ^{109,111,113}Sb [8–10], and ^{114}Te [11]. However, of all the bands seen in these nuclei, few have been directly linked to the low-spin states by γ-ray transitions and thus most do not have firm spin assignments. To fully understand the novel feature of smooth band termination, it is important to examine how the effect manifests under changing nuclear conditions. As the Fermi level changes, new configurations approach the yrast line and their smooth band terminations should have different, but predictable characteristics, if the theoretical interpretation is valid. Recent calculations have predicted that ^{110}Sb should exhibit a favored smoothly terminating band lying low in excitation energy over a large range of spins [4]. The current work reports the first observation of excited states in this neutron deficient nucleus, focusing on three intruder bands showing the features of smooth band termination. The yrast band has been linked to the low-spin level scheme and has known spins, allowing a definitive comparison with theory. Excellent agreement is obtained with the prior theoretical prediction, giving further confidence that the theoretical model of smooth band termination is applicable to these interesting structure phenomena.

High-spin states in ^{110}Sb were populated via the ^{54}Fe (^{59}Co,$2pn$) reaction with a 230 MeV ^{59}Co beam, provided by the 88-inch cyclotron at Lawrence Berkeley National Laboratory, incident on two stacked 440 μg/cm^2 targets. Gamma rays were detected with 36, 80% efficient HPGe detectors from the early implementation of GAMMASPHERE. Statistical model calculations predicted the strongly populated channels would be ^{109}Sn, ^{110}Sn, ^{107}In, and ^{110}Sb via the $3pn$, $3p$, $\alpha 2p$ and $2pn$ channels, respectively. The first three nuclei have been previously studied in-beam [7,12,13] and their known γ rays were observed, while the intense γ rays that could not be assigned to these three nuclei were believed to belong to the level scheme of ^{110}Sb.

The assignment of γ rays to ^{110}Sb was confirmed using the ^{56}Fe(^{58}Ni,$3pn$) reaction at Argonne National Laboratory with a 240 MeV ^{58}Ni beam, provided by the ATLAS accelerator, incident on a 590 μg/cm^2 target. Gamma rays were detected with the AYEBALL array, which for this experiment consisted of seven 80% and nine 30% efficient HPGe detectors. Evaporation residues recoiling out of the thin target were dispersed according to their mass/charge ratio in the fragment mass analyzer (FMA) [14], while fifteen NE213 liquid scintillator detectors (covering a total solid angle of $\sim$6% of 4π at forward angles) were used to identify neutrons via pulse shape and time of flight. Figure 1 presents the spectrum of γ rays measured in coincidence with $A=110$ recoils and at least one neutron and shows both γ rays assigned to ^{110}Sb and those from the $2p2n$ channel, ^{110}Te [15]. Note that the requirement of a neutron coincidence removes the γ rays from the $4p$ channel forming ^{110}Sn [12]. The inset shows the relative intensity ratios obtained from the zero and one-neutron gated spectra for γ rays from several of the other known channels (using various mass gates). The measured ratio for the γ rays assigned to ^{110}Sb clearly indicates that they are associated with a channel in which only one neutron is evaporated. Together with the $A=110$ identification and the fact that the compound nucleus was ^{114}Xe, this unambiguously assigns the γ rays to the $3pn$ channel, namely ^{110}Sb.

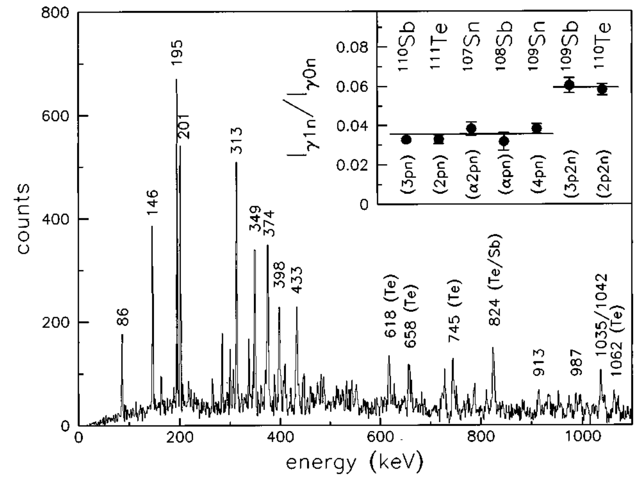

FIG. 1. Spectrum of γ rays in coincidence with $A=110$ residues and only one neutron. γ rays labeled by energy alone have been assigned to ^{110}Sb. The inset shows intensity ratios measured from zero and one-neutron gated spectra as described in the text.

