Few particle excitations of $N=83$ isotones ^{134}Sb and ^{135}Te from ^{248}Cm fission

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Gamma-ray cascades in the two- and three-valence-particle nuclei ^{134}Sb and ^{135}Te have been studied with Gammasphere using a ^{248}Cm spontaneous fission source. Isotopic assignments were based in part on coincidences with γ rays from complementary Rh and Ru fission partners. The ^{134}Sb and ^{135}Te level schemes have been considerably extended, with placement of many new high-energy γ rays; delayed γ-ray coincidences observed across a 0.51-μs yrast isomer in ^{135}Te were especially fruitful. The yrast level spectra of both nuclei are interpreted using empirical nucleon-nucleon interactions and compared with the known yrast excitations of their counterparts ^{210}Bi and ^{211}Po.

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I. INTRODUCTION

The nuclei ^{134}Sb and ^{135}Te are $N=83$ isotones, with two and three valence nucleons, respectively, outside doubly magic ^{132}Sn. The yrast spectroscopy of these nuclei is well worth studying, since it should be a prime source of information about empirical proton-neutron interactions in an important sector of the nuclidic chart. These are neutron-rich species, accessible for study only through fission of actinides, and what little is known about their properties comes mainly from fission product radioactivity measurements. In ^{134}Sb, there are two β-decaying isomers with probable I^π values of 7^- and 0^- arising from the configuration $\pi g_{7/2}\nu f_{7/2}$, with aligned and anti-aligned coupling of the nucleonic spins; the ordering of the isomers is not yet settled. In ^{135}Te, the ground state almost certainly has $I^\pi=7/2^-$, and a well-established 0.51-μs isomer at 1555 keV, assigned the aligned configuration $(\pi g^2_{7/2}\nu f_{7/2})19/2^-$, decays by an $E2$ cascade through $15/2^-$ and $11/2^-$ members of the same multiplet to the $7/2^-$ ground state.

Recent investigations using large γ-ray detector arrays to measure fission-product γ rays have opened prospects for broad exploration of many poorly known nuclei in neutron-rich regions. Our work has focused on yrast excitations of few-valence-particle nuclei in the $Z=50$–54, $N=80$–84 range, and we have analyzed fission product $\gamma\gamma\gamma$ data measured with a ^{248}Cm spontaneous fission source at the Eurogam II array. First results for the $N=82$ isotones ^{134}Te, ^{135}I, ^{136}Xe [1,2], for the $N=83$ isotones ^{134}Sb, ^{135}Te, ^{136}I, ^{137}Xe [2–4], and for the $N=84$ isotones ^{134}Sn, ^{135}Sb, ^{136}Te [5,6] have already been reported.

The γ-ray data from the Eurogam II ^{248}Cm experiment were of high quality in most respects, but they were acquired with narrow coincidence time windows. Consequently, delayed γ-ray coincidence relationships across isomers with half-lives exceeding 0.2 μs could not be investigated in an adequate way. This was a particularly serious drawback in the ^{132}Sn region, where yrast isomers abound, just as they do in the region around ^{208}Pb. The ^{135}Te results from Eurogam II serve to illustrate the problem [3]. Although ^{135}Te is a high-yield (3.2%) product of ^{248}Cm fission, the occurrence of the 0.51-μs isomer along its yrast line severely limited the spectroscopic information about high-lying excitations in this nucleus that could be gleaned from the Eurogam II data.

We have now performed new fission-product γ-ray coincidence measurements at Gammasphere, again using a ^{248}Cm source, but with more favorable control of the timing conditions. The data acquired were generally better than those from the Eurogam II experiment, and they have led to significant advances in the yrast spectroscopy of both ^{134}Sb and ^{135}Te, as detailed below.

II. EXPERIMENTAL PROCEDURE

The γ-ray measurements were performed with the Gammasphere array at Argonne National Laboratory using a ^{248}Cm source consisting of about 5 mg of curium oxide embedded in a pellet of potassium chloride. This source delivered $\sim 6.3\times 10^4$ fission/s. The fission fragments were stopped inside the source in $\sim$1 ps, with subsequent emission of the deexcitation γ rays occurring from nuclei at rest.

