PHYSICAL REVIEW C **71**, 064323 (2005)

Identification of low-spin states in ^{111}Sb: Test of spin-orbit coupling in light nuclei

J. Shergur,[1,2] D. J. Dean,[3] D. Seweryniak,[2] W. B. Walters,[1] A. Wöhr,[1,2,4] P. Boutachkov,[4] C. N. Davids,[2] I. Dillmann,[5] A. Juodagalvis,[3,6] G. Mukherjee,[2] S. Sinha,[2] A. Teymurazyan,[4] and I. Zartova[4]

[1]*Department of Chemistry, University of Maryland, College Park, Maryland 20742, USA*
[2]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*Physics Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831, USA*
[4]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[5]*Institut für Kernchemie, Universität Mainz, D-55128 Mainz, Germany*
[6]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*

(Received 29 October 2004; published 30 June 2005)

New low-spin levels in ^{111}Sb have been identified following the β^+/EC decay of proton-rich ^{111}Te. ^{111}Te was produced in the ^{58}Ni(^{56}Fe, $2pn$)^{111}Te reaction and separated using the fragment mass analyzer at Argonne National Laboratory. γ-ray singles and γ-γ coincidence spectra were collected as a function of time. Eleven new levels in ^{111}Sb were identified, including levels at 487 and 881 keV that have been tentatively assigned spins and parities of $1/2^+$ and $3/2^+$, respectively. Shell-model calculations have been performed in which the single-particle $d_{3/2}$ and $s_{1/2}$ basis levels were adjusted to fit the observed positions of the low-energy $1/2^+$ and $3/2^+$ levels in ^{109}Sb and ^{111}Sb. Good agreement for the known yrast $1/2^+$, $3/2^+$, $5/2^+$, $7/2^+$, and $9/2^+$ levels in ^{105,107,109,111}Sb is obtained.

DOI: 10.1103/PhysRevC.71.064323 PACS number(s): 23.40.−s, 21.60.Cs, 27.60.+j

I. INTRODUCTION

The systematic behavior of the low-energy levels of the odd-mass Sb nuclides with $54 \leqslant N \leqslant 82$ reflects both the monopole shifts in single-proton energies and the interaction of the single proton with the underlying levels in the even-even core Sn nuclides [1–4]. The dominant feature of these levels is the dramatic monopole shift of the $d_{5/2}$ and $g_{7/2}$ levels in which the $g_{7/2}$ level moves from a position 852 keV above the $d_{5/2}$ level in ^{111}Sb to a position 963 keV below the $d_{5/2}$ level in ^{133}Sb. The low-energy levels of the rather well-studied odd-mass Sb nuclides with $64 \leqslant N \leqslant 80$ are shown in Fig. 1. In spite of that steady change, it can be seen that the higher-spin $9/2^+$ and $11/2^+$ members of the particle-phonon multiplet are relatively insensitive to neutron number, especially near $N = 82$, and remain in close proximity to the energy of the 2^+ level in the adjacent even-even Sn core. This behavior is in sharp contrast to the low-spin $3/2^+$ member of that multiplet that first falls to a low at $N = 70$ and then rises again to a higher energy at $N = 64$. The low-energy $1/2^+$ level that arises from coupling the $d_{5/2}$ proton to the even-even Sn core also falls to a low at $N = 70$ and then rises toward $N = 64$. The behavior of both the lowest $1/2^+$ and $3/2^+$ levels supports the notion of a rather strong subshell effect for $N = 64$, at least for $Z = 50$ and adjacent Sb and In nuclides, and demonstrates a sensitivity to the microscopic structure of the excited states of the even-even Sn core.

In contrast to the considerable data available for the structures of those neutron-rich Sb nuclides, scant data are known for the low-spin levels of the proton-rich Sb nuclides, especially at lower spin. In the β^+/EC decay of ^{109}Te reported by Ressler *et al.* [5], six new levels below 2.0 MeV were identified in ^{109}Sb. These levels were predicted with reasonable agreement by two separate shell-model calculations [5,6], including the positions of the surprisingly low $1/2^+$ and $3/2^+$ states at 402 and 752 keV, respectively. Although significant data exist for the high-spin levels of ^{105,107,109,111}Sb, no data are available for the low-spin levels of ^{111}Sb. Hence, in this paper, we report new data for the low-spin levels of ^{111}Sb that are populated in the β^+/EC decay of ^{111}Te.

II. EXPERIMENTAL DETAILS

The experiment was performed using the Argonne tandem linear accelerator system (ATLAS) coupled to the fragment mass analyzer (FMA) at Argonne National Laboratory. ^{111}Te nuclei were produced using the ^{58}Ni(^{56}Fe, $2pn$)^{111}Te fusion-evaporation reaction with a beam energy of 225 MeV and a target thickness of 823 μg/cm^2. Reaction products were separated in the FMA on the basis of their mass-to-charge (A/Q) ratio at charge state 24. Following mass separation, the recoils were implanted in the tape of a moving tape collector (MTC) that was moved periodically to a Pb-shielded counting station. As the half-life of ^{111}Te was previously reported to be 19 s [7], count and collection times were varied from 40 s, to maximize coincidence events, to as long as 150 s, to permit identification of γ rays belonging to the decay of daughter and granddaughter nuclides and to the decay of nuclides that were collected on the tape owing to similar A/Q values.

Two large HPGe detectors (45% and 65%) and two small Ge detectors (~25%) were used to detect the γ rays coming from the reaction products deposited on the tape. In addition to the Ge detectors, two plastic scintillators were used to veto 0° γ-γ coincidences in the same detector and to obtain 180° γ-γ coincidences. Analyses of γ singles, γ-γ coincidences, and γ-time data were used to identify transitions in the corresponding ^{111}Sb daughter nucleus.

