Level structure of odd-odd ^{134}Sb populated in the β^- decays of ^{134,135}Sn

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The level structure of odd-odd ^{134}Sb has been studied at CERN/ISOLDE following the β^- decay of ^{134}Sn and the β-delayed neutron decay of ^{135}Sn. Elemental and isobaric separation were accomplished by use of a resonance ionization laser ion source and an on-line mass separator, respectively. Both γ-ray singles and γ-γ coincidence data were taken as a function of time. New levels at 279, 441, 555, 617, and 1385 keV have been identified and given proposed spin and parity assignments of 7^-, 5^-, 6^-, 4^-, and 5^-, respectively, following β-delayed neutron decay of $7/2^-$ ^{135}Sn. New 1^- levels have been identified at 1900, 2170, and 2430 keV following the β^- decay of 0^+ ^{134}Sn. The resulting level structures are compared to shell-model calculations using the CD Bonn interaction and scaled and unscaled Kuo-Herling interactions developed for the ^{208}Pb region. Remarkably enough, the unscaled Kuo-Herling interaction provides the best fit for the levels below 1 MeV.

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I. INTRODUCTION

The structures of the odd-odd nuclides that are adjacent to double-magic nuclides provide the best opportunities to develop and test two-body matrix elements (TBME) for the proton-neutron ($\pi\nu$) interaction. In particular, a set of TBME for the interaction of the single proton and the single neutron in ^{210}Bi$_{127}$ has been developed by Warburton and Brown that provides reasonable agreement with the positions of most of the energy levels below 2 MeV [1]. Chou and Warburton mass-scaled the same Kuo-Herling interactions from the ^{208}Pb region by a factor of $(132/208)^{-1/3}$ and denoted these interactions as KH5082 [2]. These mass-scaled interactions were used to calculate the positions of the low-energy levels in ^{134}Sb, which has a single proton and a single neutron beyond double-magic ^{132}Sn. At the time of the development of the KH5082 TBME, a new study had been published by Fogelberg *et al.* that suggested that the lowest 1^- level was at 318 keV [3]. As the initial calculations indicated that the 0^- and 1^- levels were nearly degenerate, as is known for ^{210}Bi, a second set of modified TBME, designated as CW5082 interactions, were developed. The revised interactions provided ~300-keV of separation between the 0^- ground state and 1^- first excited state, which was in agreement with the level scheme proposed by Fogelberg *et al.* [3].

Recently, Korgul *et al.* reported a study of the low-spin level structure of ^{134}Sb populated in the β^- decay of ^{134}Sn below 1.0 MeV, including a new level at 13 keV that has been assigned as the lowest 1^- level [4]. They were also able to identify additional levels at 330 (2^-), 383 (3^-), 885 (1^-), and 935 (2^-) keV and inferred a possible level at 555 (4^-) keV based on data from fission-γ studies. Use of the mass-scaled KH5082 TBME and the single-particle energies identified in ^{133}Sn and ^{133}Sb provided a reasonably good fit for the newly identified levels in ^{134}Sb [4].

In this article, we report the results of a new study of the levels of ^{134}Sb populated in both the direct β^- decay of ^{134}Sn and also in the β-delayed neutron (β^-n) decay of ^{135}Sn. The spins, parities, and relative energies of the parent and daughter nuclides are illustrated in Fig. 1. The β^- decay of 0^+ ^{134}Sn will populate the negative-parity 0^- and 1^- levels in ^{134}Sb via first-forbidden decay, with the possibility of first-forbidden unique decay branching to 2^- levels. Whereas, the β^- decay of the $7/2^-$ ^{135}Sn will decay via Gamow-Teller allowed transitions to $5/2^-$, $7/2^-$, and $9/2^-$ levels in ^{135}Sb that lie well above the neutron separation energy. From previous measurements, the P_n value for these branches is known to be 21(3)% [5]. These levels will, in turn, decay largely by the emission of $\ell = 0$ neutrons to 2^-, 3^-, 4^-, and 5^- levels in ^{134}Sb, with reduced population of 0^-, 1^-, 6^-, and 7^- levels by emission of $\ell = 2$ neutrons. The E^5 dependence of β^- decay will strongly favor population of ^{135}Sb levels in the 1.0 MeV energy range just above the neutron separation energy that will, in turn, favor population of levels in the 1.0 MeV range above the 0^- ground state of ^{134}Sb.

II. EXPERIMENTAL PROCEDURES

The ^{134,135} Sn nuclei studied in this experiment were produced at CERN/ISOLDE via fast-neutron-induced fission of a UC_2 target (20 cm long, thickness 52 g/cm^2, and ~10 g/cm^2 of graphite) following bombardment of a tungsten

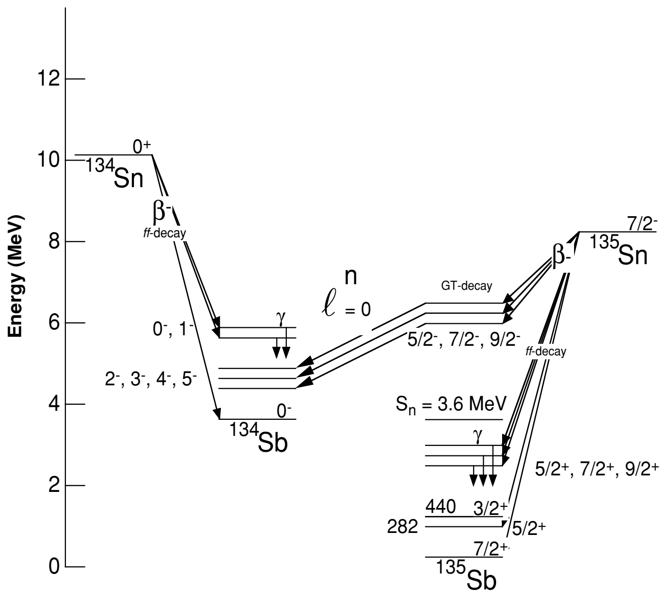

FIG. 1. Possible states in ^{134}Sb that can be populated by the β decay of ^{134}Sn and the β^-n decay of ^{135}Sn.

rod with 1.4-GeV proton pulses. These proton pulses (3.0×10^{13} protons/pulse) were accelerated in the CERN Proton Synchrotron Booster (PSB) and could be extracted as often as every 1.2 s. Following diffusion of the fission products from the UC_2 target, Sn isotopes were ionized by the use of a resonance ionization laser ion source (RILIS). Lasers in the RILIS were tuned to two sequential resonant atomic excitations in Sn, and a third laser was tuned to an energy that could then ionize the Sn atoms. Beams of $A = 134$ or 135 isobars were separated using the ISOLDE general purpose mass separator (GPS) and implanted onto a spot on a movable Al tape that is surrounded by five large Ge detectors. Following implantation of the radioactivity on the tape, γ singles and γ-γ coincidence data were collected as a function of time for 1 s, after which the tape was moved to reduce the amount of long-lived activity from the decay of the daughters and spallation produced ^{134,135}Cs isotopes.

