CONF-9607156--5
ANL/PHY/CP--90491

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First Excited States in Doubly-Odd ^{110}Sb: Smooth Band Termination in the $A \approx 110$ Region.

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Abstract

Excited states have been identified for the first time in ^{110}Sb in a comprehensive series of γ-spectroscopy experiments, including recoil-mass and neutron-fold measurements. Three high-spin decoupled bands with configurations based upon 2p-2h excitations across the $Z = 50$ shell gap, are observed to show the features of smooth band termination, the first such observation in an odd-odd nucleus. The yrast intruder band has been connected to the low spin levels and is tentatively identified up to its predicted termination at $I^\pi = (45^+)$. Detailed configuration assignments are made through comparison with configuration-dependent cranked Nilsson-Strutinsky calculations; excellent agreement with experiment is obtained. The systematic occurrence of smoothly terminating bands in the neighbouring isotopes is discussed.

1 Introduction

The $Z = 50$ region exhibits a wealth of collective structures, coexisting with the expected single-particle features. For example, prolate collective bands have long been known to occur at moderate excitation energies in the antimony [1] and tin [2] isotopes, built upon configurations involving the excitation of protons across the shell gap via the $\pi g_{9/2} - \pi g_{7/2}$ level crossing at $\beta \sim +0.2$. Perhaps the best example is ^{117}Sb [3], in which a rather complete set of rotational structures based upon 1p-1h and 2p-2h excitations are known. More recently, the lighter isotopes with $Z \geq 50$ and $A \approx 110$ have been studied with heavy beams and the new generation of arrays, extending our knowledge of the collective intruder bands to very high spin. It has been found that most of the decoupled bands built upon 2p-2h excitations exhibit a decrease in the dynamic moment-of-inertia with spin to unusually low values, typically one-third to one-half of the rigid-body value. This has been interpreted as a gradual alignment of the valence nucleons outside of the $Z = N = 50$ closed shells, resulting in the nuclear shape crossing the γ-plane, smoothly changing over a sequence of many transitions from a collective prolate shape ($\gamma = 0°$) to a non-collective oblate shape ($\gamma = +60°$) [4, 5]. When all the valence particles (and holes) have aligned, the band sequence terminates. Due to the gradual nature of the process and the fact that a single configuration

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is followed all the way from the low-spin collective regime up until the point where the band terminates, this feature has been called smooth band termination.

So far, smoothly terminating bands have been observed to near termination spins in ^{106,108}Sn [6, 7], ^{109,111,113}Sb [8, 9, 10] and ^{114}Te [11]. Of all the bands seen in these nuclei, few have been connected to the low spin states and thus most do not have firm spin assignments. Nevertheless, estimates of the spin values can be obtained from feeding arguments, giving excellent agreement with theoretical calculations for a number of cases, in particular for ^{109}Sb, in which four bands have been observed up to their smooth terminations [8].

Recent calculations predicted that the neighbouring nucleus, ^{110}Sb, should exhibit a smoothly terminating band that would be yrast over a large range of spins [5]. The current paper reports the first observation of excited states in this neutron deficient nucleus[a], including three decoupled bands showing the features of smooth termination, one of which is the previously predicted yrast configuration.

2 Experimental Method and Results

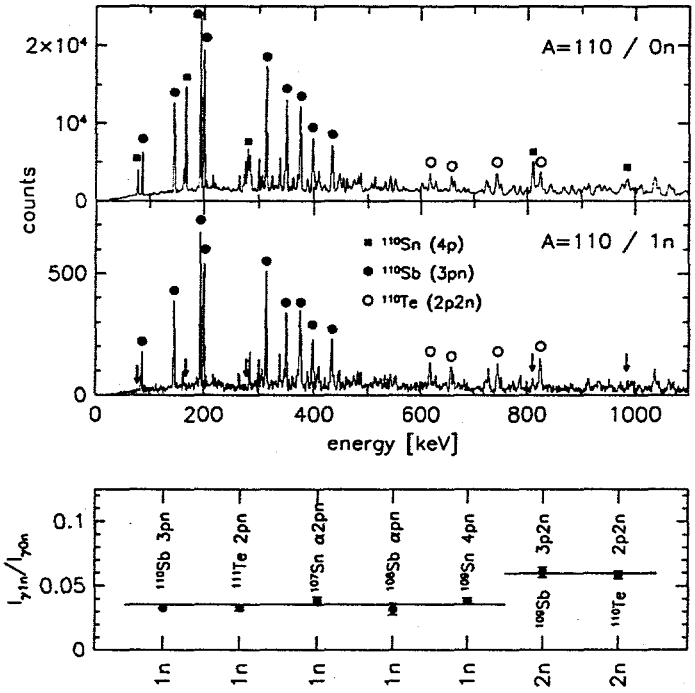

Figure 1: Spectra measured in coincidence with $A = 110$ residues and zero or one neutron. The lowest panel shows the intensity ratios measured for γ-rays in coincidence with zero and one neutron.