The γ-ray coincidence data were recorded over a 10-day period using Gammasphere, which consisted at that time of 99 escape-suppressed large-volume Ge detectors. The event trigger required detection of at least four γ rays within an 800-ns time interval, with storage of time and energy information for every γ ray registered. A total of about 1.8×10^9 events were collected, and they were subsequently sorted off line into various $\gamma\gamma$ matrices and $\gamma\gamma\gamma$ cubes, both prompt and delayed, covering energy ranges to above 5 MeV.

III. RESULTS

A. ^{134}Sb

As mentioned in the Introduction, the one-proton, one-neutron nucleus ^{134}Sb has two β-decaying isomers with $I^{\pi} = 0^-$ and 7^-, both assigned the configuration $\pi g_{7/2} \nu f_{7/2}$. Our first analysis of the Eurogam II data identified a cascade of 1073- and 1053-keV γ rays in ^{134}Sb, together with a strong 2126-keV crossover γ ray [3]. Guided by shell model considerations and by the known level structure of another $1p1n$ nucleus ^{210}Bi, we placed these transitions feeding the ^{134}Sb 7^- isomer from $(\pi g_{7/2} \nu h_{9/2})8^-$ and $(\pi h_{11/2} \nu f_{7/2})9^+$ states at 1073 and 2126 keV, respectively. Further analysis [4] located a new level at 2434 keV deexciting by 308- and 1361-keV γ rays to the 2126- and 1073-keV levels. Angular correlation results indicated stretched dipole character for the 308-keV transition and suggested that the 2434-keV level might be the $(\pi g_{7/2} \nu i_{13/2})10^+$ two-particle state firmly expected in this general region; the problem was that the $\nu i_{13/2}$ single-particle energy around ^{132}Sn was not previously known. As shown in Ref. [4], adoption of the $(\pi g_{7/2} \nu i_{13/2})10^+$ interpretation for the ^{134}Sb 2434-keV level pointed towards a value close to 2.7 MeV for the $\nu i_{13/2}$ single-particle energy.

The superior γ-ray coincidence data acquired with Gammasphere enabled us to identify many additional ^{134}Sb γ rays, including seven new transitions with energies above 1.99 MeV. As previously noted [3], the strongest ^{134}Sb γ rays appeared in coincidence with γ rays from the $2n$, $3n$, and $4n$ fission partners ^{112}Rh, ^{111}Rh and ^{110}Rh. In the analysis of the new data, double-coincidence gates on the ^{134}Sb 2126-keV γ ray and on Rh partner γ rays [Fig. 1(a)] exhibited a group of high-energy lines of 1968, 2083, 2136, and 2444 keV. Of these, the 2083- and 2136-keV lines, together with a 1991-keV transition, appeared also with a double gate set on 2126- and 308-keV γ rays [Fig. 1(b)]. These results and further checks of the prompt $\gamma\gamma\gamma$ data led to the conclusion that the 1968- and 2444-keV γ rays feed the 2126-keV level from 4094- and 4570-keV parent levels, whereas the 1991-, 2083-, and 2136-keV γ rays directly populate the 2434-keV level from 4425, 4517, and 4570 keV.

Double gating on the 2126- and 1968-keV lines, as shown in Fig. 1(c), identified a feeding cascade of 423, 249, and 279 keV. Of these, the strongest is the 423-keV transition deexciting the level at 4517 keV, which is also the parent level of the 2083-keV transition. The 249- and 279-keV transitions, together with a 196-keV γ ray found to precede the 2444- and 2136-keV transitions, located levels at 4766 and 5045 keV. In addition, double gating on the 249-, 279-, and 2126-keV γ rays identified a 2391-keV third deexcitation branch from the 4517-keV level. Gating on the 1991-keV γ ray and transitions following that γ ray showed the 249-and 279-keV lines to be in coincidence, indicating that the 4425-keV level is fed from the 4517-keV level. There was also some indications of a 92-keV connecting transition, but they were not conclusive, and the transition is not included in the level scheme of Fig. 2.