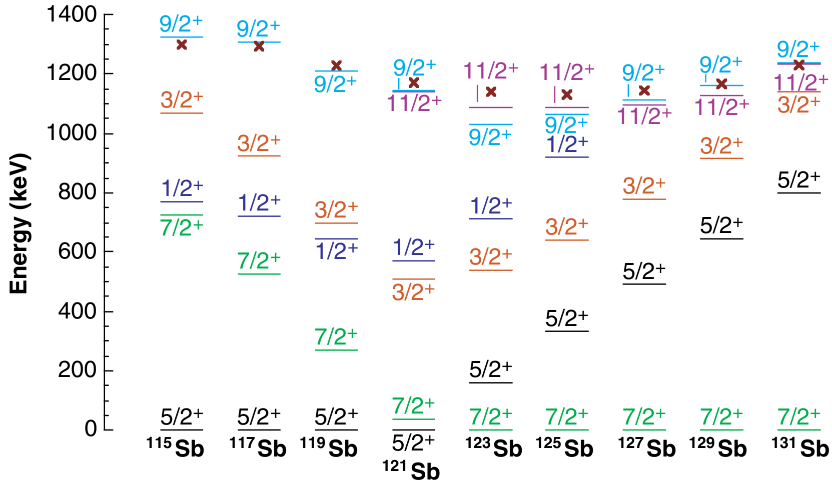

FIG. 1. (Color online) Low-spin systematics for levels below 1.5 MeV for the odd-*A* Sb isotopes between $A = 115$ and $A = 131$. The position of the 2_1^+ level in the adjacent even-even Sn core is marked by an "x".

III. RESULTS

Known contributions to the γ-singles and γ-γ coincidence spectra arose from the decay of ^{111}Sb ($T_{1/2} = 1.25$ min), ^{111}Sn ($T_{1/2} = 35$ min), ^{110}Sb ($T_{1/2} = 24$ s), and ^{110}In ($T_{1/2} = 1.15$ h) [8,9]. A γ spectrum resulting from the subtraction of a γ spectrum taken between $t = 75$ and $t = 150$ s from the first 30 s of the counting period is shown in Fig. 2. The time-gated spectra used in the subtraction were chosen to eliminate the contribution of transitions associated with the decay of 1.25 min ^{111}Sb. In Fig. 2, it can be observed that the long-lived transitions from ^{111}Sb decay were subtracted roughly to background (i.e., a single-channel spike remains at 154 keV, and no evidence remains of the presence of the 489-keV transition). Peaks associated with the growth of the decay daughters appear as dips in the spectrum as the intensity of these peaks increases as a function of time. The remaining peaks in the difference spectrum are attributed to either ^{111}Te or ^{110}Sb decay. As the decay lines of ^{110}Sb are well established, peaks in Fig. 2 not associated with ^{110}Sb decay were assigned to the decay of ^{111}Te. There were two peaks whose energies were ambiguous at 999 and 1031 keV. These are both shown with an uncertainty of 1 keV because of the strong overlap of the 997- and 1032-keV transitions, respectively, from the decay of ^{111}Sb into ^{111}Sn. The energies, intensities, and placements in the ^{111}Sb level scheme of the ^{111}Te decay lines from this study are summarized in Table I .

Three peaks at 487, 851, and 881 keV stand out below 1.0 MeV in Fig. 2. The 851-keV transition was previously identified as part of the ^{111}Sb yrast cascade by LaFosse

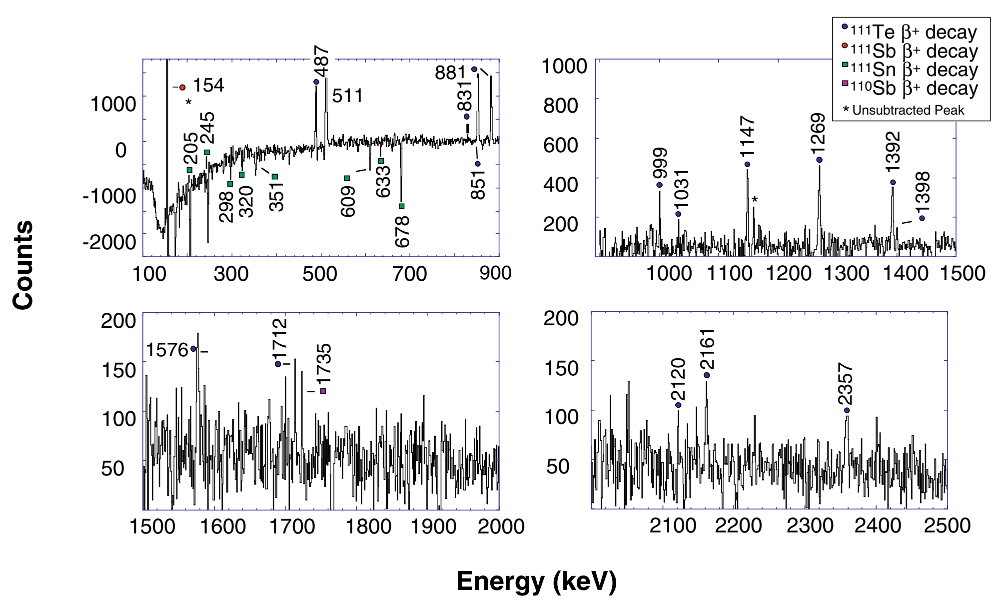

FIG. 2. (Color online) Time-subtracted spectrum showing ^{111}Sb transitions from the decay of ^{111}Te. The γ-energy spectrum shown is the residual spectrum obtained by subtraction of the spectrum taken during the first 30 s of a 150 s acquisition from the spectrum taken during the last 75 s of this counting period. Peaks present in the spectrum arise from the decay of nuclides with half-lives below ~60 s, while dips arise from the decay of nuclides that grow during the counting period.