In an earlier study of the decay of ^{135}Sn decay reported by Sherger *et al.* [5], only a single γ ray at 318 keV could be attributed to the β^-n decay to levels of ^{134}Sb owing to the intense γ rays at 746 and 825 keV in the spectrum arising from the decay of spallation-produced isobaric 53-min ^{135}Cs^m. In this experiment, yields of spallation-produced nuclei have been significantly lowered through the use of a neutron converter, which consists of a tungsten rod mounted below the normal CERN/ISOLDE target. In this arrangement, the 1.4-GeV proton beam from the CERN Proton Synchrotron Booster is focused on the tungsten rod to produce secondary neutrons that subsequently induce fission in the UC_2 target. Although the

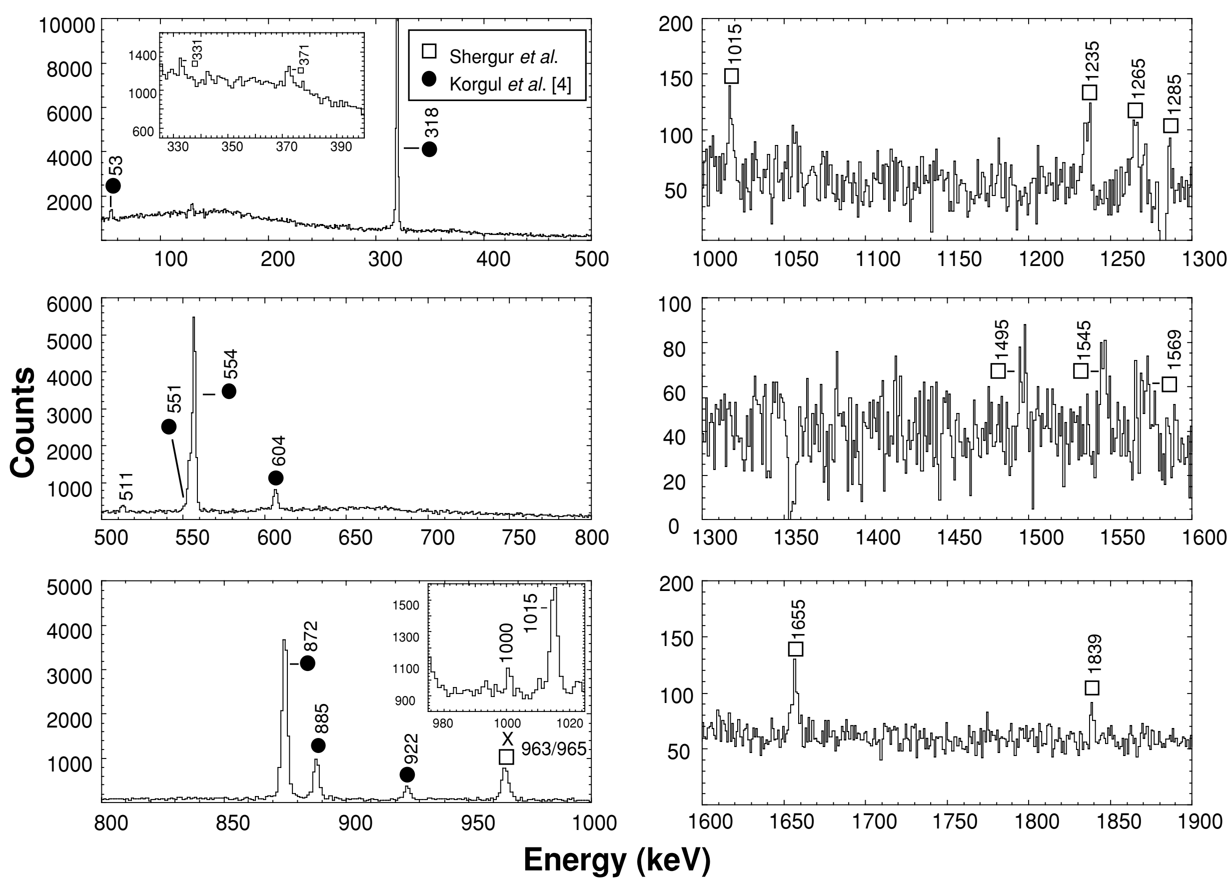

FIG. 2. β-gated γ-difference spectrum obtained by subtracting datataken from 600 ms to 1 s after following the proton pulse from that taken from the first 300 ms after the pulse. An x is used to label the 965-keV peak because most of the counts in this peak arise from the β^-n decay of ^{134}Sn to the 963-keV first excited state in ^{133}Sb.

TABLE I. Data for γ rays and levels in ^{134}Sb observed in the β decay of ^{134}Sn

Level (keV)	J^π	E_γ^a (keV)	I_γ^b	Reported in Ref. [3] or Ref. [4]	Final level (keV)	Final J^π
331	2^-	331	1.6(2)		0	0^-
		318	62(2)	X	13	1^-
384	3^-	53	0.9(3)	X	331	2^-
		371	0.6(1)		13	1^-
885	1^-	885	24.1(2)	X	0	0^-
		872	100(1)	X	13	1^-
		554	38(1)	X	331	2^-
935	2^-	935	0.31(9)		0	0^-
		922	8.0(1)	X	13	1^-
		604	3.8(3)	X	331	2^-
		551	9(1)	X	384	3^-
1331	(2^-)	1000	0.2(2)		331	2^-
		947	0.4(3)		384	3^-
1900	1^-	1569	0.59(9)		331	2^-
		1015	1.1(1)		885	1^-
		965	0.5(3)		935	2^-
2170	1^-	1839	0.5(2)		331	2^-
		1285	0.9(2)		885	1^-
		1235	0.81(8)		935	2^-
2430	1^-	2417	0.55(5)		13	1^-
		2098	0.30(6)		331	2^-
		1545	0.45(4)		885	1^-
		1495	0.92(4)		935	2^-

[a]Uncertainty in γ-ray energies is ± 0.5 keV.
[b]Relative to the 872-keV transition in ^{134}Sb.