High spin states in ^{110}Sb were populated in three different experiments as summarised in Table 1. The upper panels of Figure 1 show the γ-ray spectra measured (at Argonne) in coincidence with $A = 110$ residues and zero or one neutron. Note how the neutron coincidence requirement removes the γ-rays from ^{110}Sn (4p channel) in the lower spectrum. The relative intensity ratios for the γ-rays in the zero and one-neutron gated spectrum give a measure of the neutron fold associated with the different reaction channels, as shown in the bottom panel. The ratio averaged over the different γ-rays assigned to ^{110}Sb clearly indicates a single neutron is evaporated, and, since $A = 110$, a 3pn reaction channel.

With the positive assignment of γ-rays to ^{110}Sb, the high-fold 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 cube, while the LEVIT8R software was used to project background-subtracted, gated coincidence spectra. Data from a third backed target experiment performed at the Hahn-Meitner Institute provided important lifetime information.

Fig. 2 presents a partial level scheme for ^{110}Sb showing three decoupled bands at high spin feeding into both an intensely populated strongly coupled band and a number of irregularly spaced spherical states. The labelled spins and parities are deduced from a DCO analysis in

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[a] Pan *et al.* have also identified excited states in ^{110}Sb, as evidenced by their abstract submitted to this conference.

Table 1: Experiments performed

Reaction	Energy [MeV]	Target [mg/cm^2]	Location	Detectors
^{54}Fe(^{59}Co,2pn)	230	2 × 0.440	Berkeley	EI-GAMMASPHERE (36 × 80% dets)
^{56}Fe(^{58}Ni,3pn)	240	0.590	Argonne	AYEBALL (9 × 25% and 7 × 80% dets) + FMA + 15 neutron dets.
^{55}Mn(^{58}Ni,2pn)	240	2.0 + 23 of Au	Hahn-Meitner Institute	OSIRIS (11 × 25-35% dets)

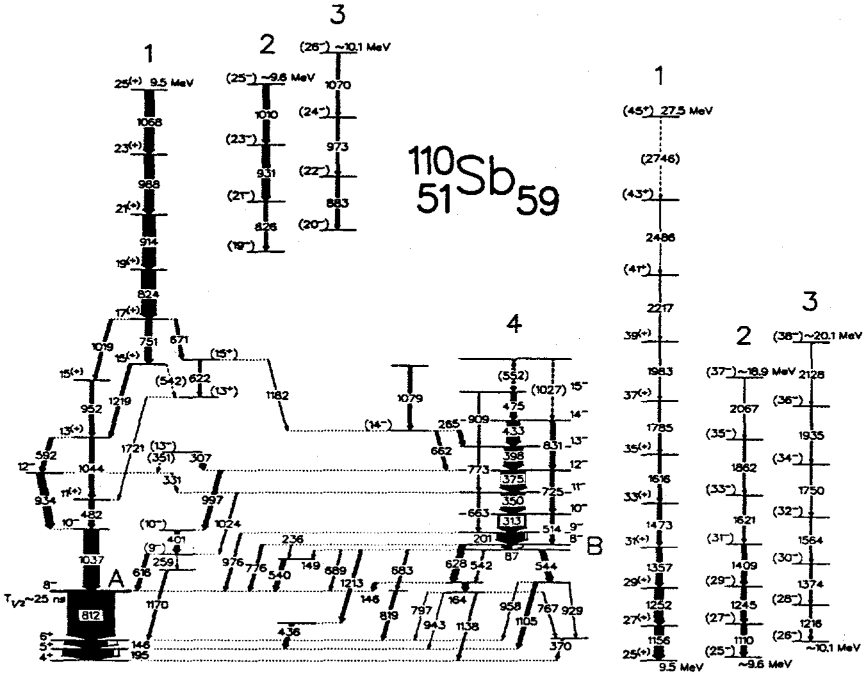

Figure 2: Partial level scheme for ^{110}Sb with the high-spin extensions of bands 1, 2 and 3 on the right drawn to half-scale. All the spins and parities are tentative since the ground state spin is not definitively known (see text).