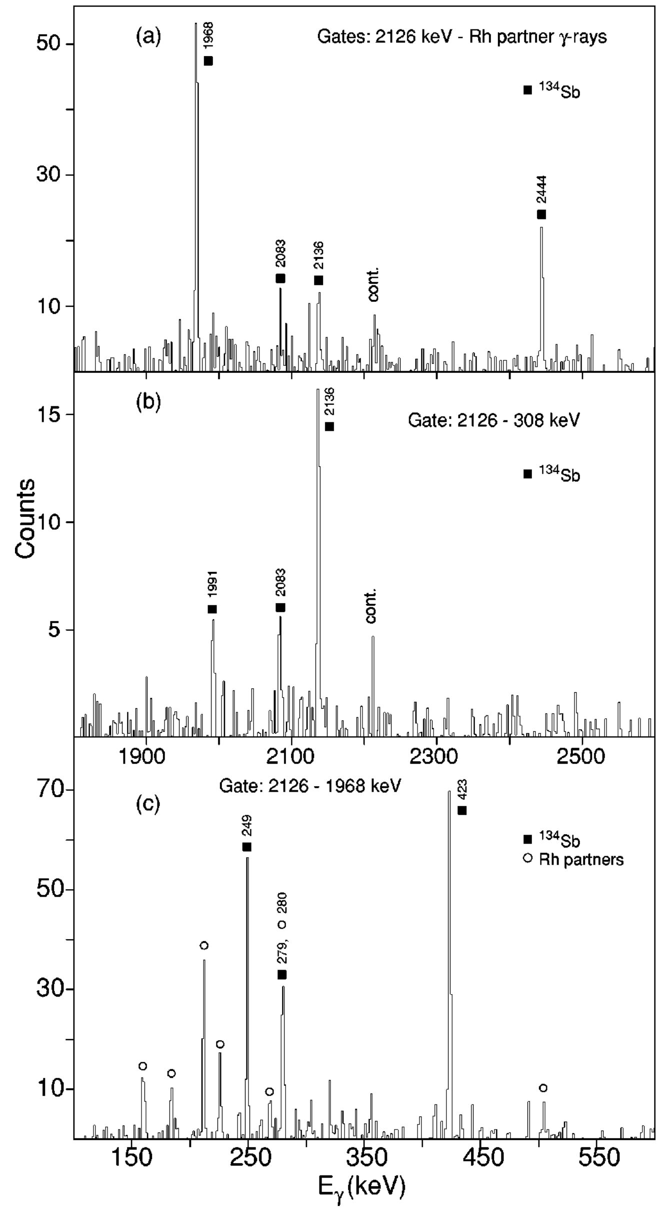

FIG. 1. Gamma-ray coincidence spectra for ^{134}Sb. (a) displays γ rays coincident with the 2126-keV ^{134}Sb transition and the strongest transitions from the complementary $A = 110-113$ Rh products. (b) and (c) show γ rays coincident with double gates on the ^{134}Sb transitions specified. Contaminant lines of known origin are also indicated.

One particular problem concerning the proposed interpretation of the ^{134}Sb 2434-keV level as the $(\pi g_{7/2} \nu i_{13/2})10^+$ two-particle state required special investigation. In Ref. [4],

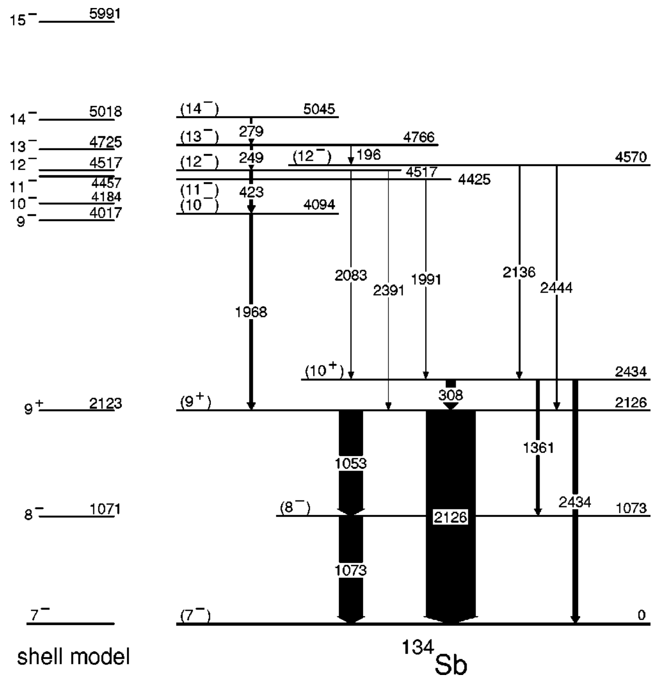

FIG. 2. The proposed level scheme for ^{134}Sb. Arrow widths denote the relative transition intensities. The results of the shell model calculations described in the text are shown to the left.