Data from a third experiment, in which excited states in ^{109}Sn were investigated [7], were also used in the analysis. A beam of 240 MeV ^{58}Ni ions from the VICKSI accelerator at the Hahn-Meitner Institute was incident on a 2 mg/cm^2 ^{55}Mn target backed with 23 mg/cm^2 gold, thick enough to stop the recoiling residues. This reaction formed the same compound nucleus as the GAMMASPHERE experiment, although at a higher-excitation energy so that the ^{110}Sb and ^{110}Sn channels, with only three particles emitted, were less intensely populated than the four particle emission channels leading to ^{109}Sb and ^{109}Sn. Nevertheless, this experiment resulted in improved energy resolution for some of the lower spin transitions in ^{110}Sb, as well as providing lifetime information through the use of γ-beam timing techniques [7]. The γ rays were detected using the OSIRIS spectrometer, consisting of eleven 25–35% efficient HPGe detectors.

With the positive assignment of γ rays to ^{110}Sb, the highfold GAMMASPHERE data set was predominantly used to construct the level scheme. The data were unfolded into $\sim 2.3\times 10^9$ $\gamma\gamma\gamma$ coincidences and incremented into a RADWARE [16] three-dimensional histogram, from which the LEVIT8R [16] software was used to project background-subtracted, double-gated coincidence spectra. Figure 2 presents a partial level scheme for ^{110}Sb showing three decoupled bands (1–3) at high spin, feeding into both an intensely populated strongly coupled band (4) and a number of irregularly spaced spherical states. Sums of double-gated coincidence spectra showing the transitions in the two most intense decoupled bands are presented in Fig. 3, while γ rays from band 4 are shown in Fig. 1. The construction of the level scheme was made difficult by the tendency for the rotational bands to have a fragmentary decay near their bandheads, with intensity being lost over a number of transitions. Indeed, there is still considerable unplaced intensity in the complex decay of band 1, while bands 2 and 3 are unconnected to the lower-spin states.