TABLE I. Gamma intensities in ^{111}Sb following ^{111}Te β^+ decay.

Level (keV)	To Level (keV)	E_γ	I_γ
487	0	487	45(7)
851	0	851	100(2)
881	0	881	92(3)
1147	851	296	2(1)
	0	1147	30(2)
(1268)	0	(1268)	(25(15))
1398	851	547	7.4(1)
	0	1398	16(5)
1576	851	727	14(2)
	0	1576	21(3)
1712	881	831	6(2)
	0	1712	13(3)
1879	881	999(1)	22(5)
	851	1031(1)	22(3)
	487	1392	25(5)
	0	1879	6.9(4)
2027	851	1176	19(4)
	0	2027	8.5(9)
2120	851	1269	30(15)
	0	2120	17(3)
2161	851	1310	4(1)
	0	2161	15(2)
2357	881	1477	10(1)
	851	1506	18.1(5)
	0	2357	18(2)
2613	851	1762	19(3)
	0	2613	6(1)

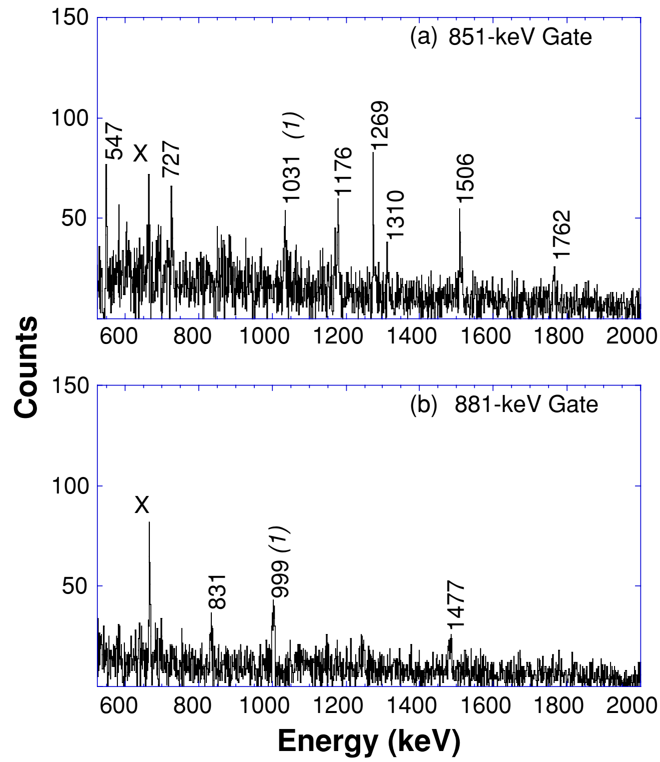

FIG. 3. (Color online) γ-γ coincidence spectra gated on the 851-keV (a) and the 881-keV (b) transitions in ^{111}Sb following β^+/EC decay of ^{111}Te. The peak labeled with an 'x' corresponds to the sum of the 154- and 511-keV γ-rays.

et al. [10] among the γ rays observed following a heavy-ion reaction. As the 851-keV transition is the most intense peak in Fig. 2, the remaining γ rays in the spectrum can be assigned to ^{111}Sb with confidence. The gated spectra for the 851- and 881-keV transitions are shown in Fig. 3. The 851-keV gate in Fig. 3(a) shows the coincidence at 547 keV expected on the basis of the data reported by LaFosse *et al.* [10]. Additional peaks are observed at 727, 1031, 1176, 1269, 1310, 1506, and 1762 keV. As placing gates on these peaks show only coincidences with the 851-keV γ ray, these transitions are likely to depopulate states that feed the 851-keV level directly. Hence, these coincidences, along with ground-state crossover transitions, provide support for the placement of new levels at 1576, 1879, 2027, 2120, 2161, 2397, and 2613 keV.

The coincidence spectrum obtained by gating on the 881-keV γ ray is shown in Fig. 3(b). Despite the overlap of the 878-keV transition from the β^+/EC decay of ^{111}Sb in the 881-keV gate, clean peaks not associated with transitions in ^{111}Sn are observed at 831, 999, and 1477 keV. The 999- and 1477-keV γ rays are placed as depopulating levels at 1879 and 2357 keV that have already been established by ground-state transitions and transitions to the $7/2^+$ level at 851 keV. The 831-keV γ ray provides support for a new level at 1712 keV, which also depopulates via a crossover transition to the $5/2^+$ ground state.

Peaks also appear in Fig. 2 at 487 and 1392 keV. These γ rays appeared in coincidence with each other and support a cascade from the level at 1879 keV established by other coincidence data through a level at 487 keV to the ground state.

The time dependence of the combined decay rates of the peaks at 851 and 881 keV is shown in Fig. 4. These data were used to determine a half-life of 26.2(6) s for ^{111}Te decay. This value is somewhat longer than the previously reported value of 19.3(4) s [7]. As those data came from the decay rate of β-delayed protons that were not directly associated with any single nuclide, the presence of any short-lived ^{111}I in their sources could give rise to a shorter half-life value.