the 308-keV $10^+\rightarrow 9^+$ and 1361-keV $10^+\rightarrow 8^-$ were the only deexciting transitions reported, but one would expect also a 2434-keV $10^+\rightarrow 7^-$ $E3$ decay branch at least as strong as the 1361-keV transition. This problem was not easily settled, because only weak ^{134}Sb γ rays feed the 2434-keV level. However, in the present work, by multiple gating on these γ rays and on Rh partner lines, it was possible to observe a 2434-keV photopeak and to determine the γ-ray branching ratio $I(308)/I(2434)=1.8(4)$. (Unfortunately, the region around 1361 keV was obscured by a strong 1363-keV γ ray from one of the Rh partners.) However, other spectra gave the branching $I(308)/I(1361)=8(2)$, and from these one could obtain the branching ratio of most interest, $I(2434)/I(1361)=4.4\pm 1.5$. We return to this result in a later section.

The extended ^{134}Sb level scheme displayed in Fig. 2 incorporates these new findings.

B. ^{135}Te

The low-energy portion of the ^{135}Te level scheme consists of $7/2^-$, $11/2^-$, $15/2^-$, and $19/2^-$ levels of $\pi g^2_{7/2}\nu f_{7/2}$ character, the $19/2^-$ state being an $E2$ isomer with a 0.51-μs half-life. The Eurogam II study [3] identified four γ rays of 1086, 1357, 1679, and 2407 keV preceding the $19/2^-$ isomer and deexciting levels at 2641, 3234, 4591, and 5641 keV. On the basis of shell model calculations in which empirical proton-proton interactions were taken from the ^{134}Te level spectrum and proton-neutron interactions were estimated from known ^{210}Bi interactions, the 2641- and 3234-keV levels were interpreted as $(\pi g^2_{7/2}\nu h_{9/2})21/2^-$ and $(\pi g_{7/2}h_{11/2}\nu f_{7/2})25/2^+$ states.

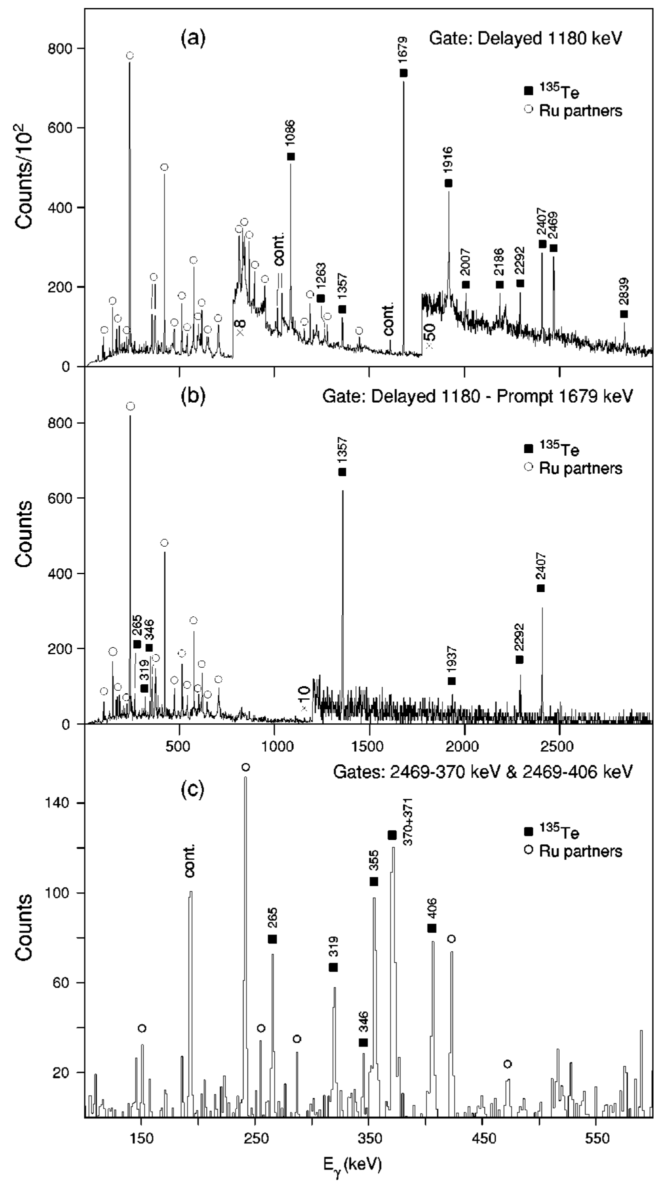

FIG. 3. Gamma-ray coincidence spectra for ^{135}Te. (a) shows γ rays preceding the 1180-keV ^{135}Te transition. (b) and (c) display γ rays coincident with double gates on the ^{135}Te γ rays indicated.