which the levels marked A and B are assumed to have $J^\pi = 8^-$. These two assignments follow from systematic features known in the heavier odd-odd antimony isotopes. Firstly, all the heavier odd-odd antimony isotopes exhibit an isomer with spin and parity 8^- [12], 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. The isomeric state identified in ^{110}Sb in the present experiments has similarities with the 8^- isomer in the heavier isotopes. Another feature common to the heavier isotopes is a strongly coupled band with a $9^- \rightarrow 8^-$ transition of around 200 keV [12], formed from a rotation-aligned $h_{11/2}$ neutron coupled to the high-Ω $g_{9/2}$ proton hole; band 4 in Fig. 2 is just such a structure.

Using the 8^- assignment to the isomer as a starting point, the DCO analysis has determined the spins of band 1, although the band parity assignment rests upon the assumed E1 character of the 592 and 482 keV transitions. The spins and parities of bands 2 and 3 have been estimated from their observed decay patterns. Note also that the authors of Ref. [13] assign 3^+ ground states to both ^{108}Sb and ^{110}Sb, deduced from the observed feeding of the 2^+ and 4^+ levels in ^{108,110}Sn during the β^+ and EC decay of ^{108,110}Sb. However, Ref. [14] gives the ground state spin and parity of ^{108}Sb as 4^+ on the basis of measured angular correlations for some of the low-spin transitions and comparison with shell model calculations. For ^{110}Sb, assuming the isomer has $J^\pi = 8^-$, the DCO analysis also gives a 4^+ ground state.

3 Discussion

For nuclei in the $A \approx 110$ region and configurations involving only a few holes in the $\pi g_{9/2}$ subshell, calculations with a configuration-dependent cranked Nilsson-Strutinsky model predict that, due to the limited valence space, the collective bands built on a particular configuration eventually terminate [4, 5]. As discussed in the introduction, such bands undergo a gradual shape change as the valence particles and holes align. This results in a decrease of the dynamic moment-of-inertia with spin, and, since $\mathcal{J}^{(2)} \propto 1/\Delta E_\gamma$, an increase in the γ-ray energy spacings within the band. Bands 1, 2 and 3 all exhibit this phenomenon. It is also found 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 $(d_{5/2}/g_{7/2})$ sub-shells are essentially half-filled [5]. This unfavoured band termination is manifest as a characteristic minimum when the excitation energy relative to a rigid rotor reference is plotted versus spin $(E - E_{RLD})$.

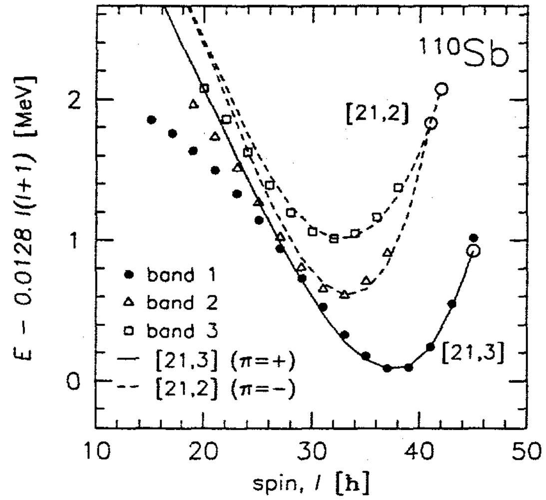

Figure 3: Theoretical $E - E_{RLD}$ curves for the three bands calculated to be most favoured in the spin range $25 - 45\hbar$ (lines), compared to the three decoupled bands experimentally observed in ^{110}Sb (symbols). Large open circles indicate the predicted terminating states.

This can be seen in Fig. 3, where the solid and dashed lines are the results of calculations within the formalism of Ref. [5] for the three rotational bands predicted to lie lowest in energy in the spin region $25-45\hbar$. Note that the theoretical results for the [21,3] configuration had been presented prior to the experimental results being obtained (see Fig. 13 of Ref. [5]). The notation used here to describe the configurations is the same as Ref. [5], namely $[p_1p_2, n]$ 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.