The spins and parities assigned to the levels in ^{110}Sb are

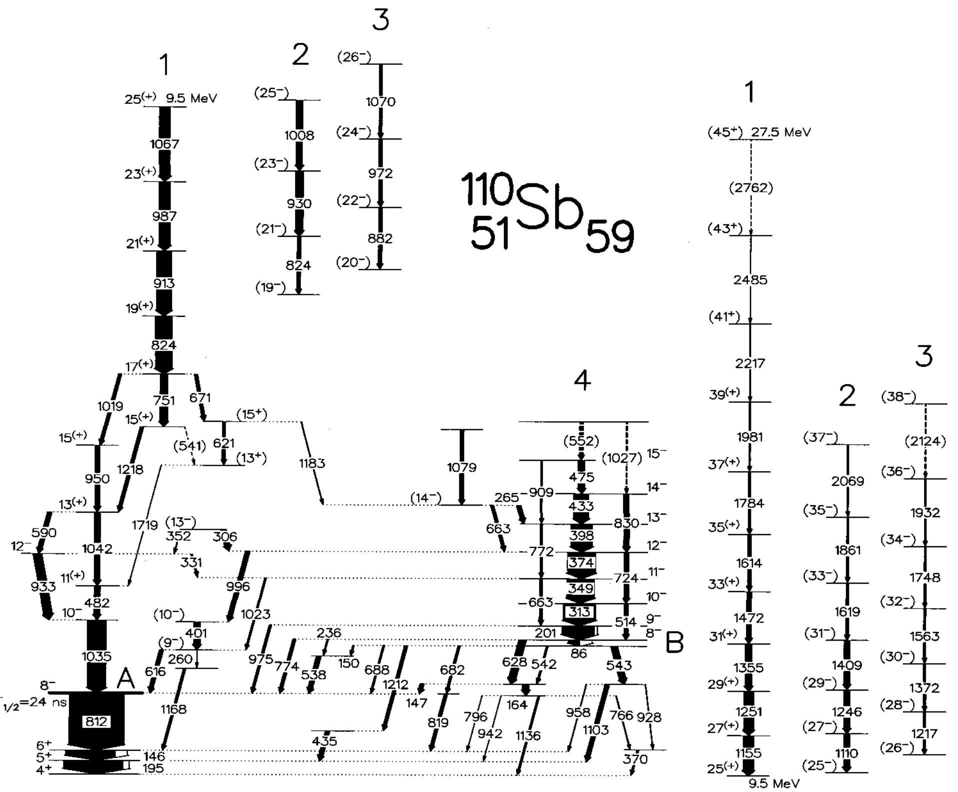

FIG. 2. Partial level scheme for ^{110}Sb with the widths of the arrows proportional to the transition intensities (white portions show the contribution from internal conversion). Note that the high-spin extensions of bands 1, 2, and 3 drawn on the right are at half scale and that all the spins and parities are tentative since the ground state spin is not definitively known. The levels marked A and B are assumed to have $J^{\pi}=8^{-}$. See the text for further details.

all tentative, since not even the ground state spin and parity are known with certainty. Reference [17] suggests a 3^{+} ground state for ^{110}Sb from the observed feeding of the 2^{+} and 4^{+} levels in ^{110}Sn during the β^{+} and electron capture decay of ^{110}Sb, with similar assumptions made for the ground state in ^{108}Sb [17]. However, the authors of Ref. [18] suggest that the spin and parity of the ground state in ^{108}Sb is more likely 4^{+} on the basis of measured angular correlations for some of the low-spin transitions and comparison with shell model calculations. We suggest the ground state for ^{110}Sb also has $I^{\pi}=4^{+}$ based upon the following arguments.

A ubiquitous feature of all the heavier odd-odd antimony isotopes is an isomeric state with spin and parity 8^{-} [19]. Magnetic and quadrupole moment measurements have shown that this isomer is formed from the $\pi h_{11/2}\otimes \nu d_{5/2}$ and $\pi h_{11/2}\otimes \nu g_{7/2}$ spherical configurations in the lighter and heavier isotopes, respectively (see, for example, Refs. [19,20]). A similar isomer is expected in ^{110}Sb. Indeed, examination of the OSIRIS data set reveals that the 812, 146 and 195 keV transitions in ^{110}Sb show a common time-delayed component, while the 1035 keV transition occurs prompt with respect to the beam pulse. This implies that the state at 1153 keV is isomeric; the measured half-life is 24(1) ns. This is short enough that in the thin target experiments it is still possible to observe γ-ray coincidences between transitions above and below the isomer, despite the fact that some of the recoiling nuclei decay out of view of the detectors.

An angular correlation analysis using the method of directional correlations from oriented states (DCO) [21] has been applied to both the GAMMASPHERE and OSIRIS data sets. The results obtained from gating on some of the intense, uncontaminated transitions at the base of band 1 (assuming they are stretched $E2$ transitions) are consistent with all the in-band transitions having stretched quadrupole character up to the 1981 keV transition. The DCO ratios measured for the transitions decaying out of and below band 1 suggest that the 812 keV transition has stretched quadrupole character, while the 146 and 195 keV transitions are stretched dipoles with small multipole mixing ratios. Based on systematics [19] and the observed lifetime, we suggest the 812 keV transition has $M2$ character, while the 146 and 195 keV transitions are $M1/E2$. Assuming the isomeric state at 1153 keV has spin and parity 8^{-}, this implies a 4^{+} ground state. Another feature common to all the odd-odd antimony isotopes is a

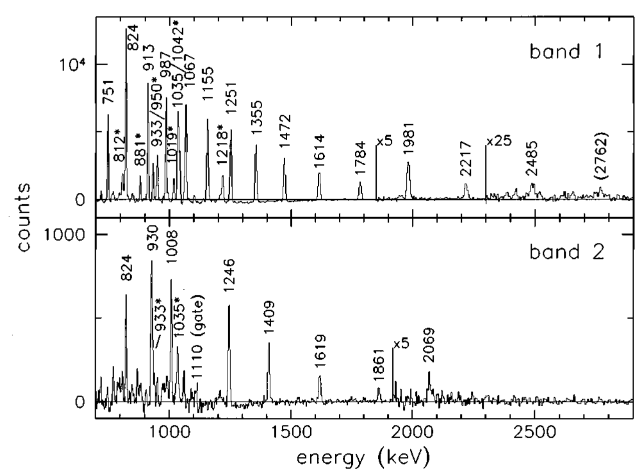

FIG. 3. Coincidence spectra for bands 1 and 2 in ^{110}Sb. The upper panel is a sum of spectra double gated on all combinations of transitions in band 1 from 913 to 1981 keV inclusive. The lower panel is a sum of spectra double gated on the 1110 keV transition and transitions in band 2 between 930 and 1861 keV inclusive. The peaks marked with asterisks are lower-spin transitions or are associated with the decay out of the bands.