As mentioned earlier, the Eurogam II γ-ray data were acquired with narrow coincidence timing ranges, which were unsuitable for investigating delayed coincidences across μs isomers. In this respect, the timing conditions in the Gammasphere experiment were much more favorable, as is illustrated in Fig. 3(a) by a coincidence spectrum gated on delayed 1180-keV γ rays. The 1086-, 1357-, 1679-, and 2407-keV γ rays (seen previously as weak lines) are prominent peaks in Fig. 3(a), with statistics higher by a factor of 50 and much improved peak to background compared to the corresponding Fig. 1(a) of Ref. [3]. Other γ rays seen in Fig. 3(a), including those at 1263, 1916, 2007, 2186, 2292, 2469, and 2839 keV, must also be ^{135}Te transitions preceding the 0.51-μs isomer.

Particularly useful prompt $\gamma\gamma$ matrices for high-lying transitions in ^{135}Te were sorted by selecting only those

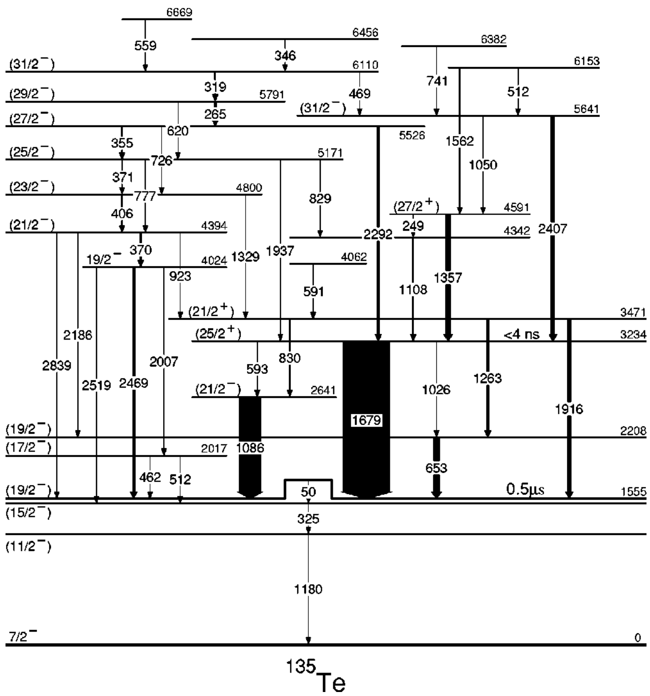

FIG. 4. The proposed level scheme for ^{135}Te.

events with 1180-keV γ rays in delayed coincidence. For example, such gating on the 1180-keV delayed and 1679-keV prompt transitions generated the coincidence spectrum of Fig. 3(b), where new ^{135}Te γ rays of 265, 319, 346, and 1937 keV are to be seen. The prompt γ-ray triples data were also important in establishing coincidence relationships between the observed transitions. Among the new results, the 653-, 1916-, 2469-, and 2839-keV transitions were found to feed the $19/2^-$ isomer directly, and a cascade of 370-, 406-, 371-, 355-, 265-, 319-, and 346-keV γ rays with 777-, 726-, and 620-keV crossover transitions appeared to feed a state at 4024 keV. Other weak γ rays connecting or feeding already located levels were added. Figure 3(c) shows, as an example, the coincidence γ-ray spectrum with double gating on the 2469- and 370- or 406-keV lines. The final ^{135}Te level scheme, which includes all the new findings, is displayed in Fig. 4.