The data points in Fig. 3 are the experimental energies of the three decoupled bands. Since the pairing correlations are neglected in the calculations, when comparing theory and experiment, the absolute energies relative to the ground state should not be considered, but rather the energy relative to some high spin state. Thus the excitation energies of the theoretical bands have been adjusted in Fig. 3 so that the predicted [21,3] configuration agrees with band 1 at $I = 37\hbar$. Excellent agreement between theory and experiment for the region above $25\hbar$ is obtained. Note that the tentative 2746 keV transition would decay from the terminating state with $I^\pi = 45^+$.

The states which bands 2 and 3 feed suggest that these bands have the opposite parity to band 1, making it natural to associate them with the two signatures of the [21,2] configuration. Since linking transitions connecting the bands to the low spin states have not been found it is necessary to estimate their spins. Experimentally it is found that bands 2 and 3 feed into states with known spins of up to $18\hbar$ (full level scheme to be published), so that the suggested spins in Fig. 2 are reasonable. To make a comparison with theory, the experimental bandheads for bands 2 and 3, which have unknown energies, are adjusted so that the minimum of the $E - E_{RLD}$ curves agrees with the energies of the theoretical predictions. With this reasonable choice there is again excellent agreement with theory in the region above $25\hbar$, as shown in Fig. 3. Furthermore, the measured intensities for the three bands are in qualitative agreement with their 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 line (see Fig. 3), with a consequent loss in feeding. Note also, that for all three bands the theory begins to deviate from experiment at low spin where pairing becomes increasingly important [5, 8].

With the detailed configuration assignments it is now possible to compare the smoothly ter-