strongly coupled band with a $9^- \rightarrow 8^-$ transition of around 200 keV (see, for example, Ref. [22] and references therein); band 4 in Fig. 2 is just such a structure. The decay out of this band via the 8^- isomer and a sequence of other spherical states is similar to the pattern observed in the heavier odd-odd antimony isotopes, giving further credence to the 8^- assignment for the isomeric state.

For transitions above the isomer, the DCO results suggest stretched E2 assignments for the 751, 1218, 950, 1019, 933, 1035, and 1042 keV transitions and stretched dipole character for the 482 and 590 keV transitions, giving the spins of band 1 as shown. The assumption of $E1$ character for the 482 and 590 keV transitions and hence positive parity for band 1, is in agreement with the predictions of the calculations presented below. All but one of the transitions placed in band 1 can be clearly observed in individual coincidence spectra. The exception is the 2762 keV transition, which is only seen in summed spectra (see Fig. 3) and is thus tentative. No evidence for higher feeding transitions has been found with the current statistics.

The transitions in bands 2 and 3 also have DCO ratios consistent with stretched $E2$ transitions. Although the discrete decay of bands 2 and 3 to the lower part of the level scheme has not been observed, examination of the individual coincidence spectra has shown that bands 2 and 3 preferentially feed the negative parity low-spin states. For example, the transitions from band 2 are in coincidence with the 933 and 1035 keV transitions (which decay from negative parity states), but are only in weak coincidence with the 482 keV and 1042 keV transitions (which decay from assumed positive parity states). This preferential feeding most likely indicates that bands 2 and 3 have the opposite parity to band 1. The remainder of this work will concentrate on the decoupled bands 1, 2, and 3 and their interpretation as smoothly terminating bands.

An extensive theoretical paper investigating smooth band termination has previously been published [4]. The calculations in Ref. [4] use a configuration-dependent cranked Nilsson-Strutinsky model, with special techniques so that it is possible to follow a specific single-particle configuration to high spin. For nuclei in the $A \approx 110$ region and configurations involving only a few holes in the $\pi g_{9/2}$ subshell, the calculations predict that, due to the limited valence space, the collective bands built on specific configurations eventually terminate. One of the characteristics of the terminating bands in this region is a decrease of the dynamic moment of inertia ($\mathcal{J}^{(2)} \approx 4/\Delta E_\gamma$) with spin to unusually low values, a fraction of the rigid-body value. The increase in the γ-ray energy spacings which is apparent in Fig. 3 for bands 1 and 2 in ^{110}Sb, implies such a decreasing dynamic moment of inertia. These low values of $\mathcal{J}^{(2)}$ correspond to the fact that the building of the last spin units before termination has a large energy cost, determined mainly from (i) the difficulty of aligning the high-Ω, $\pi g_{9/2}$ holes and (ii) the fact that the neutron $(d_{5/2}/g_{7/2})$ subshells are essentially half filled [4]. This unfavored band termination manifests as a characteristic minimum when the excitation energy is plotted versus spin in the form E-E_{RLD}, where E_{RLD} is a rigid rotor reference. Such plots for ^{110}Sb are discussed further below.

Prior calculations have predicted that ^{110}Sb should have an especially favored intruder band, yrast over the spin range

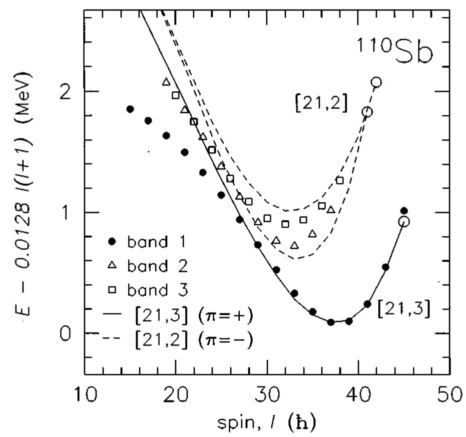

FIG. 4. Theoretical $E-E_{\mathrm{RLD}}$ curves for the three bands calculated to be most favored in the spin range $30\hbar$–$40\hbar$ (lines), compared to results for the three decoupled bands experimentally observed in ^{110}Sb (symbols). Large open circles indicate the predicted terminating states.