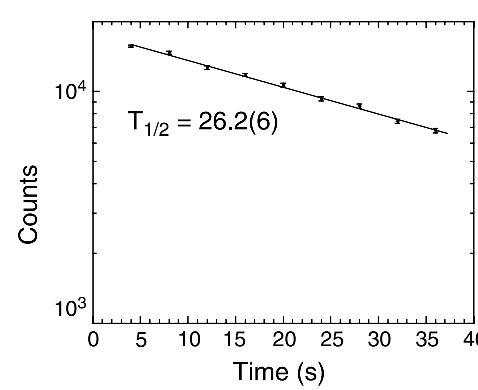

FIG. 4. Least-squares fit of the combined decays of the 851- and 881-keV transitions in ^{111}Sb following β^+/EC decay of ^{111}Te.

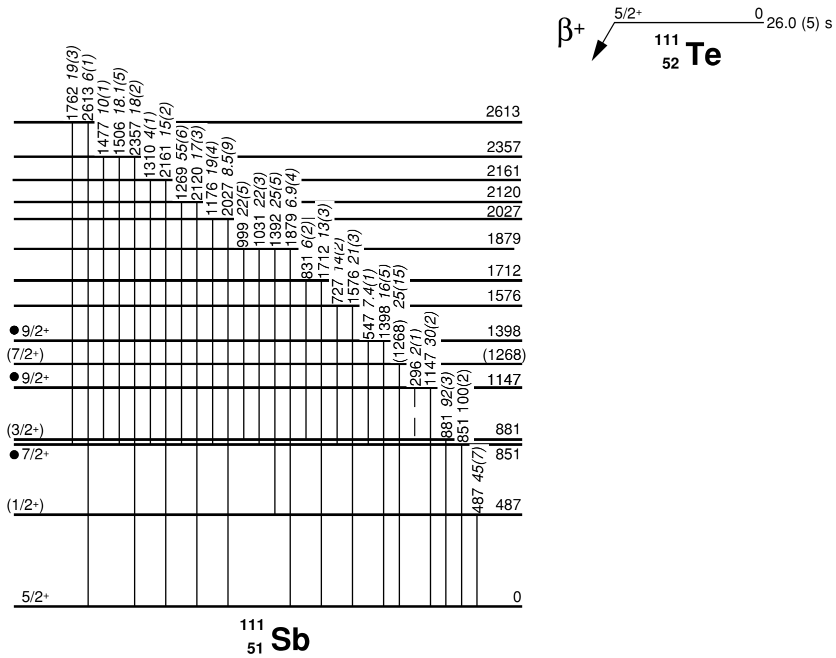

FIG. 5. Levels populated in ^{111}Sb following β^+ decay of ^{111}Te. Level energies and transitions are shown in units of keV. Levels already established in heavy-ion reaction studies are denoted by a filled circle. All transition intensities are given relative to the intensity of the 851-keV γ ray, with tentative transitions being shown by a dashed line.

IV. ^{111}Sb LEVEL SCHEME

The decay scheme for ^{111}Te based on the interpretation of γ-time and γ-γ coincidence spectra is shown in Fig. 5. The levels at 851, 1147, and 1398 keV were identified by LaFosse *et al.* [10] and assigned spins and parities of $7/2^+$, $9/2^+$, and $9/2^+$, respectively. The $9/2^+$ level at 1398 keV was interpreted as a 1-proton-hole-2-proton particle prolate intruder state. No coincidence relationships were observed in the gates on the 1147- and 1398-keV γ rays reported in this previous high-spin study.

The ground-state spin and parity for ^{111}Te have been tentatively assigned as $5/2^+$ by Boston *et al.* [11] from heavy-ion reaction studies. This assignment is consistent with similar spin and parity assignments for ^{107,109}Te as well as ^{113}Te. Excited levels in ^{111}Sb are populated as a result of a β-decay phenomenon described by Kisslinger and Sorenson as "even jumping" [12]. This occurs when the ground state of a β^+/EC-decaying proton-rich parent has one or more pairs of valence protons [$(d_{5/2})^2$ or $(g_{7/2})^2$ for ^{111}Te] and an unpaired neutron (in this case, $d_{5/2}$ for ^{111}Te).

When EC/β^+ decay occurs from ^{111}Te to the ground state of ^{111}Sb, the valence pair of $d_{5/2}$ protons must be broken as one of the $d_{5/2}$ protons decays to form a $d_{5/2}$ neutron to pair with the existing $d_{5/2}$ neutron, leaving behind the ^{111}Sb nucleus with the single $d_{5/2}$ proton ground state. The even jumping in the case of ^{111}Te decay occurs when a member of either a $d_{5/2}$ or $g_{7/2}$ proton pair undergoes a Gamow-Teller transition to form a $d_{3/2}$ or $d_{5/2}$ neutron or a $g_{7/2}$ neutron, respectively, producing a three-quasiparticle state with one of the following configurations: $(\pi d_{5/2}\nu d_{5/2}\nu d_{5/2})_{3/2^+,5/2^+,7/2^+}$, $(\pi d_{5/2}\nu d_{5/2}\nu d_{3/2})_{3/2^+,5/2^+,7/2^+}$, or $(\pi g_{7/2}\nu d_{5/2}\nu g_{7/2})_{3/2^+,5/2^+,7/2^+}$. As these final states populated in β decay have configurations that involve the single remaining proton coupled to a broken neutron pair, these levels will lie above the neutron pairing energy in regions of rather high level density [12]. Consequently, these states will mix with adjacent levels and give rise to the population of a large number of levels, each fed rather weakly in direct β decay that will, in turn, cascade to the ground state through the levels below 2 MeV. For this reason, it is not surprising that it is possible to observe significant population of the two well-established $9/2^+$ levels at 1147 and 1398 keV in ^{111}Sb, even though direct 2nd forbidden β decay from a $5/2^+$ ^{111}Te parent should be negligible. A measure of the many weak levels whose depopulation must contribute to the population of these $9/2^+$ levels is the absence of any identifiable peaks in the coincidence gates on the 1147- and 1398-keV γ rays.