TABLE II. Data for γ rays and levels in ^{134}Sb observed in the $\beta^- n$ decay of ^{135}Sn

Level (keV)	J^π	E_γ^a (keV)	I_γ^b	Observed in ^{134}Sn β^- decay	Final level (keV)	Final J^π
331	2^-	331	0.23(7)	X	0	0^-
		318	18.7(2)	X	13	1^-
384	3^-	53	1.3(5)	X	331	2^-
		371	0.83(7)	X	13	1^-
441	5^-	162	6.3(1)		279	7^-
555	4^-	171	3.5(4)		384	3^-
		114	0.6(2)		441	5^-
617	6^-	338	3.7(1)		279	7^-
		176	1.0(2)		441	5^-
885	1^-	554	0.4(2)	X	331	2^-
935	2^-	604	0.5(2)	X	331	2^-
		551	0.8(1)	X	384	3^-
1385	(5^-)	830	0.2(1)		555	4^-
		768	0.48(8)		617	6^-
		800[c]	0.8(4)			

[a]Uncertainty in γ-ray energies is ± 0.5 keV.
[b]Relative to the 282-keV transition in ^{135}Sb.
[c]Unplaced γ ray in coincidence with the 318-keV transition.

fission-produced yields of Sn nuclei are slightly lowered, the isobaric spallation-produced Cs nuclei are lowered by several orders of magnitude. Consequently, dramatically improved γ ray and γ-γ coincidence spectra could be obtained.

III. RESULTS

A. β^- decay of ^{134}Sn

Low-spin levels of ^{134}Sb were identified following β^- decay of 0^+ ^{134}Sn ($T_{1/2} = 1.04$ s). A spectrum that shows the γ rays that follow the decay of ^{134}Sn is shown in Fig. 2. To eliminate the γ rays that arise from the decay of the 1.7-s ^{134}Sb daughter, this spectrum was obtained by subtracting data taken during the period between 600 and 1000 ms from data taken during the first 300 ms. The peaks previously reported by Korgul *et al.* [4], are marked with filled circles. The energies, intensities, and placements for the γ rays assigned to ^{134}Sn decay are listed in Table I. The level scheme for ^{134}Sb constructed from the singles and coincidence data is shown in Fig. 3. These levels are in complete agreement with the levels under 1.0 MeV reported by Korgul *et al.*, although we have been able to observe three new weak E2 transitions.

Coincidence spectra resulting from gates on the 922- and 872-keV γ rays are shown in Fig. 4(a) and Fig. 4(b), respectively. Transitions in coincidence with the 872-keV γ ray that depopulate the 885-keV level in ^{134}Sb are at 1015, 1285, and 1545 keV. Peaks at 965, 1235, and 1495 keV in coincidence with the 922-keV γ ray that depopulates the 935-keV level support the placement of new levels in ^{134}Sb at 1900, 2170, and 2430 keV, respectively. Gates on the two most intense new γ rays, the 965- and 1015-keV lines, are also shown in Fig. 4(c) and Fig. 4(d), respectively. The 965-keV gated spectrum shows coincidences at 318, 551, 604, and 922 keV; which are the three most intense γ rays that depopulate the 935-keV level. Similarly, the gate on the 1015-keV γ ray shows coincidences at 318, 554, 872, and 885 keV that would be expected if this transition populated the 885-keV level. As all the newly identified transitions populate the 331-keV level either directly or indirectly through the 935- and 885-keV levels, their presence in the 318-keV gated coincidence spectrum in Fig. 5(a) further support their placement in the ^{134}Sn β^- decay scheme shown in Fig. 3.

Also of note in the coincidence spectrum shown in Fig. 5(a) is a peak at 947 keV. This γ ray could populate the level at either 331 or 384 keV. The presence of a weak peak at 1000 keV in the laser-on singles spectrum that is 53-keV higher than the 947-keV peak suggests that there could be two transitions that depopulate a new level at 1331 keV to the 1^- and 2^- levels at 330 and 383 keV, respectively. The inset in Fig. 2 shows peaks at 1000 and 1015 keV, but, unlike the difference spectrum, was taken from a spectrum covering the full 1-s data collection time, hence the peaks are much larger. The relative intensity values listed in Table I are taken from analysis of this spectrum. The placement of the 1331-keV level is tentative in the ^{134}Sn decay scheme, as indicated by the dashed line in Fig. 3.

B. $\beta^- n$-decay of ^{135}Sn

In the previous study by Shergur *et al.* [5], the only γ ray observed from the $\beta^- n$ decay of ^{135}Sn was the strong line at