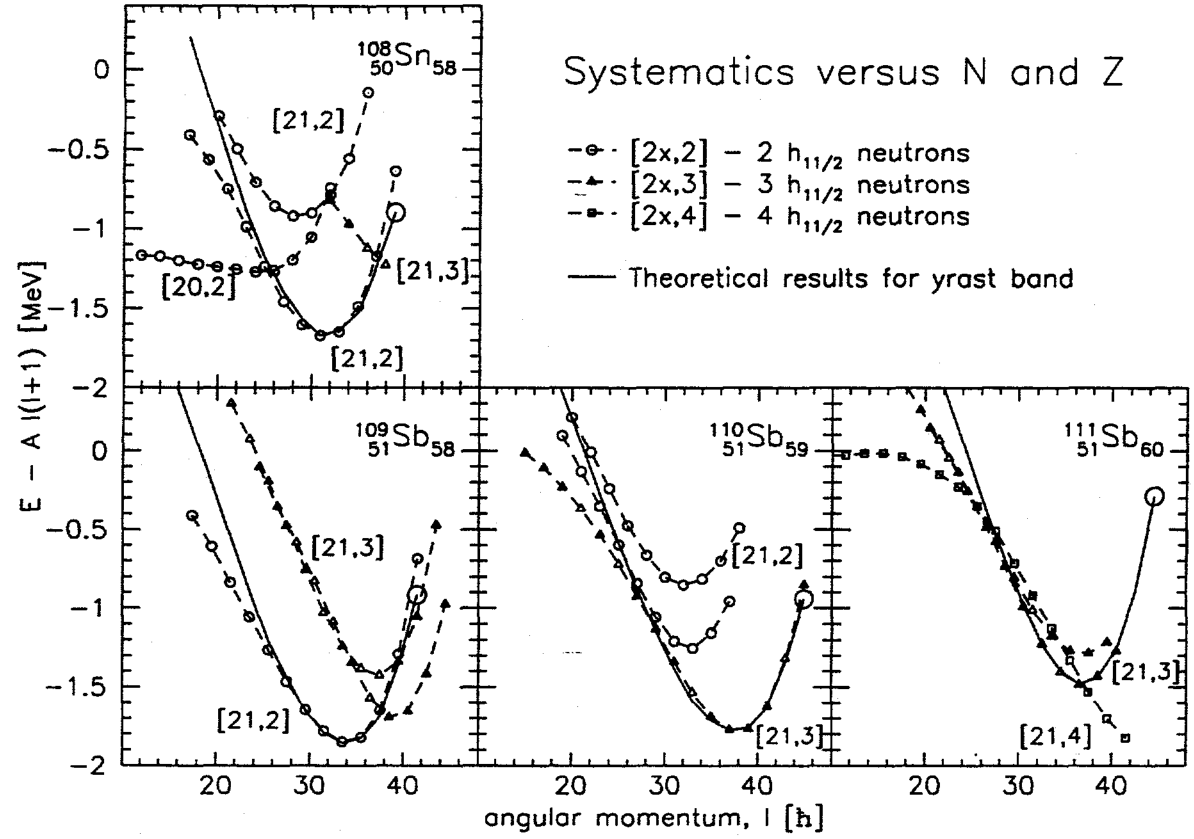

Figure 4: Experimental systematics of smoothly terminating bands observed in the isotopes neighbouring ^{110}Sb. The overall energy scales for the different isotopes have been shifted to bring them all into the same energy region, while the solid lines are the results of theoretical calculations for the yrast band in each case. Of the bands plotted, only the favoured signatures of the following configurations have known spins: [20,2] and [21,2] in ^{108}Sn, [21,3] in ^{110}Sb and [21,4] in ^{111}Sb.

minating bands observed in ^{110}Sb to those observed in the neighbouring nuclei, building upon the summary previously presented in Ref. [15]. Figure 4 shows the three smoothly terminating bands most intensely populated in four different isotopes, together with their assigned configurations. The results of theoretical calculations for the yrast band are shown as solid lines for each isotope.

The yrast terminating bands which are observed in ^{108}Sn are the [20,2], [21,2] and [21,3] configurations, going from lower to higher spins, respectively [7]. Thus we see that the simple $(g_{7/2})^2(g_{9/2})^{-2}$ proton excitation occurs at lower spin, while to form the yrast line at higher spins, the $(g_{7/2}h_{11/2})(g_{9/2})^{-2}$ excitation is more favourable. At the very highest spins observed, an extra $h_{11/2}$ neutron is needed to create the necessary angular momentum.

In the $N = 58$ isotone, ^{109}Sb, the yrast neutron configurations are exactly analogous, with the [21,2] occurring at lower spin than the [21,3] configuration [8]. Since the $(g_{7/2}h_{11/2})(g_{9/2})^{-2}$ proton excitation begins to dominate at higher spin in ^{108}Sn, it is not surprising that with the slightly higher Fermi level in the antimony isotope, the extra valence proton prefers to go into the $h_{11/2}$ sub-shell. Indeed calculations for the antimony isotopes show that the [20,n] configurations generally lie far above the yrast line.

In ^{110}Sb, the [21,3] configuration begins to dominate over the [21,2] configuration due to the rise of the neutron Fermi level within the $h_{11/2}$ sub-shell. Along a similar vein, in ^{111}Sb the [21,3] and [21,4] configurations are both observed to lie at the yrast line [5, 9]. In all cases the theoretical calculation for the yrast band gives excellent detailed agreement for spins above $25\hbar$, but deviates at lower spins due to the increase in the pairing correlations.

Moving on to nuclei not shown in Figure 4, ^{112}Sb currently provides a gap in the systematics. However, ^{113}Sb is known, with the [21,4] configuration forming the yrast line and the [21,3] configuration lying somewhat above it [10, 15]. The observed configurations in the $N = 62$ isotone, ^{114}Te [11], are identical to ^{113}Sb except with the addition of the extra valence proton in the $h_{11/2}$ sub-shell, i.e. [22,4] and [22,3]. In these heavier isotopes, which have more valence particles and a higher level density, the calculations begin to lose the detailed agreement which is seen in Figure 4. Thus for the $N = 62$ isotones, the position in spin of the minima of the $E - E_{RLD}$ curves is well reproduced by calculations; however, the slopes of the curves around the minima are not, as can be seen in Figs. 5 and 6 of Ref. [15] and Fig. 2 of LaFosse's abstract to this conference [10].

4 Conclusions

Excited states have been observed in ^{110}Sb for the first time, including three decoupled bands with configurations based upon 2p-2h intruder excitations, which show the characteristic properties of smooth band termination. The yrast band, which has been linked to the low spin states and has known spins, is in excellent agreement with the results of prior calculations for the [21,3] configuration, while the other two unlinked bands are believed to be the two signatures of the [21,2] configuration. The changing structure of the smoothly terminating bands seen in the neighbouring isotopes can be understood in terms of the varying proton and neutron Fermi levels.

Acknowledgements: This work was supported by the NSF (U.S.A.), EPSRC (U.K.), DOE (U.S.A.), BMBF (Germany) and the Swedish Natural Science Research Council. A.V.A. and I.R. are grateful for financial support from the Crafoord Foundation (Lund, Sweden) and the Royal Swedish Academy of Sciences. The authors are grateful to many colleagues at Berkeley, Argonne and the H.M.I. for their help in the various experiments.

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