Hence, spin and parity assignments for low-energy levels, including the two new levels identified at 487 and 881 keV in ^{111}Sb, cannot be based on implied direct β feeding by comparing the difference between the intensity of the γ rays that depopulate the level and the observed γ rays that populate the level. We start by noting that these levels are not populated in heavy-ion-induced reactions; hence, their spins and parities are likely to be less than $7/2^+$, i.e., $1/2^+$, $3/2^+$, or $5/2^+$. For the lowest excited level at 487 keV, we note that the lowest excited state in the adjacent ^{113}Sb nuclide at 645 keV is assigned as $1/2^+$ on the basis of an $\ell = 0$ angular distribution in the (^{3}He, d) reaction [13], and is also populated indirectly in the decay of $5/2^+$ ^{113}Te [14]. About half of the observed intensity of the 487-keV line can be accounted for by the feeding of the 1392-keV γ ray. Hence, we have tentatively assigned this state as the low-energy $1/2^+$ level. On a strictly experimental basis, neither $3/2^+$ nor $5/2^+$ can be completely ruled out. Similarly, the level at 881 keV can be considered comparable to the $3/2^+$ level at 1018 keV in ^{113}Sb that is populated in an $\ell = 2$ transition in the (^{3}He, d) reaction. We have provisionally assigned the 881-keV level as $3/2^+$, but cannot entirely rule out either $1/2^+$ or $5/2^+$.

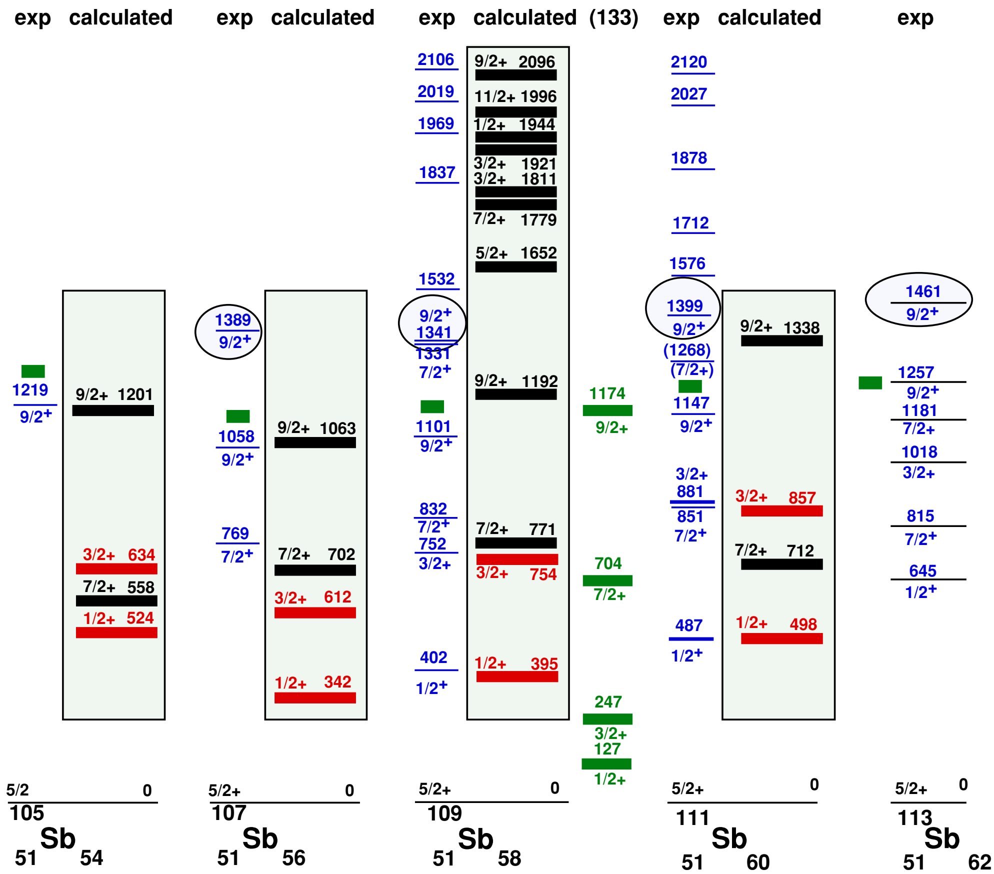

FIG. 6. (Color online) Comparison of shell-model calculations with experimental levels of ^{105,107,109,111}Sb. Values are in units of keV. The 2^+ energies in the even-even Sn core nuclides at 1259, 1205, 1206, 1212, and 1257 keV for ^{104,106,108,110,112}Sn, respectively, are marked with a small rectangle in the column with the experimental data. The $9/2^+$ levels enclosed in an oval have been identified as particle-hole intruder levels and are not in the model space used for these calculations. Also shown are the experimental levels for ^{113}Sb. The calculated levels for ^{109}Sb shown in the column labeled (133) were obtained using basis single-proton $d_{3/2}$ and $s_{1/2}$ energies of 1.48 and 1.7 MeV, respectively.