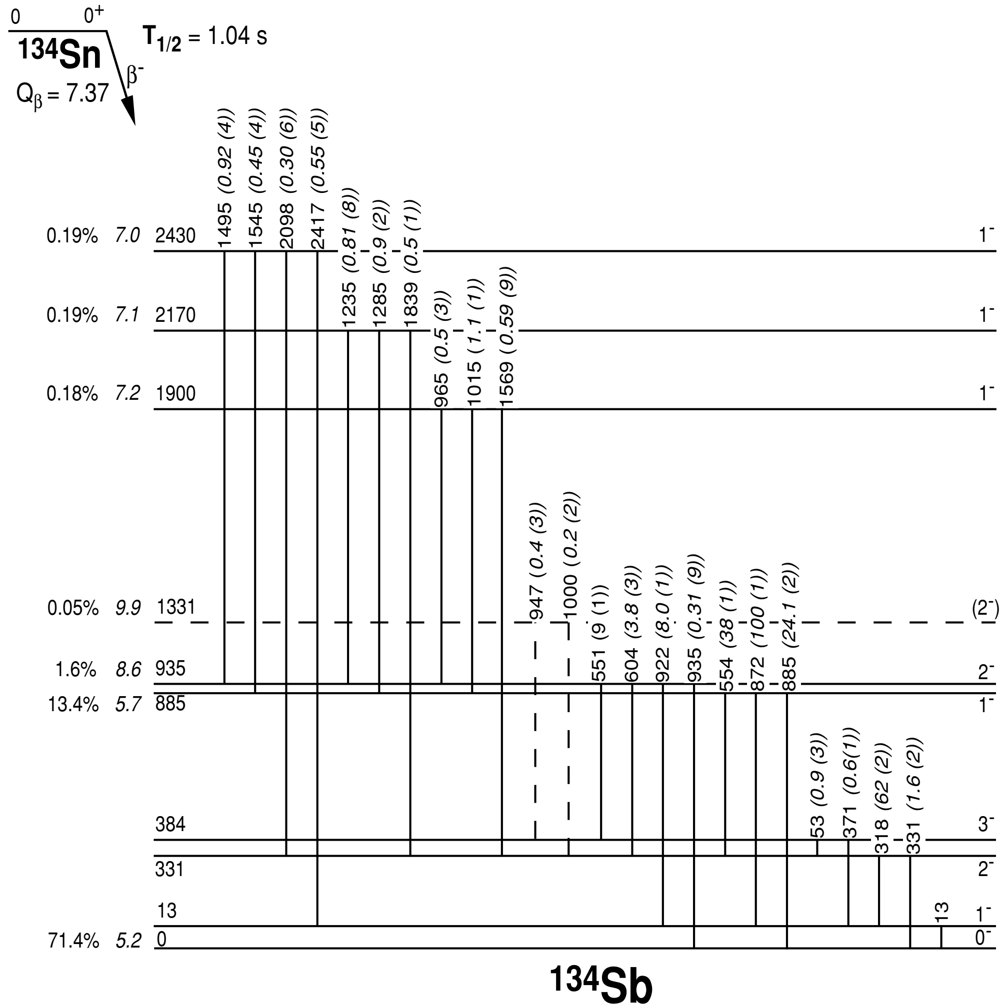

FIG. 3. Levels in ^{134}Sb populated in the β^- decay of 1.0-s ^{134}Sn. Log *ft* values were calculated using the Q_β and ground state β feeding reported in Ref. [3].

318 keV. However, the intensity of the 318-keV γ ray that is shown in Table II is 18.7% of the intensity of the 282-keV γ ray but carries only $\sim$10% of the total β decay strength of ^{135}Sn. Moreover, the presence of the 115-, 297-, and 1297-keV γ rays from the decay of high-spin 10-s ^{134}Sb^m in the $A = 135$ γ spectrum indicates that there must be significant population of the 7^- isomer in the $\beta^- n$ decay of ^{135}Sn. Thus, as the P_n is 21%, observation of γ rays arising from population of other levels in ^{134}Sb would be expected. These γ rays would most likely be low in energy, as a consequence of the tendency in delayed neutron decay to populate levels near the ground state in the daughter nuclide.

Direct evidence for the population of the 7^- isomer is shown in Fig. 6. The plot in Fig. 6 shows two γ spectra: in Fig. 6(a), the data was acquired during the first 100 ms of a 1.0-s acquisition, and the spectrum in Fig. 6(b) was obtained from 600 ms to 1000 ms in the counting period. As shown, the intensity of the 114-keV peak decreases in intensity by a factor of $\sim$1/2, which would be consistent with the 530(25) ms half-life of ^{135}Sn. The peak at $\sim$115 keV is shown to grow in as a function of time and is likely the well-established 115-keV transition following β^- decay of the 7^- isomer.

A comparison of the data taken with the laser on and off is shown in Fig. 7. Peaks associated with the decay of ^{135}Sn are present only in the spectrum obtained with the laser on [Fig. 7(a)]. Peaks marked with open squares correspond to γ rays that correspond to transitions in ^{135}Sb that have been established by coincidence relationships by Shergur *et al.* [6,7]. The transitions that show no coincidence relationships to any of the 52 γ rays identified in ^{135}Sb [6,7] are labeled with filled circles and are assigned to ^{134}Sb. Two known transitions that can be attributed to the decay of the 7^- isomer of ^{134}Sb are both labeled with an x. The peak at 115 keV seen to grow in with time as would be expected from decay of the 7^- daughter. In Fig. 7, it can be seen that the peaks at 114 and 115 keV disappear when the laser is off.

Of the peaks in Fig. 7 labeled with filled circles, the 53- and 171-keV transitions were assigned to ^{134}Sb by Korgul *et al.* [4]. In their article, Korgul showed a γ ray at 171 keV that had been observed in fission-γ studies as a transition from

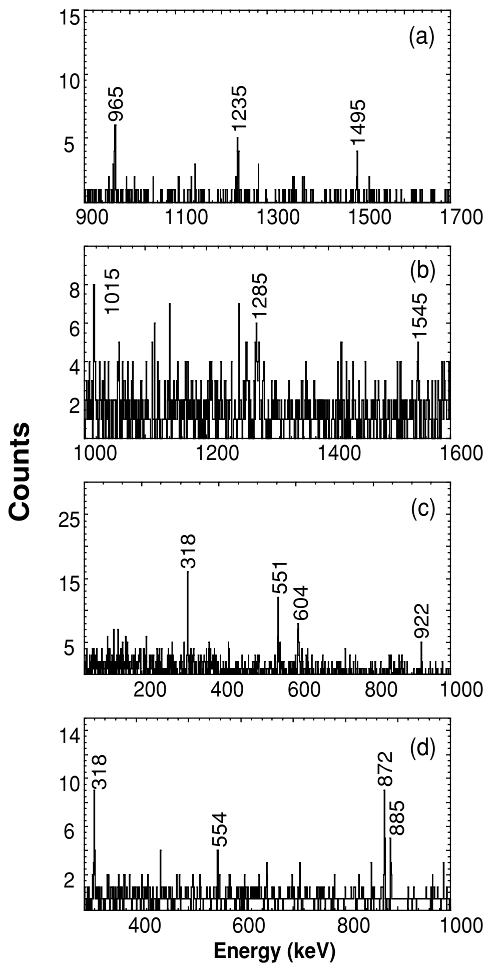

FIG. 4. Coincidence spectra for gates on the (a) 922-, (b) 872-, (c) 965-, and (d) 1015-keV γ rays that depopulate levels in ^{134}Sb following β^--decay of ^{134}Sn.