IV. DISCUSSION

A. ^{134}Sb

Yrast states below 4 MeV in the $1p1n$ nucleus ^{134}Sb should have simple two-particle structures. The number of possible configurations is small, and it is easy to list the yrast excitations with $I>7$ that might deexcite by emission of γ rays to the ^{134}Sb $(\pi g_{7/2}\nu f_{7/2})7^-$ state. The possibilities in order of increasing energy would seem to be $(\pi g_{7/2}\nu h_{9/2})8^-$, $(\pi h_{11/2}\nu f_{7/2})9^+$, $(\pi g_{7/2}\nu i_{13/2})10^+$, and $(\pi h_{11/2}\nu i_{13/2})12^-$. In earlier reports [3,4], we assigned the 8^- and 9^+ configurations to ^{134}Sb levels at 1073 and 2126 keV, and suggested $(\pi g_{7/2}\nu i_{13/2})10^+$ for a level at 2434 keV.

The detection in the present work of a moderately strong 2434-keV transition to the 7^- ''ground state'' strengthens the above 10^+ assignment. As described earlier, the relevant branching ratio $I(2434)/I(1361)$ in the deexcitation of the 2434-keV level was determined to be 4.4 ± 1.5. If one takes 0.5 Weisskopf units (W.u.) as a reasonable value for $B(M2;$ 1361 keV), one obtains $B(E3;2434\text{ keV})=20\pm7$ W.u., a result in excellent agreement with those found for other $E3$ transitions in the ^{132}Sn region [8,9].

Most of the ^{134}Sb levels above 4 MeV located in the present study appear to be members of a multiplet connected by low-energy transitions. An exception is the level at 4570 keV, which decays only by high-energy γ rays to the 2434-keV $(\pi g_{7/2}\nu i_{13/2})10^+$ and 2126-keV $(\pi h_{11/2}\nu f_{7/2})9^+$ states. We suggest that the 4570-keV level could be the $(\pi h_{11/2}\nu i_{13/2})12^-$ state. The relative energies of the $(\pi g_{7/2}\nu i_{13/2})10^+$ and $(\pi h_{11/2}\nu i_{13/2})12^-$ two-particle states in ^{134}Sb have been estimated using empirical proton-neutron interactions extracted from the counterpart $(\pi h_{9/2}\nu j_{15/2})12^+$ and $(\pi i_{13/2}\nu j_{15/2})14^-$ excitations in ^{210}Bi, with mass scaling as $A^{-1/3}$. The calculated level energy separation of 2393 keV is in fairly good agreement with the experimental value 2136 keV. On balance, this interpretation of the ^{134}Sb 4570-keV level as the $(\pi h_{11/2}\nu i_{13/2})12^-$ state, which would imply similar $\nu i_{13/2}\rightarrow\nu f_{7/2}$ $E3$ character for the close-lying 2434- and 2444-keV transitions, may be regarded as probable, but by no means certain.

The sequence of levels 4094, 4425, 4517, 4766, and 5045 keV must involve excitations across the shell gap, and we naturally interpret them as $\pi g_{7/2}\nu f_{7/2}^2 h_{11/2}^{-1}$ excitations of the ^{132}Sn core. The energies of these states have been calculated using known single-particle energies and empirical nucleon-nucleon interactions. The $\nu f_{7/2}h_{11/2}^{-1}$ and $\nu f_{7/2}^2$ two-body matrix elements were taken from ^{132}Sn and ^{134}Sn, and those for $\pi g_{7/2}\nu h_{11/2}^{-1}$ and $\pi g_{7/2}\nu f_{7/2}$ were adopted from corresponding multiplets in ^{208}Bi and ^{210}Bi, with $A^{-1/3}$ scaling as described in Ref. [3]. The results are displayed in Fig. 2 with the calculated energies normalized to 4517 keV for the (12^-) level. The good overall agreement with experiment provides solid support for the proposed interpretation of these ^{134}Sb levels.

The two 12^- levels proposed at 4517 keV (core excitation) and at 4570 keV$(\pi h\nu i)$ are separated by only 53 keV. The weak 196-keV branch from the (13^-) core excitation to the 4570-keV level, and the 2391- and 2083-keV branches from the 12^- (core excitation) to the 9^+ and 10^+ states may be due to a small degree of mixing between the close-lying 12^- states.

B. ^{135}Te

The ^{135}Te level scheme has been considerably extended in the present work, although it is obvious from Fig. 4 that only a few yrast states above the 0.51-μs isomer are strongly populated following fission of ^{248}Cm. In this section, we discuss the interpretation of the level structure of this $2p1n$ nucleus, bearing in mind the results for the neighboring $2p$ nucleus ^{134}Te previously obtained [1], and those for the pn nucleus ^{134}Sb reported in Refs. [3,4] and the present paper.

