PHYSICAL REVIEW C, VOLUME 64, 054312

Yrast excitations in $N=81$ nuclei ^{132}Sb and ^{133}Te from ^{248}Cm fission

P. Bhattacharyya, P. J. Daly, C. T. Zhang, Z. W. Grabowski, and S. K. Saha*
Chemistry and Physics Departments, Purdue University, West Lafayette, Indiana 47907

B. Fornal and R. Broda
Chemistry Department, Purdue University, West Lafayette, Indiana 47907
and Niewodniczanski Institute of Nuclear Physics, PL-31342, Cracow, Poland

W. Urban
Institute of Experimental Physics, Warsaw University, PL-00-681 Warsaw, Poland

I. Ahmad, D. Seweryniak, I. Wiedenhöver, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, T. Lauritsen,
C. J. Lister, and P. Reiter
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

J. Blomqvist
Department of Physics Frescati, Royal Institute of Technology, S-10405 Stockholm, Sweden

(Received 20 June 2001; published 12 October 2001)

Gamma rays in the ^{132}Sb and ^{133}Te $N=81$ isotones near doubly magic ^{132}Sn have been studied at Gammasphere using a ^{248}Cm fission source. Previously unknown yrast cascades in the two nuclei were identified in cross coincidence with known γ rays from complementary Rh and Ru fission fragments. The ^{132}Sb levels are explained as proton-neutron hole states as well as core excited states of $2p$-$2h$ character, while the interpretation of the ^{133}Te level scheme is mainly based on results of shell model calculations using empirical proton-proton interaction energies from ^{134}Te together with estimated proton-neutron hole interactions.

DOI: 10.1103/PhysRevC.64.054312 PACS number(s): 23.20.Lv, 21.60.Cs, 27.60.+j, 25.85.Ca

Spectroscopic investigations of few-valence particle nuclei near doubly magic ^{132}Sn are important because they can yield information about nucleon-nucleon interactions and effective charges in an interesting but poorly studied region of neutron-rich nuclei. Recent experiments using large γ-ray detector arrays to study fission products from ^{252}Cf and ^{248}Cm sources [1–3] have identified prompt and delayed γ-ray cascades in individual product nuclei around ^{132}Sn. Initial findings for the two and three valence particle nuclei ^{134}Sn, ^{134}Sb, ^{134}Te, ^{135}Sb, ^{135}Te, and ^{135}I have already been reported [2,4–7]. In the present paper, we turn attention to the $N=81$ species ^{132}Sb and ^{133}Te, which are key nuclei in the $Z>50$, $N<82$ quadrant above ^{132}Sn. The proton-neutron hole nucleus ^{132}Sb is known [8] to have two β-decaying isomers with the configurations $(\pi g_{7/2}\nu d_{3/2}^{-1})4^+$ and $(\pi g_{7/2}\nu h_{11/2}^{-1})8^-$; the relative energies of the isomeric states have not been determined, but there are indications [9] that the 8^- isomer is located less than 200 keV above the 4^+ ground state. Similarly, in the two proton-neutron hole nucleus ^{133}Te, there are two β-decaying isomers, with I^π values of $3/2^+$ and $11/2^-$. Here, the $11/2^-$ isomer with $t_{1/2}=55$ min decays by a 334-keV $M4$ transition to the $3/2^+$ ground state of ^{133}Te [8]. In the present study of ^{248}Cm fission products using Gammasphere, extensive γ-ray cascades populating the higher-spin isomers in both these $N=81$ nuclei have been identified. Some transitions feeding the low-spin isomers have also been observed, but they are not discussed here.

Our first results for nuclei around ^{132}Sn came from analyses of ^{248}Cm fission product $\gamma\gamma\gamma$ data measured at Eurogam II by a Manchester-Argonne-Strasbourg collaboration [2,3]. More recently, we performed new fission product γ-ray measurements at Gammasphere, again using a ^{248}Cm source, but with more favorable control of the timing conditions. A total of about 1.8×10^9 fourfold and higher-fold coincidence events were collected, and the data acquired were generally better than those from Eurogam II. More details about the Gammasphere experiment may be found in Ref. [6].