a new level at 555 keV to the 3^- level at 384 keV. As is seen in Fig. 2 and Table I, this line was not observed in our study of the decay of 0^+ ^{134}Sn decay. However, this γ ray is seen to be present in the $\beta^- n$ decay of ^{135}Sn. And, the assignment as populating the 3^- level at 384 keV is confirmed by the gate on the 53-keV γ ray shown in Fig. 8(a) that also shows the 318-keV γ ray. These placements are consistent with the assignments of these three γ rays as a yrast cascade from a 555-keV 4^- level to a 384-keV 3^- level to a 331-keV 2^- level to the 1^- level at 13 keV. The coincidence spectrum showing the gate on the 171-keV γ ray in Fig. 8(b) also shows evidence of feeding from a higher energy state. As the 171-keV γ ray depopulates an established state at 555 keV, the 830-keV peak in the coincidence spectrum suggests the placement of a new level at 1385 keV.

Spectra gated on the 162- and 338-keV γ rays are shown in Fig. 8(c) and Fig. 8(d), respectively. As 176- and 162-keV transitions sum to 338 keV, a level sequence is suggested that includes decay of an pperevel via a crossover γ ray of 338 keV, and a 176-keV/162-keV cascade, with the lower intensity 176-keV γ ray depopulating the same level as the 338-keV γ ray. The presence of no other strong lines in the 162-keV gated spectrum in Fig. 8(c) except the peak at 114 keV and the absence of γ rays at 53, 171, and 318 keV support the placement of the the 114-, 162-, 176-, and 338-keV γ rays as populating the 7^- isomer in ^{134}Sb. Moreover, the absence of the 171- and 53-keV lines in Fig. 8(c) suggests that the 114-keV transition depopulates the established 4^- level at 555 keV and provides evidence for the placement of a level at 441 keV. The placement of a new level at 441 keV would then suggest the placement of two levels at 279 and 617 keV, based on the 162–176 keV coincidence relationship, and the presence of the 338-keV γ ray. Further support for the placement of a level at 617 keV is shown in the 338-keV gated spectrum in Fig. 8(d). The peak at 768 keV can be seen as a transition from the established level at 1385 keV to the level at 617 keV.

C. Spin and parity assignments

Experimental data for nuclei with a few valence nucleons outside of ^{132}Sn suggest that this is a region for which little collective enhancement is present for $E2$ transitions. In a Coulomb-excitation study by Radford *et al.*, $B(E2; 0^+ \rightarrow 2^+)$ values were measured to be 0.172, 0.096, and 0.103 e^2b^2 for ^{132,134,136}Te, respectively [8]. In a similar study by Beene *et al.*, a $B(E2; 0^+ \rightarrow 2^+)$ value of 0.029 e^2b^2 was measured for ^{134}Sn [9]. In addition, Mach *et al.* [10], also recently reported a measurement of the lifetime of the 282-keV $5/2^+$ to $7/2^+$ transition in ^{135}Sb that showed little collective enhancement. These data are consistent with the low relative intensities shown in Table I for the 2^- to 0^- $E2$ crossover transitions that depopulate the 331- and 935-keV levels compared to the 2^- to 1^- $M1$ transitions at 318 and 922 keV, respectively. Based on these observations, spin and parity assignments are proposed for the new levels identified in this study that are based on the assumption that $E2$ transitions will be weak or nonexistant.

For example, log *ft* values are deduced for the three new levels at 1900, 2170, and 2430 keV in ^{134}Sb that limit the possible spin and parity values to 0^- or 1^-. All three levels show rather strong population to the 2^- levels at 331 and 935 keV, along with transitions to the 1^- levels at 885 and 13 keV, but no observable transitions to the 3^- level at 384 keV. Hence, all three are assigned a 1^- spin and parity. In contrast, the log *ft* value for population of the possible new level at 1331 keV is large enough to allow for first-forbidden unique decay to a 2^- level. This level decays only to the 2^- and 3^- levels at 331 and 384 keV via transitions that are of about the same intensity. Hence, if the 947- and 1000-keV are both M1 transitions, then only a 2^- assignment is consistent with the weak population in β^- decay and γ decay to the 3^- level at 384 keV (Fig. 9).

The 10.6-s β decaying isomer in ^{134}Sb has long been assigned as a 7^- level owing to the strong forbidden population of the 6^+ level at 1691 keV along with the population of the 8^- level at 4562 keV in ^{134}Te [11]. The level at 441 keV is fed from the 4^- level at 555 keV by a 114-keV transition that must be competitive with the 171-keV 4^- to 3^- transition; hence, it would appear to be limited to spins and parities of 3^-, 4^-, and 5^-. As this level does not decay to the 2^- level at