Ressler *et al.* [5] noted ambiguities in the literature for the spin and parity assignments for the levels in ^{113}Sb that lie at 1018 and 1181 keV. These ambiguities have been resolved on the basis of new (α, t) transfer data upon which a recent Letter by Schiffer *et al.* [15] was based and by new studies of the decay of ^{113}Te [16]. One result of interest is the observation that the level at 1181 keV shown in Fig. 6 is populated by an $\ell = 4$ transition and is likely to be the second $7/2^+$ level [15,17]. Also, a level at 1331 keV in ^{109}Sb shown in Fig. 6 appears to be the second $7/2^+$ level. Both levels are populated in the decay of their respective Te parents ~30% of the most intense γ ray. Hence, if the positions of the levels in the odd-A Sb nuclides vary smoothly, expectations of a level in ^{111}Sb between 1200 and 1300 keV would not be unfounded.

In the difference spectrum shown in Fig. 2, no peak of that magnitude stands out. A small peak decays at 1244 keV, but it is in the correct ratio to be from the decay of ^{110}Sb to levels of ^{110}Sn. However, in the gate on the 851-keV γ ray shown in Fig. 3, the intensity of the peak at 1269 keV is present at only about half the expected intensity, based on the intensities of the 1176- and 1506-keV peaks. Hence, we included a possible level at 1268 keV in the level scheme shown in Fig. 5, in which the level is dashed and parentheses are used to enclose both the energy and the spin and parity.

V. DISCUSSION AND INTERPRETATION

In the paper by Ressler *et al.* [5], which identified new low-spin levels for ^{109}Sb in the β decay of ^{109}Te, comparisons were made with shell-model calculations that used literature values [18] for the single-proton and single-neutron energies that are tabulated in Table II. Schiffer *et al.* [15] recently reported the evolution of the positions of the higher-spin $h_{11/2}$ and $g_{7/2}$ levels in odd-mass Sb nuclides and postulated that the remarkable monopole shift observed for the $g_{7/2}$ and $d_{5/2}$ levels in these nuclides, which can be clearly seen in Fig. 1, arises as a consequence of a spin-orbit interaction that diminishes as N/Z increases [15]. Although the focus of that paper was the splitting of the proton $g_{9/2}$ and $g_{7/2}$ orbitals, consideration of the splitting of the $d_{5/2}$ and $d_{3/2}$ proton orbitals is also possible.

The monopole shift of the $g_{7/2}$ neutron orbital by ~3 MeV as N and Z changed from $^{91}Zr_{50}$ to $^{131}Sn_{81}$ was pointed out by Heyde [19] and attributed to the interaction of the $g_{7/2}$ neutron

TABLE II. Proton and neutron single-particle energies for these calculations and ^{133}Sb in MeV.

Orbital	Neutron s.p	Proton s.p.	Reduced proton s.p	^{133}Sb
$0h_{11/2}$	3.0	3.0	3.0	1.82
$0g_{7/2}$	0.2	0.2	0.2	−0.963
$1d_{5/2}$	0.0	0.0	0.0	0.0
$1d_{3/2}$	2.55	3.55	2.9	1.48
$2s_{1/2}$	2.45	3.45	2.6	∼1.7

orbital with the filling of the spin-orbit partner $g_{9/2}$ proton orbital as suggested by Federman and Pittel [20]. Similar effects were pointed out by Walters in other mass regions [21]. A shift in position as large as can be partially seen in Fig. 1, however, means either that the spin-orbit splitting is narrowing and drawing the $g_{7/2}$ orbital deeper into the nucleus, or that the $g_{7/2}$, and $g_{9/2}$ orbitals are both being more tightly bound with respect to the $d_{5/2}$, $d_{3/2}$, and $h_{11/2}$ orbitals. As these changes surround shell gaps, direct measurement is often difficult. On the other hand, study of spin-orbit splitting for lower-ℓ orbitals such as the $d_{5/2}$ and $d_{3/2}$ orbitals within a major shell can be more quantitative.

The results are mixed as noted by Walters [21]. In his Fig. 2, the $f_{7/2}$ to $f_{5/2}$ and $p_{3/2}$ to $p_{1/2}$ splittings change only slightly (2004 to 1570 keV and 854 to 898 keV, respectively) in going from ^{133}Sn$_{83}$ to ^{207}Pb$_{125}$, in a region where N/Z also changes little. In contrast, in his Fig. 5, the $p_{3/2}$ to $p_{1/2}$ split changes from 1112 keV in ^{57}Ni$_{29}$ to 2023 keV in ^{49}Ca$_{29}$ to, as N/Z evolves from ∼1 to 1.45, an evolution opposite to that suggested by Schiffer *et al.* [15].

Although the parameters of the calculations which reproduce the experimentally observed levels in ^{111}Sb do not provide a direct measurement of this splitting, they do at least reveal values that are consistent with available experimental data. To test this idea, we varied the positions of the single-proton basis $d_{3/2}$ and $s_{1/2}$ levels in the shell-model calculation to provide as good a fit as possible for the low-energy $1/2^+$ and $3/2^+$ levels in ^{109}Sb and then tested the usefulness of these new energies against the new $1/2^+$ and $3/2^+$ levels in ^{111}Sb.