The low-lying $7/2^-$, $11/2^-$, $15/2^-$, and $19/2^-$ levels in ^{135}Te are interpreted as $\pi g_{7/2}^2\nu f_{7/2}$ states corresponding to the 0^+, 2^+, 4^+, and 6^+ $\pi g_{7/2}^2$ states in ^{134}Te. The

$B(E2;19/2^- \rightarrow 15/2^-)$ of 4 W.u. is about twice as large as the ^{134}Te $B(E2;6^+ \rightarrow 4^+)$, which can be understood as an effect of the mixing in the $15/2^-$ state of the $(\pi g_{7/2}^2)4^+ \times \nu f_{7/2}$ and $(\pi g_{7/2}^2)6^+ \times \nu f_{7/2}$ couplings, with coherent contributions from protons and neutron to the $E2$ amplitude. The new level at 2017 keV, decaying to the $15/2^-$ and $19/2^-$ levels, is very likely the $17/2^-$ member of the same $\pi g_{7/2}^2 \nu f_{7/2}$ multiplet. There is little doubt that the level at 2208 keV is the $19/2^-$ state of $\pi g_{7/2} d_{5/2} \nu f_{7/2}$ character, with full alignment of the three angular momentum vectors—it would correspond to the $(\pi g_{7/2} d_{5/2})6^+$ state at 2398 keV in ^{134}Te.

The ^{135}Te level at 2641 keV was reported previously and tentatively interpreted as a $21/2^-$ state from $\pi g_{7/2}^2 \nu h_{9/2}$ maximum-spin coupling; its energy and that of the $(\pi g_{7/2} \nu h_{9/2})8^-$ state at 1073 keV in ^{134}Sb are consistent with this interpretation. The strongly populated 3234-keV^{135}Te level is almost certainly the fully aligned $(\pi g_{7/2} h_{11/2} \nu f_{7/2})25/2^+$ state. New γ rays deexciting this level are the 1026- and 593-keV transitions, which should have $E3$ and $M2$ character, respectively. For the $E3$ transitions deexciting the 3234-keV level, the observed branching ratio $I(1026)/I(1679)$ is smaller by a factor of 6 than what one would estimate by assuming that the two $19/2^-$ levels at 1555 and 2208 keV have the same proton composition as the corresponding 6^+ excitations in ^{134}Te. The level at 3471 keV may be the $21/2^+$ state of $\pi g_{7/2} h_{11/2} \nu f_{7/2}$ character. It lies 237 keV above the $25/2^+$ state of the same configuration, compared to a spacing of 285 keV between the $\pi g_{7/2} h_{11/2}$ 9^- and 7^- states in ^{134}Te.

The 4591-keV level in ^{135}Te, already reported in Ref. [3], has the right energy to be the $27/2^+$ fully aligned $\pi g_{7/2} h_{11/2} \nu h_{9/2}$ state. Its decay to the 3234-keV level would involve the $\nu h_{9/2} \rightarrow \nu f_{7/2}$ $M1$ transition, as expected. The 5641-keV level, populated moderately strongly, appears the perfect candidate to be the $(\pi g_{7/2} h_{11/2} \nu i_{13/2})31/2^-$ state. The 2407-keV γ ray from that level would then be a $\nu i_{13/2} \rightarrow \nu f_{7/2}$ single-particle transition, an $E3$ analogous to the 2434-keV transition in ^{134}Sb. The 1050-keV branch to the 4591-keV level would be a competing $\nu i_{13/2} \rightarrow \nu h_{9/2}$ $M2$ transition like the 1361-keV transition from the 2434-keV level in ^{134}Sb. The branching ratio determined for the transitions deexciting the 5641-keV ^{135}Te level was determined to be $I(2407)/I(1050)=17(5)$, giving within errors the same $B(E3)/B(M2)$ ratio as observed for the deexcitation of the ^{134}Sb 2434-keV level. Such agreement bolsters confidence in the proposed configurations for both ^{134}Sb and ^{135}Te.