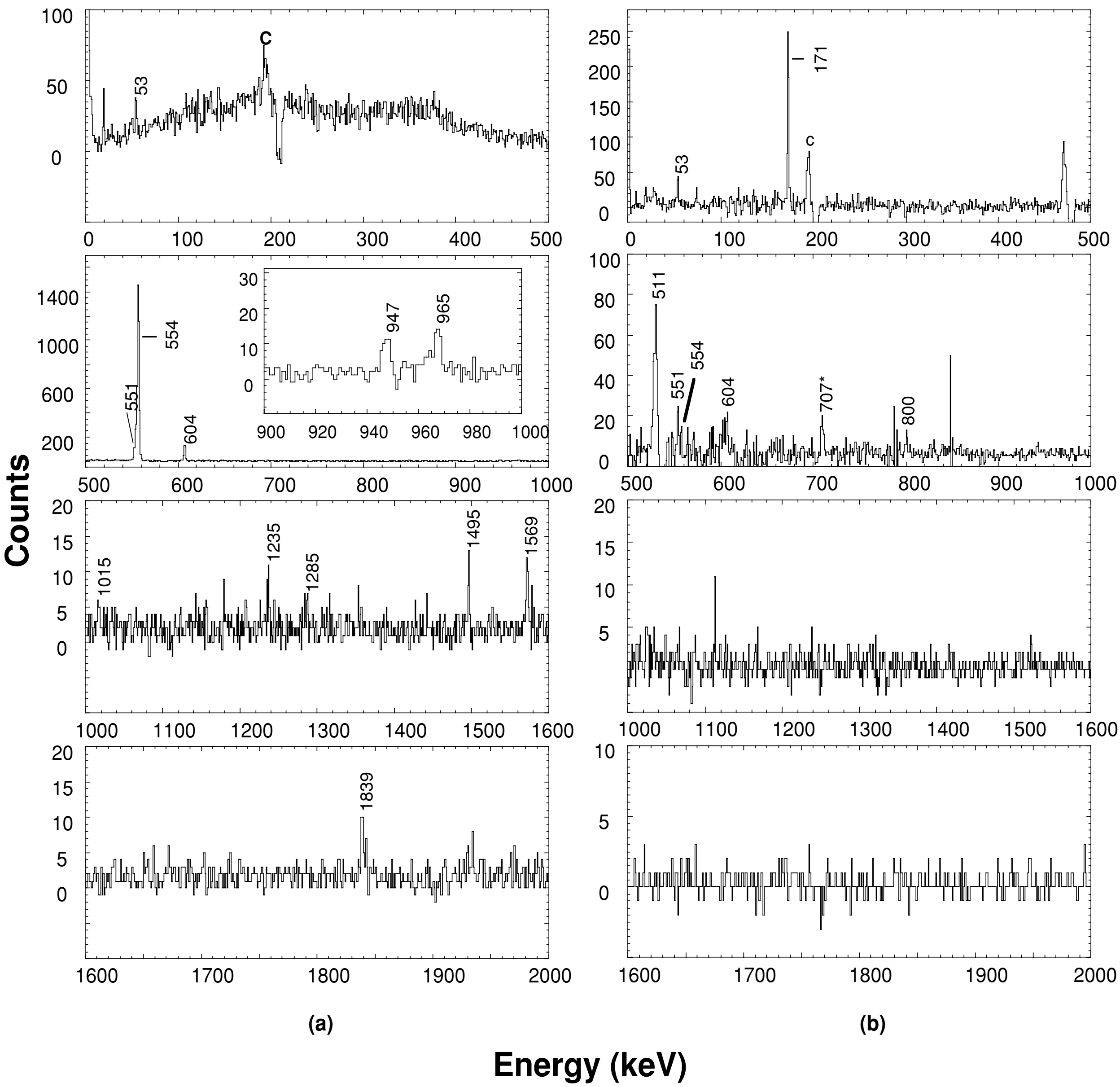

FIG. 5. Coincidence spectra for gates taken on the 318-keV transition in ^{134}Sb following (a) β^- decay of ^{134}Sn and (b) $\beta^- n$ decay of ^{135}Sn. The asterisk on the 707-keV peak in (b) denotes that the presence of a 319-keV transition in ^{135}Sb that shows a coincidence in the 318-keV gate.

331 keV nor to the 3^- level at 384 keV, a spin and parity of 5^- are suggested. The new level at 617 keV decays by transitions of approximately equal reduced transition intensity to both the 7^- level at 279 keV and the possible 5^- level at 441 keV, hence indicating a spin and paritiy assignment of 6^- for this level. With these assignments, the 162-keV transition would be a noncompetitive $E2$ transition and could have a rather long lifetime. We examined our time-to-amplitude spectrum gated on β start pulses and 162-keV stop pulses, but the time resolution and low intensity of the transition did not permit observation of a lifetime. Notice that if the 441-keV level were to be a 4^- level, the level at 617 keV could not decay by transitions of approximately equal intensity to this level and also to the 7^- level at 279 keV. And, if the 617-keV level were to be 5^-, then the $E2$ branch to the 7^- level at 279 keV would not be competitive.

As the new level at 1385 keV decays by transitions of approximately equal intensity to the 6^- level at 617 keV and the 4^- level at 555 keV, it is given a tentative spin and parity assignment of 5^-.

In the high-spin fission fragment study by Urban *et al.*, the positions of the yrast 8^-, 9^+, and 10^+ levels were determined relative to the position of the 7^- state [12]. The placement of the 7^- isomer at 279 keV now establishes the positions of the previously reported 8^-, 9^+, and 10^+ levels in ^{134}Sb by Urban *et al.* at 1351, 2407, and 2714 keV, respectively.

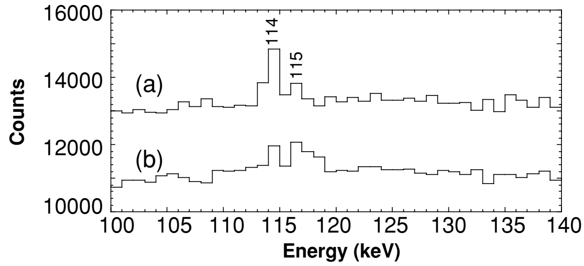

FIG. 6. The spectra of γ rays following decay of ^{135}Sn taken during the first 100 ms after source collection (a) and during the period from 600 to 1000 ms after source collection (b).

IV. SHELL-MODEL CALCULATIONS

With these new data that include new higher-spin levels below 1.0 MeV, and new 1^- levels up to 2.5 MeV, more detailed comparisons to level structures calculated with two-body matrix elements are now possible. Calculations have been performed with the OXBASH code using TBME from the Kuo-Herling interaction and from the CD Bonn interaction. A ^{132}Sn core was used along with single-proton and single-neutron energies taken from the observed levels in ^{133}Sb and ^{133}Sn, respectively. Results for our calculations with the CD Bonn interaction and the unscaled Kuo-Herling interaction [13], denoted KH208, along with the results taken from Korgul *et al.*, for the scaled Kuo-Herling interaction, denoted as KH5082, are shown in Fig. 10 [4]. The calculated binding energy difference between ^{134}Sb and ^{132}Sn using the KH208 interaction is 12.83 MeV. This value is in reasonable agreement with the measured binding energy difference of 12.97(4) MeV. The average deviation for the 8 levels of the $\nu f_{7/2} \otimes \pi g_{7/2}$ multiplet is ~20 keV for the unscaled KH208 interaction as compared to ~40 MeV for the scaled KH5082 interaction and ~150 keV for the CD Bonn interaction. Even when Korgul *et al.*, adjusted five of the eight TBME (their KH5082N interaction) to fit exactly the energies of the 0^-, 1^-, 2^-, 3^-, and 4^- levels, the fit for the positions of the 5^- and 6^- levels were still 42 and 76 keV too high in energy, respectively [4].