Calculations were also performed for the lowest five levels of ^{109}Sb using the single-proton energies for the $d_{3/2}$ and $s_{1/2}$ levels shown in Table II for ^{133}Sb, namely, 1.48 and 1.7 MeV, respectively. These results are shown in Fig. 6 under the column marked (133). As can be seen, the calculated positions of the yrast $1/2^+$ and $3/2^+$ levels are far below the positions of the observed levels, with some lowering for the yrast $7/2^+$ level. Hence, at least for this interaction, reproduction of the positions of the yrast $1/2^+$ and $3/2^+$ levels requires a much larger spin-orbit splitting than is found for ^{133}Sb.

The levels for the odd-A Sb isotopes with $A = 101$ to $A = 111$ calculated with both the old and new single-proton energies are shown in Fig. 7. The new single-proton energies required to fit the positions of the lowest $1/2^+$ and $3/2^+$ levels in ^{109}Sb are tabulated in Table II. Currently, one proton and ten neutrons is as far from the ^{100}Sn core as such calculations are practical. Detailed comparisons of the level structure for ^{105,107,109,111}Sb are shown in Fig. 6, along with the levels of ^{113}Sb that were referred to earlier. The calculated levels are shown in shaded rectangles, and the $9/2^+$ levels that have been identified in heavy-ion reactions as $g_{9/2}$ proton-hole intruder states are identified with a shaded oval. These states are not in the calculation. In Table II, we normalized the single-proton basis levels for ^{133}Sb to the $d_{5/2}$ state for easy comparison with the ^{101}Sb energies. If the calculated values for the single-particle energies in ^{101}Sb are close to the actual values, then the spin-orbit splitting for the $d_{5/2}$ and $d_{3/2}$ orbitals would have narrowed from 2.9 MeV in ^{101}Sb to 1.48 MeV in ^{133}Sb [22],

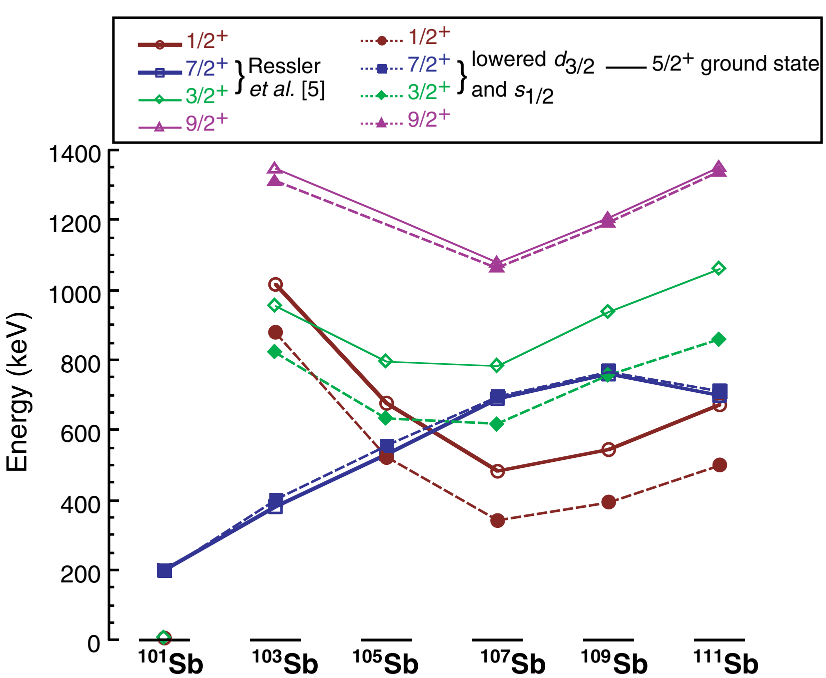

FIG. 7. (Color online) Comparisons of the calculated positions of the lowest $1/2^+$, $3/2^+$, $7/2^+$, and $9/2^+$ levels in ^{101,103,105,107,109,111}Sb using the unshifted [5] (solid lines) and lowered (dashed lines) $d_{3/2}$ and $s_{1/2}$ single-proton energies.

a reduction of almost a factor of 2, which is similar to the postulate set forth by Schiffer *et al.* [15]. However, such a conclusion implies that the $3/2^+$ level at 2440 keV in ^{133}Sb carries the full spectroscopic strength for the $d_{3/2}$ orbital. If, for example, the rueposition of the $d_{3/2}$ orbital lies much nearer to the 4-MeV core in ^{132}Sn, then the narrowing implied by the energies in Table II may well be too large.

Other approaches to these monopole shifts have been stimulated by the evolution of the $N = 16$ and $N = 20$ shell closures and noted by Otsuka *et al.* [23] and Hamamoto [24]. The narrowing that we have deduced for the $d_{5/2}$ and $d_{3/2}$ orbitals as N/Z increases in this work (even if is it not a full factor of 2 as implied by the energies in Table II) is almost exactly opposite to the widening of the $p_{3/2}$ to $p_{1/2}$ gap in the $N = 29$ isotones. Hence, it may be that nuclear size, the N/Z ratio, and the underlying microscopic structure of the respective neutrons or proton all play a role in the evolution of the positions of nuclear energy levels and that no single feature provides a simple description for the observed structure changes.

Several features do stand out in Figs. 6 and 7. First, the lowered single-particle $d_{3/2}$ and $s_{1/2}$ basis states for ^{101}Sb give rise to an excellent fit for the lowest observed $1/2^+$ and $3/2^+$ levels in both ^{109}Sb and ^{111}Sb. At the same time, the energies for the higher-spin $7/2^+$ and $9/2^+$ levels are almost unchanged. Second, the fits for the $9/2^+$ level in ^{105}Sb and the $7/2^+$ and $9/2^+$ levels in ^{107}Sb are also quite good. The prolate $g_{9/2}$ intruder appears to have no effect on the position of the particle-core $9/2^+$ levels in ^{105,107}Sb; but as N increases, some mixing appears to keep the lowest $9/2^+$ level below the calculated position.