Earlier inspections of ^{248}Cm fission product γ-ray data have identified [3,6,7] new γ-ray cascades in ^{133}Sb, ^{134}Sb, and ^{135}Sb from the γ-ray intensity patterns observed in cross-coincidence spectra gated on known transitions in fission partner Rh nuclei with $A=110$–113. The same techniques identified in ^{132}Sb prominent 1025 and 1774 keV γ rays that appeared most strongly in spectra double gated on 211 and 232 keV γ rays of ^{113}Rh, its $3n$ fission partner. Gating on these two intense ^{132}Sb transitions [Fig. 1(a)] then pinpointed other transitions in this nucleus, and established a main cascade of 1025, 1774, 401, and 1247 keV γ-rays deexciting levels at 1025, 2799, 3199, and 4446 keV (Fig. 2). A rather strong 2799-keV crossover transition parallel to the 1025 and 1774-keV cascade was clearly seen in coincidence with the 401 keV line. Double gates on the 1025 keV and ^{113}Rh γ rays also identified a fairly intense cascade of 957 and 2464-keV γ rays, but detailed inspection of all the coin-

---

*On leave from Radiochemistry Division, VECC, BARC, Kolkata, India.

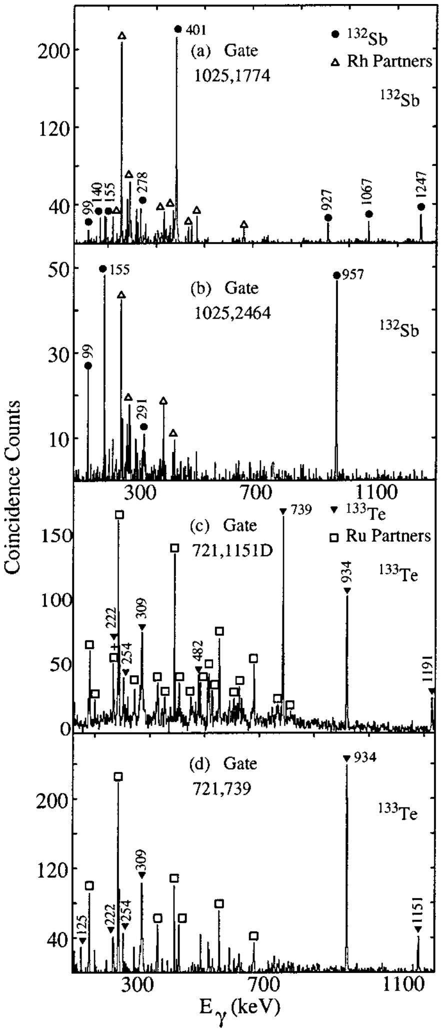

FIG. 1. (a)–(d) Key γ-ray coincidence spectra acquired with double gates on the indicated transitions in ^{132}Sb and ^{133}Te. For (c) prompt coincidence with 721 keV and delayed coincidence with 1151 keV γ rays of ^{133}Te were required; the other cases involved prompt coincidences only.

cidence data failed to settle decisively the ordering of these two transitions. The sequence shown in Fig. 2, with the intermediate level at 3489 keV, was preferred on the basis of theoretical considerations that will be explained below. The ^{132}Sb levels at 4126, 4266, and 4544 keV are well established by the cascades into the 3199 keV level, while the three levels at 4601, 4892, and 5109 keV accommodate the γ-ray cascade feeding the 4446 keV level.