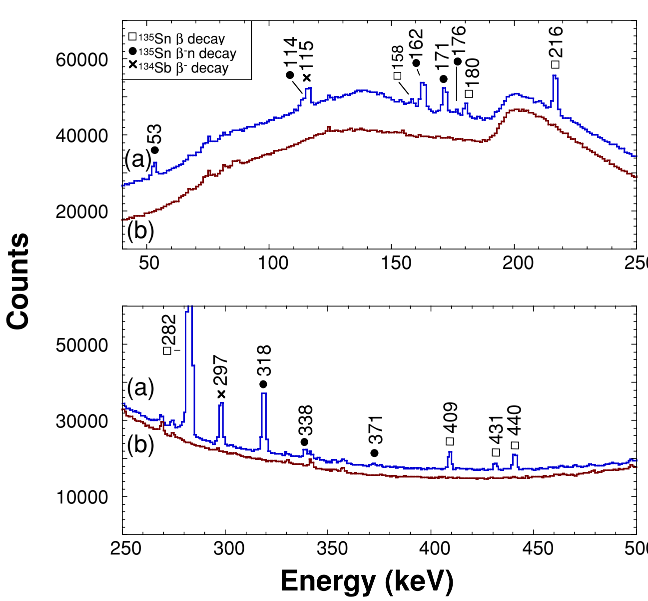

FIG. 7. (Color online) Comparison of γ spectra taken at $A = 135$ with the (a) laser on and (b) with the laser off.

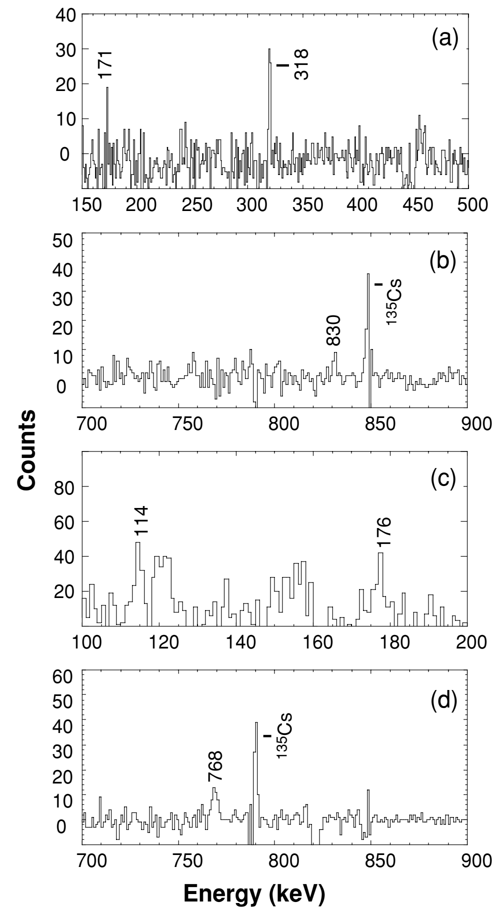

FIG. 8. Coincidence spectra for gates taken on the (a) 53-, (b) 171-, (c) 162-, and (d) 338-keV γ rays that depopulate levels in ^{134}Sb following $\beta^- n$ decay of ^{135}Sn.

The Kuo-Herling interaction has a bare G matrix derived from the Hamada-Johnston nucleon-nucleon interaction and contains first-order particle-hole (bubble-diagram) corrections. In a previous study of these levels, Chou and Warburton, in the absence of a renormalized G matrix for the ^{132}Sn core, used a set of matrix elements taken from studies of valence particle and hole spectra around ^{208}Pb that were scaled by a factor of $(208/132)^{-1/3}$, as estimated by the mass dependence of a finite range interaction in an oscillator basis [1,13–15]. As reported by Korgul *et al.*, there was agreement with experiment at a degree that is perhaps unexpected [4]. The calculated binding-energy difference between ^{134}Sb and ^{132}Sn of 12.83 MeV is also in reasonable agreement with the experimental value of 12.97(4) [16].

In our calculations, the lowest multiplet (0^- to 7^-) has wave functions dominated (90% or more) by the $0g_{7/2} - 1f_{7/2}$ proton-neutron configuration. We note that the M3Y interaction [17] (that gives bare G matrix elements that are similar to Kuo-Herling) that all components of the *NN*

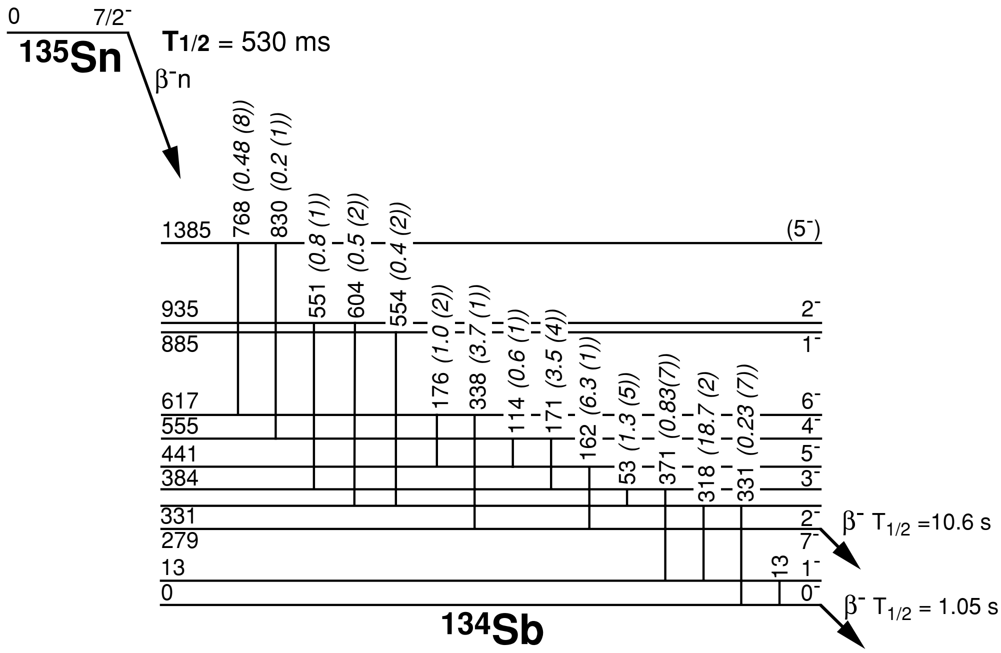

FIG. 9. The levels of ^{134}Sb populated in the $\beta^- n$ decay of 530-ms ^{135}Sn.