We have performed more extensive calculations for ^{109}Sb and show the calculated levels ^{109}Sb in Fig. 6 up to ∼2.1 MeV as well as the levels observed in β decay for both ^{109}Sb and ^{111}Sb. ^{109}Sb was chosen for the additional calculations as it is the heaviest for which the time involved in the calculations is reasonable. Furthermore, it is also the lightest odd-mass Sb nuclide for which some low-spin structure is known up to that energy. It can be seen that below the ∼2-MeV pairing energy, few levels are expected from this model, and the level density in both nuclides is reasonably consistent with the number of observed low-spin levels, inasmuch as the even-jumping β-decay process limits the ability to determine spins and parities. As the level structures are not expected to undergo large changes with variations in neutron number, these calculated levels for ^{109}Sb should give some indication of the positions of similar levels in ^{111}Sb and ^{113}Sb.

VI. SUMMARY AND OUTLOOK

The β^+/EC and γ decay of ^{111}Te to low-spin levels of ^{111}Sb has been studied for the first time using sources produced via recoil separation of the products of a heavy-ion reaction. Eleven new levels have been identified, including proposed levels at 487 and 881 keV that are tentatively assigned spins and parities of $1/2^+$ and $3/2^+$, respectively. In addition, a more precise half-life value of 26.2(6) s for ^{111}Te has been determined by following the decay of the strongest γ rays as a function of time. New shell-model calculations have been performed in which the positions of the single-proton basis states were adjusted to fit the observed energies for the lowest $1/2^+$ and $3/2^+$ levels of ^{109}Sb. With this adjustment, the fits for the six lowest excited states in ^{111}Sb and, where known, for the lighter odd-mass Sb nuclides proved to be excellent. Comparison of the relative energies of the $d_{5/2}$-$d_{3/2}$ orbitals in ^{101}Sb used for these calculations with the known single-proton energies in ^{133}Sb could be evidence for a reduction in the spin-orbit splitting of as much as ∼50%, which is consistent with recent postulations by Schiffer *et al.* [15] for the $g_{9/2}$ and $g_{7/2}$ orbitals.

In Figs. 6 and 7, these calculations show a minimum in the energies for the lowest $1/2^+$ and $3/2^+$ levels in ^{107}Sb and then a rapid rise in energy as N approaches the closed neutron shell at 50. As ^{107}Te is known to undergo α decay with a 3-ms half-life, the low-spin levels of ^{107}Sb cannot be readily studied by a β-decay experiment. However, the low-spin structure of ^{107}Sb (and ^{105}Sb) could be studied via the use of radioactive ^{104,106}Sn beams with a ^{3}He target in inverse kinematics, where the strongest population should be to the low-ℓ $1/2^+$ and $3/2^+$ levels.

ACKNOWLEDGMENTS

This work was supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract Nos. W-31-109-ENG-38, DE-FG02-94-ER40834, DE-FG02-96ER40963, and DE-AC05-00OR22725.

[1] R. E. Shroy *et al.*, Phys. Rev. C **19**, 1324 (1979).
[2] D. Bucurescu *et al.*, Phys. Rev. C **52**, 616 (1995).
[3] Yu N. Lobach and D. Bucurescu, Phys. Rev. C **57**, 2880 (1998).
[4] Yu N. Lobach *et al.*, Phys. Rev. C **58**, 1515 (1998).
[5] J. J. Ressler *et al.*, Phys. Rev. C **66**, 024308 (2002).
[6] E. Dikmen *et al.*, Phys. Rev. C **64**, 067305 (2001).
[7] J. C. Hardy *et al.*, Nucl. Data Tables A **11**, 327 (1972).
[8] J. Blachot, Nucl. Data Sheets **100**, 182 (2003).
[9] D. DeFrenne and E. Jacobs, Nucl. Data Sheets **89**, 481 (2000).
[10] D. R. LaFosse *et al.*, Phys. Rev. C **50**, 1819 (1994).
[11] A. J. Boston *et al.*, Phys. Rev. C **61**, 064305 (2000).
[12] L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. **35**, 853 (1963).
[13] M. Conjeaud *et al.*, Nucl. Phys. **A117**, 449 (1968).
[14] M. E. J. Wigmans *et al.*, Phys. Rev. C **14**, 243 (1976).
[15] J. P. Schiffer *et al.*, Phys. Rev. Lett. **92**, 162501 (2004).
[16] J. Shergur *et al.*, work in progress.
[17] J. Shergur *et al.*, Ph.D. thesis, University of Maryland, in press (2005).
[18] M. Hjorth-Jensen, T. T. S. Kuo, and E. Osnes, Phys. Rep. **261**, 125 (1995).

[19] K. Heyde, in *Research Reports in Physics: Nuclear Structure of the Zirconium Region*, edited by J. Eberth, R. A. Meyer, and K. Sistemich (Springer-Verlag, Berlin, 1988), p. 3.
[20] P. Federman and S. Pittel, Phys. Rev. C **20**, 820 (1979).
[21] W. B. Walters, AIP Conf. Series **447**, 196 (1998).
[22] M. Sanchez-Vega *et. al.*, Phys. Rev. C **60**, 024303 (1999).
[23] T. Otsuka *et al.*, Phys. Rev. Lett. **87**, 082502 (2001).
[24] I. Hamamoto, Nucl. Phys. **A731**, 211 (2004).