There is a general close resemblance between the spectroscopy of the ^{132}Sn and ^{208}Pb regions, and we have previously noted that specific nucleon-nucleon interactions needed for shell model calculations in nuclei around ^{132}Sn can be estimated from empirical interactions known for corresponding ^{208}Pb region nuclei [2]. The counterpart of the $(\pi g_{7/2}\nu h_{11/2}^{-1})8^-$ state in ^{132}Sb is a well-known $(\pi h_{9/2}\nu i_{13/2}^{-1})10^-$ isomeric state located at 1571 keV in ^{208}Bi. Since the 11^- member of the same multiplet lies 856 keV above the 10^- isomer in ^{208}Bi, we estimate using $A^{-1/3}$ scaling that in ^{132}Sb the 8^- to 9^- spacing for the $\pi g_{7/2}\nu h_{11/2}^{-1}$ multiplet should be close to 996 keV. Moreover, a shell model calculation for ^{132}Sb using a realistic effective interaction derived from the Bonn A nucleon-nucleon potential has given a value of about 900 keV for the same 8^- to 9^- spacing [10]. Consequently, the level at 1025 keV (Fig. 2) is confidently interpreted as the $(\pi g_{7/2}\nu h_{11/2}^{-1})9^-$ state. The next ^{132}Sb level at 2799 keV is interpreted as the $(\pi h_{11/2}\nu h_{11/2}^{-1})10^+$ state, deexciting by the strong 1774 keV transition to 9^-, and by the 2799 keV transition to the $(\pi g_{7/2}\nu h_{11/2}^{-1})8^-$ state. This high-energy $M2$ transition is an obvious counterpart of the 2792 keV $\pi h_{11/2}\rightarrow\pi g_{7/2}$ $M2$ transition known in the neighboring one-proton nucleus ^{133}Sb [3,11]. The strongly fed 3199 keV level, which deexcites exclusively by the 401 keV γ ray to the 2799 keV level is very likely the aligned $(\pi h_{11/2}\nu h_{11/2}^{-1})11^+$ state. [In this case, comparison with ^{208}Bi is not possible, since the $(\pi i_{13/2}\nu i_{13/2}^{-1})$ 12^+ to 13^+ spacing is not yet known.] Spins higher than 11 cannot be generated in ^{132}Sb without excitation of the core.

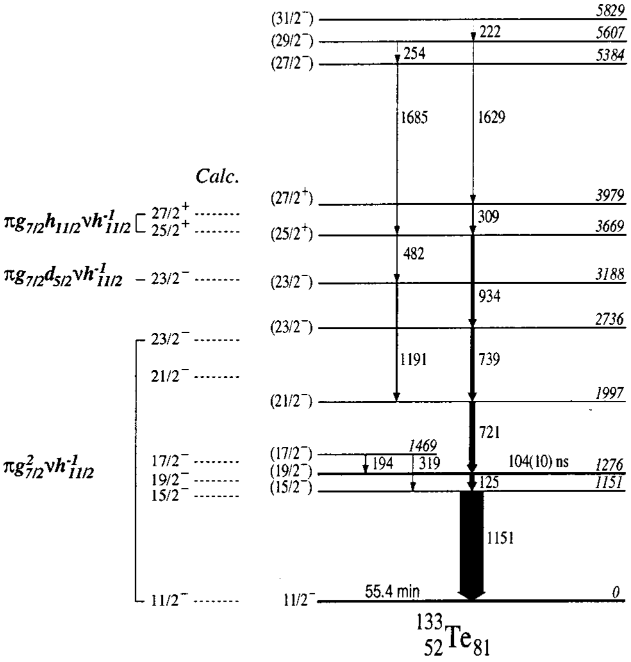

FIG. 2. Level scheme for ^{133}Te showing the yrast γ-ray cascades observed following fission of ^{248}Cm; the widths of the arrows are proportional to the observed γ-ray intensities. The dashed levels indicate calculated energies for $\pi^2\nu^{-1}$ states in ^{133}Te. Level energies are expressed relative to zero for the $11/2^-$ isomeric state.