interaction are important. For example, for the 0^- state the various contributions are -0.54 ($T = 0$ central), -0.21 ($T = 1$ central), 0.42 ($T = 0$ tensor), -0.41 ($T = 1$ tensor), and 0.19 (spin-orbit) MeV. Thus, the fact that the total agrees

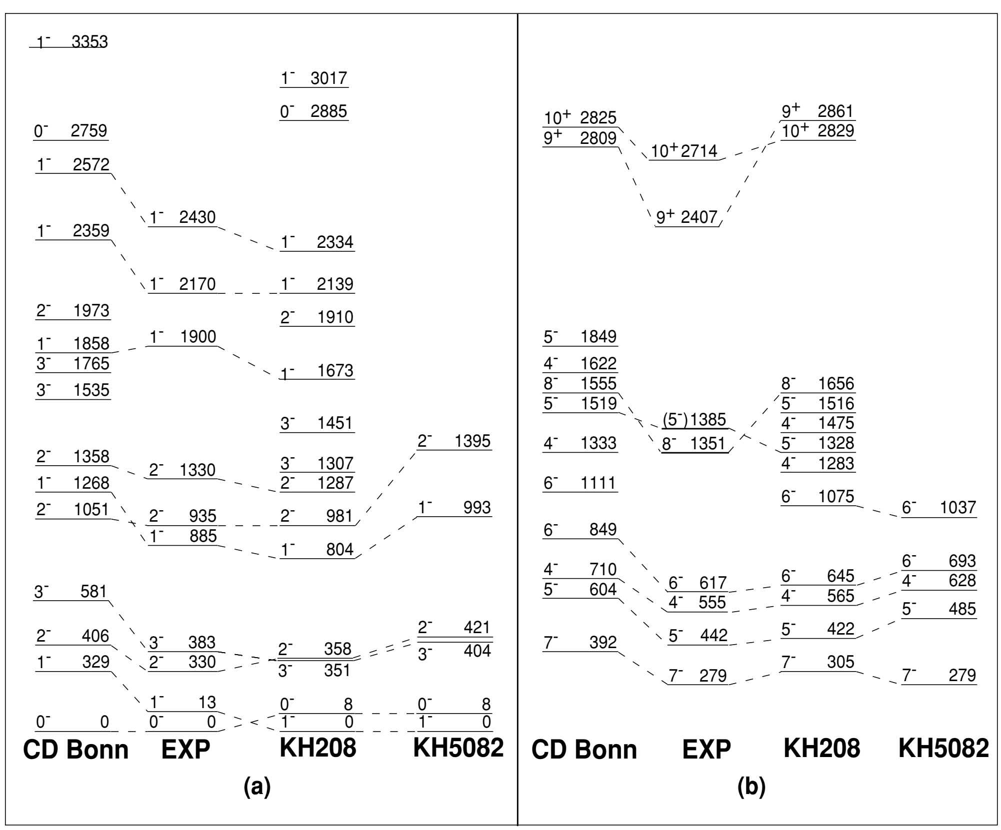

FIG. 10. Comparison of experimental levels of ^{134}Sb with shell-model calculations using CD Bonn, KH208, and KH5028 interactions. In (a) are levels observed in the β^- decay of ^{134}Sn, and in (b) are levels populated via $\beta^- n$ decay of ^{135}Sn, along with high-spin levels identified in a fission-fragment study [11].

with experiment is an exquisitely sensitive test of the NN interaction in nuclei. In addition, the renormalized (bubble) part of Kuo-Herling gives significant shifts that contributes to the agreement. In particular, without the bubble diagram the 1^- level lies 230 keV above the 0^-. The renormalization turns out to act in opposite directions for the 0^- and 1^- and brings them into degeneracy as observed in experiment.parities.

Attempts to improve on the basic original Kuo-Herling interaction have not succeeded. In general, it may be expected that the G matrix and core polarization to be quantitatively different for ^{132}Sn and ^{208}Pb. Therefore, it is not understood why the unscaled KH208 that was derived for ^{208}Pb provides such a good fit for the ^{134}Sb spectrum. The more recent renormalized G matrix obtained by Hjorth-Jensen from the CD-Bonn potential (the spectrum labeled CD-Bonn in Fig. 10) that was used for the spectrum of ^{135}Sb and ^{134}Sn in Ref. [5] has bare G matrix elements that are similar to Kuo-Herling but has higher order renormalizations that in total are different from the first-order corrections used for the Kuo-Herling calculations. Although it should be expected that going to higher order is better, there appear to be dependences on the underlying single-particle spectrum that need further investigation [18].

In a companion article in which we report new data for the level structure of ^{135}Sb, we found that the CD Bonn interaction provided a somewhat better fit for the levels in ^{135}Sb below 2.0 MeV as compared to a calculation in which the CD Bonn interaction was used for the neutron-neutron interactions and the Kuo-Herling interaction was used for the proton-neutron interactions [6]. Hence, a consistent Hamiltonian for this mass region (^{134}Sn, ^{134,135}Sb) has yet to be found.

V. CONCLUSIONS

In summary, new experimental data have been collected, separately, for the decays of mass separated ^{134}Sn nuclei and ^{135}Sn nuclei to levels of odd-odd ^{134}Sb. The Sn sources were produced at CERN/ISOLDE in high-energy neutron induced fission in a setup that minimized isobaric interference. From these time-dependent γ-ray singles and γ-γ coincidence spectra, the position of the 7^- β^--decaying isomer has been established at 279 keV, along with new low-energy 5^- and 6^- levels and new higher energy 1^- levels. These new data now permit much more detailed testing of calculations for the structure of the one-proton-one-neutron levels in ^{134}Sb over a larger range of energies and broader range of spins and parities.

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