$25\hbar$–$45\hbar$ (see Fig. 13 of Ref. [4]). The solid and dashed lines in Fig. 4 are the results of more extensive calculations within the same formalism and show the three rotational bands predicted to lie lowest in energy, plotted with a rigid rotor reference subtracted. The three bands are the favored signature of the [21,3] (the previously predicted band) and the two signatures of the [21,2] configuration. (The notation used here to describe the configurations is the same as in Ref. [4], namely $[p_1 p_2, n]$ where p_1 is the number of $g_{9/2}$ proton holes, p_2 the number of $h_{11/2}$ protons, and n the number of $h_{11/2}$ neutrons.) That these are the energy-favored configurations is easily understood from comparison with the neighboring isotope, ^{109}Sb, in which the yrast band is due to the [21,2] configuration [8]. Adding either an $h_{11/2}$ or $(d_{5/2}/g_{7/2})$ neutron to this configuration in ^{109}Sb results in the [21,3] and [21,2] configurations, respectively, in ^{110}Sb.

The data points in Fig. 4 are from the experimental energies of the three decoupled bands, however, for comparison the theoretical energies must be adjusted since the theory is normalized to a liquid drop energy rather than the experimental ground state mass. In Fig. 4, the excitation energies of all three theoretical bands have been adjusted so that the predicted [21,3] configuration agrees with band 1 at $I = 37\hbar$. Band 1 is the most strongly populated of the decoupled bands, indicating that it is yrast, in agreement with the calculations. Furthermore, it has the appropriate signature, and, assuming the 482 and 590 keV transitions are E1, the correct parity. The tentative 2762 keV transition would decay from the terminating state with $I^\pi = 45^+$. The agreement between theory and experiment in the region of the minimum is extremely good for the [21,3] configuration, implying that the theory explains the important underlying physics. It is worth noting that the calculations predict the states in the favored signature of the [21,3] configuration to be the lowest $[\pi, \alpha] = [+,1]$ states by approximately 1 MeV for much of the observed spin range. Thus the experimental configuration is expected to be very pure, with the absence of admixtures allowing for a proper comparison with theory.

The states which bands 2 and 3 feed suggests that these bands have the opposite parity to band 1, making it natural to associate them with the two signatures of the negative-parity [21,2] configuration. Since the bands are unconnected to the low-spin states it is necessary to estimate their spins. Experimentally in the full level scheme [23] it is found that bands 2 and 3 feed into states with known spins of up to $18\hbar$, so that the suggested spins in Fig. 2 are reasonable. To compare bands 2 and 3 (unknown absolute energies) with theory, the experimental E-E_{RLD} curves are approximately normalized to the calculations at the minima, consistent with keeping the expected zero signature splitting. With these reasonable assumptions for the experimental spins and energies, the important energy characteristics manifest in the shapes of the curves in the region above $25\hbar$ are in agreement with theory, as shown in Fig. 4. Furthermore, the measured intensities for all three bands are in qualitative agreement with the theoretically predicted relative excitation energies. In contrast to band 1, neither bands 2 nor 3 are observed up to termination, probably because at high spin they are predicted to rise above the yrast configuration (see Fig. 4), with a consequent loss in feeding intensity. Since other possible configurations are predicted to yield substantially different experimental features, this agreement for bands 2 and 3 corroborates the theoretical interpretation of band 1. Note also, that for all three bands the theory begins to deviate from experiment at low spin where pairing becomes increasingly important [4,8].

In conclusion, excited states have been observed in ^{110}Sb for the first time in a comprehensive series of thin and thick target γ-ray experiments, including recoil-mass and neutron-fold measurements for channel identification. The dominant features of the level scheme at high spin are three decoupled bands with configurations based upon proton 2p-2h intruder excitations. These three bands exhibit the characteristic properties of smooth band termination. In particular, the yrast band, which has been linked to the low-spin states and has known spins, is tentatively observed up to the expected band termination. The known spins allow for a definitive comparison with theory and the results are in excellent agreement with prior calculations for the [21,3] configuration. This provides substantial confirmation of the validity of the smooth band termination interpretation.

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