We next consider the 957 and 2464 keV γ-ray cascade between the 4446 and 1025 keV levels. In view of the uncertain transition ordering, the possibility of an intermediate level at 1982 keV was first examined. At such a low energy, this cannot be a core-excited state and the only feasible $\pi\nu^{-1}$ configuration $(\pi d_{5/2}\nu h_{11/2}^{-1})$ 8^- appears to be ruled out by the absence of any trace of a 1982 keV transition to the 8^- "ground state." The other, more appealing, possibility would place the intermediate level at 3489 keV (as in Fig. 2), and would interpret it as the 10^- proton core excitation with the configuration $(\pi g_{7/2}^2)_0\pi g_{9/2}^{-1}\nu h_{11/2}^{-1}$. The energy required to lift a proton from $g_{9/2}$ to $g_{7/2}$ is about 5.5 MeV as seen from the 6^+, 7^+, 8^+ $\pi g_{7/2} g_{9/2}^{-1}$ states in ^{132}Sn [12]; out of this, about -1.25 MeV is restored by the proton pairing, and the hole-hole 10^- interaction is about –0.95 MeV, resulting in an estimated energy of about $5.5–1.25–0.95=3.3$ MeV for this ^{132}Sb 10^- excitation, in satisfactory agreement with the experimental 3489 keV. The expected decay of this state by a strong $\pi g_{7/2} \rightarrow \pi g_{9/2}$ $M1$ transition to the $(\pi g_{7/2} \nu h_{11/2}^{-1})9^-$ state is also in accord with the observations.

The seven ^{132}Sb levels located above 4 MeV are probably $2p2h$ states, without 0^+ coupling for either particles or holes; possible spin-parity values suggested by the observed γ-ray decay patterns are shown in Fig. 2. States of this type with $\pi g \nu f h^{-2}$ and $\pi g \nu d^{-1} h^{-1}$ configurations are expected in this energy range, and the multiplet level energies have been calculated with Oxbash, as in Ref [2], using empirical nucleon-nucleon interactions. The results are included in Fig. 2, with calculated energies normalized to 4446 keV for the 12^- level, and to 4544 keV for the 13^+ level. While there is fairly good agreement between the calculated and experimental level spectra, our detailed interpretation of the individual states above 4 MeV in ^{132}Sb must be considered somewhat speculative.

Nothing was known up to now about high-spin states in $N=81$ nucleus ^{133}Te. The γ rays of tellurium appearing in coincidence with known ^{110,111,112}Ru transitions included a fairly strong 1151 keV γ ray, and the Ru γ-ray intensity ratios observed in cross coincidence with this new line clearly marked it as a ^{133}Te transition. Further analysis revealed a coincident 125 keV γ ray deexciting an isomer in ^{133}Te with $t_{1/2}=104\pm10$ ns. (These two transitions were first reported many years ago by John *et al.* [13], but they were not then assigned.) A cascade of strong 721, 739, 934 keV transitions was found to feed the 104 ns isomer from excited states at 1997, 2736, and 3669 keV (Fig. 3). The ^{133}Te level scheme was further extended using the prompt $\gamma\gamma\gamma$ data, as well as a special $\gamma\gamma$ matrix sorted with the extra requirement of a delayed coincidence with a 1151 keV γ ray. A typical spectrum obtained in this way [Fig. 1(c)] shows seven additional ^{133}Te transitions that have all been accommodated in the Fig. 3 level scheme. The placements of even weak transitions are well supported by coincidence data [Fig. 1(d)]. Finally, a weakly populated 1469 keV level, deexciting by 194 and 319 keV γ rays, is also included in the ^{133}Te scheme.

The spin-parity assignments for the ^{133}Te levels in Fig. 3 are based on the observed γ-ray decay properties and on shell model energy calculations. One could expect that the ^{133}Te yrast excitations above the $11/2^-$ isomer would be those arising from coupling of the known two-proton states of ^{134}Te with the $\nu h_{11/2}^{-1}$ neutron hole. Energies of these $\pi^2 \nu^{-1}$ states were calculated using ^{134}Te π^2 energies together with estimated $\pi g_{7/2} \nu h_{11/2}^{-1}$, $\pi d_{5/2} \nu h_{11/2}^{-1}$, and $\pi h_{11/2} \nu h_{11/2}^{-1}$ interactions, with the $(\pi g_{7/2} \nu h_{11/2}^{-1})8^-,9^-$ and $(\pi h_{11/2} \nu h_{11/2}^{-1})10^+,11^+$ matrix elements adjusted to fit the ^{132}Sb experimental levels presented earlier in this paper. The dashed levels in Fig. 3 show the calculated $\pi^2 \nu^{-1}$ energies, which support an interpretation of the ^{133}Te levels up to 2736 keV as $11/2^-$, $15/2^-$, $19/2^-$, $17/2^-$, $21/2^-$, and $23/2^-$ members of the $\pi g_{7/2}^2 \nu h_{11/2}^{-1}$ multiplet. For the 125 keV isomeric transition, the $B(E2;\ 19/2^- \rightarrow 15/2^-)$ is determined to be 99(10) e^2fm^4 or 2.5(3) W.u., only slightly larger than the $B(E2;\ 6^+ \rightarrow 4^+)$ between $\pi g_{7/2}^2$ states in ^{134}Te [14]. The $19/2^-$ to $23/2^-$ level spacing is well reproduced in the calculation, but the intermediate $21/2^-$ is calculated too high, for no obvious reason. The 3188 keV level is probably the aligned $(\pi g_{7/2} d_{5/2} \nu h_{11/2}^{-1})23/2^-$ state, corresponding to the second 6^+ state of $\pi g_{7/2} d_{5/2}$ character in ^{134}Te.