The regular sequence of levels above 4 MeV shown at the left side of the ^{135}Te level scheme (Fig. 4) are probably core-excited states, involving $\nu f_{7/2} h_{11/2}^{-1}$ and other particle-hole excitations. We have performed shell model calculations with the OXBASH code of $\pi g_{7/2}^2 \nu f_{7/2}^2 h_{11/2}^{-1}$ level energies using empirical nucleon-nucleon interactions, but in this case the calculated level spacings could not be matched to the experimental ^{135}Te level spectrum in a convincing way. Accordingly, a detailed interpretation of the ^{135}Te level sequence cannot be given, although there are many points of

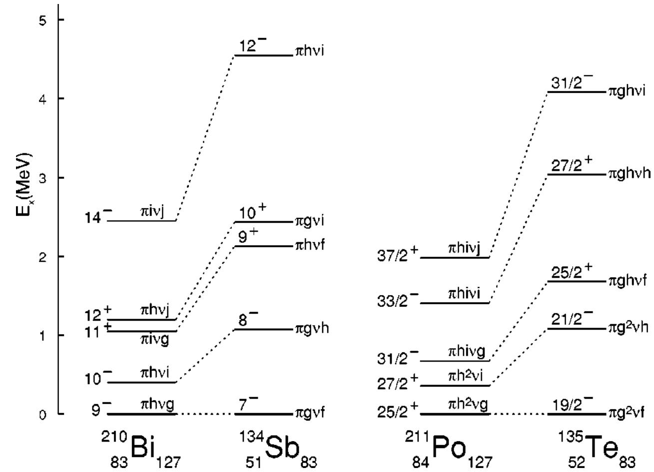

FIG. 5. Comparison of yrast two-particle states in ^{210}Bi and ^{134}Sb, and of the yrast three-particle states in ^{211}Po and ^{135}Te. Dominant shell model configurations are indicated.

correspondence between these ^{135}Te levels and the known core-excited states in neighboring ^{134}Te. For example, the 4394-keV level in ^{135}Te is probably the $I^\pi = 21/2^-$ member of the above five-quasiparticle multiplet and a counterpart of the $(\pi g_{7/2}^2 \nu f_{7/2} h_{11/2}^{-1})8^+$ state at 4557 keV in ^{134}Te. The 4394-keV level deexcites to the ^{135}Te $19/2^-$ isomer by a 2839-keV γ ray, very close in energy to the 2866-keV transition from the 4557-keV level to the ^{134}Te 6^+ isomer. Our broad conclusion is that this sequence of levels in ^{135}Te extending from 4394 keV to above 6 MeV is composed of core-excited states analogous to those identified at similar excitation energies in the simpler nuclei ^{132}Sn, ^{133}Sb, ^{134}Sb, and ^{134}Te.

C. Comparison of yrast states in ^{134}Sb,^{135}Te and ^{210}Bi,^{211}Po

It has been known for some time that the spectroscopy of the ^{132}Sn region closely resembles that of the well-studied nuclei around doubly magic ^{208}Pb [7]. The orbitals above and below the energy gaps in the two cases are similarly ordered, and every single-particle state in the ^{132}Sn region has its counterpart around ^{208}Pb with the same radial quantum number *n* and one unit larger in angular momenta *l* and *j*. Moreover, nucleon-nucleon interactions required for calculations in the ^{132}Sn region can be estimated from the corresponding empirical interactions known in few-valence-particle nuclei around ^{208}Pb; this aspect was of central importance in the present work. It should be noted that the spectroscopic information obtained directly from these fission-product γ-ray measurements was quite limited, consisting of a few short γ-ray cascades in ^{134}Sb and more extended cascades in ^{135}Te, but essentially nothing about transition multipolarities and spin-parity assignments. Our interpretation of the ^{134}Sb and ^{135}Te results was vitally influenced by existing knowledge of yrast excitations in their counterpart nuclei ^{210}Bi and ^{211}Po.

We conclude by displaying in Fig. 5 the assigned two- and three-particle yrast states in ^{134}Sb and ^{135}Te and the corresponding states known in ^{210}Bi and ^{211}Po. Each two-particle state in ^{134}Sb has its counterpart in ^{210}Bi with the same parity and larger in spin by 2 units; for the three-valence-particle nuclei ^{135}Te and ^{211}Po, corresponding states have opposite parity and the spins differ by 3 units. For both pairs of nuclei, the order of the corresponding states is the same and their relative spacings are seen to follow a similar pattern, reflecting the fact that the results for ^{134}Sb and ^{135}Te could be interpreted in a consistent way using a fixed set of single-particle energies and nucleon-nucleon interactions.

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