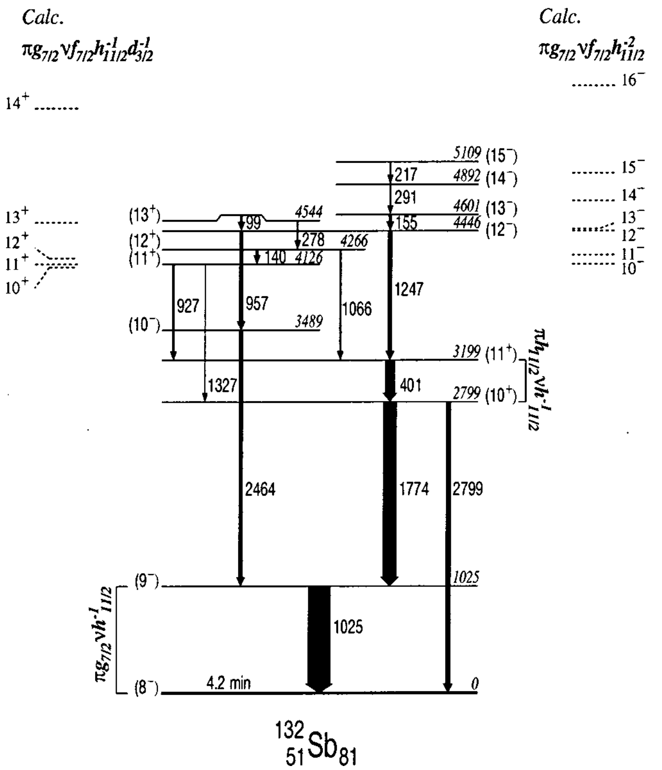

FIG. 3. Level scheme for ^{132}Sb showing the yrast γ-ray cascades observed following fission of ^{248}Cm; the widths of the arrows are proportional to the observed γ-ray intensities. The dashed levels indicate calculated energies for the specified core-excited states. Level energies are expressed relative to zero for the (8^-) isomeric state.

The energies and decay modes of the 3669 and 3979 keV levels in ^{133}Te indicate that they are $25/2^+$ and $27/2^+$ states of $\pi g_{7/2} h_{11/2} \nu h_{11/2}^{-1}$ type. The aligned $29/2^+$ member of this multiplet is calculated to be much higher, at about 5 MeV, and it may not have been detectably populated in the ^{248}Cm fission. The top three levels at 5384, 5607, and 5829 keV must be core-excited states, and there is a good possibility that they are the $27/2^-$, $29/2^-$, and $31/2^-$ states of $\pi g_{7/2}^2 \nu f_{7/2} h_{11/2}^{-2}$ character expected in this energy range.

The $\pi^2 \nu^{-1}$ counterpart of ^{133}Te in the lead region is the well studied ^{209}Po nucleus [15–17], but the yrast level spectra of these two nuclei do not resemble one another closely. This is mainly because the $(\pi^2)_0 \nu i_{13/2}^{-1}$ $I^\pi=13/2^+$ state at 1761 keV in ^{209}Po is nonyrast, lying almost 300 keV above a $17/2^-$ isomer of $\pi h_{9/2}^2 \nu p_{1/2}^{-1}$ character; consequently, many of the yrast configurations in ^{209}Po do not involve the $i_{13/2}$ neutron hole. In contrast, the $(\pi^2)_0 \nu h_{11/2}^{-1}$ $I^\pi = 11/2^-$ state at 334 keV in ^{133}Te is a clear yrast state, and the ^{133}Te yrast configurations generally involve the $h_{11/2}$ neutron hole. Still, one can recognize some counterpart yrast excitations—differing by three units in spin and having opposite parity—such as $(\pi g^2 \nu h^{-1})19/2^-$, $23/2^-$, and $(\pi g h \nu h^{-1})25/2^+$, $27/2^+$ states in ^{133}Te, and the corresponding $(\pi h^2 \nu i^{-1})25/2^+$, $29/2^+$, and $(\pi h i \nu i^{-1})31/2^-$, $33/2^-$ states in ^{209}Po.

In summary, this fission product γ-ray study using Gammasphere has provided the first information about yrast excitations in the $\pi\nu^{-1}$ nucleus ^{132}Sb and the $\pi^2\nu^{-1}$ nucleus ^{133}Te. The results have been interpreted using a consistent set of single particle energies and empirical nucleon-nucleon interactions from both the ^{132}Sn and ^{208}Pb regions, and they open up the yrast spectroscopy of the $Z>50$, $N<82$ quadrant above ^{132}Sn.

This work was supported by the U.S. Department of Energy under Contract Nos. DE-FG02-87ER40346 and W-31-109-ENG-38, and by Polish Scientific Committee Grant No. 2PO3B-074-18. The authors are indebted for the use of ^{248}Cm to the Office of Basic Energy Sciences, U.S. Department of Energy through the transplutonium element production facilities at the Oak Ridge National Laboratory.

[1] J. H. Hamilton *et al.*, Prog. Part. Nucl. Phys. **35**, 635 (1995).
[2] C. T. Zhang *et al.*, Phys. Rev. Lett. **77**, 3743 (1996).
[3] W. Urban *et al.*, Phys. Rev. C **62**, 027301 (2000).
[4] C. T. Zhang *et al.*, Z. Phys. A **358**, 9 (1997).
[5] P. Bhattacharyya *et al.*, Phys. Rev. C **56**, R2363 (1997).
[6] B. Fornal *et al.*, Phys. Rev. C **63**, 024322 (2001).
[7] P. Bhattacharyya *et al.*, Eur. Phys. J. A **3**, 109 (1998).
[8] *Table of Isotopes*, 8th ed., edited by R. B. Firestone and V.S. Shirley (Wiley Interscience, New York, 1996), and references therein.
[9] C. A. Stone, S. H. Faller, and W. B. Walters, Phys. Rev. C **39**, 1963 (1989).
[10] F. Andreozzi, L. Coraggio, A. Covello, A. Gargano, T. T. S. Kuo, and A. Porrino, Phys. Rev. C **59**, 746 (1999).
[11] M. Sanchez-Vega, B. Fogelberg, H. Mach, R. B. E. Taylor, A. Lindroth, J. Blomqvist, A. Covello, and A. Gargano, Phys. Rev. C **60**, 024303 (1999).
[12] B. Fogelberg, M. Hellstrom, D. Jerrestram, H. Mach, J. Blomqvist, A. Kerek, L. O. Norlin, and J. P. Omtvedt, Phys. Scr. **T56**, 79 (1995).
[13] W. John, F. W. Guy, and J. J. Wesolowski, Phys. Rev. C **2**, 1451 (1970).
[14] J. P. Omtvedt *et al.*, Phys. Rev. Lett. **75**, 3090 (1995).
[15] I. Bergstrom, J. Blomqvist, C. J. Herrlander, and K. Wikström, Phys. Scr. **10**, 287 (1974).
[16] K.-G. Rensfelt, C. Roulet, and K. Westerberg, Phys. Scr. **14**, 95 (1976).
[17] A. R. Poletti, G. D. Dracoulis, A. P. Byrne, A. E. Stuchbery, P. Fabricius, T. Kibédi, and P. M. Davidson, Nucl. Phys. **A665**, 318 (2000).