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Yrast states of neutron-rich $N=83$ nuclei from fission product γ-ray studies

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Prompt γ-ray cascades in $N=83$ fission product nuclei near ^{132}Sn have been studied at Eurogam II using a ^{248}Cm source. Cross coincidences observed between γ rays from complementary light and heavy fission fragments were vital for isotopic assignments. Yrast states in the $N=83$ isotones ^{134}Sb, ^{135}Te, and ^{136}I are reported. The interpretation of the level schemes is based mainly on results of shell model calculations using empirical proton-proton interaction energies from ^{134}Te, and proton-neutron interactions estimated from the well-known ^{210}Bi level spectrum. [S0556-2813(97)50711-4]

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The doubly magic nucleus ^{132}Sn and the few valence particle nuclei around it are neutron-rich species inaccessible for study by the common tools of nuclear reaction spectroscopy. The limited information available concerning the structure of these nuclei comes mostly from β^- decay studies of fission product radionuclides, supplemented in a few cases by γ-ray decay data for yrast isomers with μs half-lives. Blomqvist [1] has pointed out that there should be many points of resemblance between the spectroscopy of the ^{132}Sn region and the well-studied nuclei around doubly magic ^{208}Pb. 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. One consequence with particular impact on the present work is that specific nucleon-nucleon interactions required for shell model calculations in the ^{132}Sn region may be estimated from the corresponding empirical interactions in ^{208}Pb region nuclei, which are known in some detail [2].

Recent investigations using multidetector Ge arrays to study fission product γ rays from ^{252}Cf or ^{248}Cm sources have identified prompt and delayed γ-ray cascades from individual product nuclei in the ^{132}Sn neighborhood [3,4]. In the present measurements, the Eurogam II array consisting of 124 Ge detector elements and four LEPS spectrometers recorded 2×10^9 threefold or higher-fold γ-ray coincidence events from a ^{248}Cm source delivering $\sim6\times10^4$ fissions/sec. Additional experimental details have been given in previous publications, which have presented results for the two- and three-proton $N=82$ nuclei ^{134}Te and ^{135}I [4], and for the two-neutron nucleus ^{134}Sn [5]. We now turn attention to the $N=83$ isotones near ^{132}Sn, which should provide key information about empirical proton-neutron interactions in the region. Although the fission yields for several of the interesting $N=83$ products were predicted to be fairly large [6], one could anticipate that their unusually small neutron separation energies might result in drastically reduced γ-ray cascade intensities. (Indeed, no trace of the known [7] 1561 keV $\nu h_{9/2}\rightarrow\nu f_{7/2}$ γ-ray in ^{133}Sn could be detected in cross coincidence with ^{110,111,112}Pd γ rays even though the yrast γ rays of neighboring ^{132}Sn and ^{134}Sn were clearly seen.) Here we report first results for the three $N=83$ isotones ^{134}Sb, ^{135}Te, and ^{136}I.

The occurrence of a 0.51 μs yrast isomer in the three valence particle nucleus ^{135}Te has long been known from fission fragment mass separator studies by Kawade *et al.* [8]. These workers showed that the isomer decays by a 50 keV $E2$ transition followed by 325 and 1180 keV γ rays, and they proposed a ^{135}Te scheme consisting of $7/2^-$, $11/2^-$, $15/2^-$, and $19/2^-$ (isomeric) levels of mainly $\pi g^2_{7/2}\nu f_{7/2}$ character. This isomeric decay scheme provided a point of departure for the present study. Unfortunately, the Eurogam II $\gamma\gamma$ coincidence data were acquired with rather narrow TAC time ranges, not well suited for investigating delayed

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coincidence relationships across μs isomers. The best sorting conditions that could be achieved for the ^{135}Te case preferentially selected prompt γ rays in an 80–240 ns time interval preceding the 1180 and/or 325 keV γ rays. The resulting spectrum of γ rays preceding the 1180 keV transition [Fig. 1(a)] shows several low-energy Ru lines from cross coincidences, and four γ rays above 1 MeV that could be firmly assigned to ^{135}Te. The weak 1357 and 2407 keV γ rays, barely visible in Fig. 1(a), are seen much more convincingly in prompt coincidence with the 1679 keV γ ray, as shown in the Fig. 1(a) inset. No other transition appeared in prompt coincidence with the 1085 keV γ ray, which must feed the 0.51 μs isomer in parallel with the stronger 1679 keV transition. The extended ^{135}Te level scheme is displayed in Fig. 2, and will be discussed below.

Little was known up to now about high-spin states in $A>135$ iodine nuclei. In the present work, detailed systematic examinations of $\gamma\gamma$ cross coincidence intensity patterns between complementary I and Tc fission fragments led to identification of yrast cascades in both ^{136}I and ^{137}I, as well as the $A=108$–111 Tc isotopes [9]. For example, a double gate on γ rays assigned to ^{109}Tc [Fig. 1(b)] shows in coincidence the yrast γ-ray cascades of ^{135}I, ^{136}I, and ^{137}I, which are the $4n$, $3n$, and $2n$ fission product partners of ^{109}Tc. The bottommost transitions placed in ^{135}I are 1133.5 and 288.1 keV, in ^{136}I are 1111.4 and 260.5 keV, and in ^{137}I are 554.2 and 400.2 keV. The literature provides substantial support for these isotopic assignments, since 1133.3 and 554.0 keV γ rays are known strong ^{135}I and ^{137}I transitions observed in β-decay studies of ^{135}Te and ^{137}Te [10], while a 261 keV γ ray deexciting a $\sim$4 ns ^{136}I isomer populated in ^{252}Cf fission was reported by two groups many years ago [11,12].

A double gate on the 1111 and 261 keV γ rays [Fig. 1(c)] showed the yrast transitions of ^{108,109,110}Tc as well as seven new ^{136}I γ rays, all but one above 1 MeV. Easily the most intense of these is the 243 keV γ ray, which is thus placed in the ^{136}I level scheme deexciting a 1615 keV level (Fig. 2). The clean spectrum obtained in coincidence with 1111 and 1284 keV γ rays [Fig. 1(d)] firmly locates the level at 2899 keV, and the 3016 keV level, with four deexciting γ rays, is also established with certainty. In fact, the 3077 keV level is the only one shown in Fig. 2 that may be regarded as somewhat doubtful. The 1372 keV level deexciting by the 261 keV transition is assumed to be the $t_{1/2}\sim$4 ns ^{136}I isomer mentioned earlier [11,12]. Probable spin-parity assignments for the ^{136}I levels, and their interpretation, are discussed below.

Low-lying yrast transitions were previously known in ^{131}Sb and ^{133}Sb but not in the $N=83$ nucleus ^{134}Sb. Here again, detailed study of $\gamma\gamma$ cross coincidence intensities, in this case between complementary Sb and Rh products, led to identification of yrast cascades in $A=110$–113 Rh isotopes, and of 1053, 1073, and 2126 keV γ rays in ^{134}Sb [9]. Specifically, the ^{111}Rh, ^{112}Rh, and ^{113}Rh γ-ray families all appeared in strong coincidence with the well-known 2793 keV ground state transition of ^{133}Sb; on the other hand, a gate on the new 2126 keV γ ray showed dominant ^{110}Rh, ^{111}Rh, and ^{112}Rh γ rays in coincidence, but no additional γ rays that might be associated with ^{134}Sb. The 1073 and 1053 keV γ rays were found to occur in cascade parallel to the 2126 keV

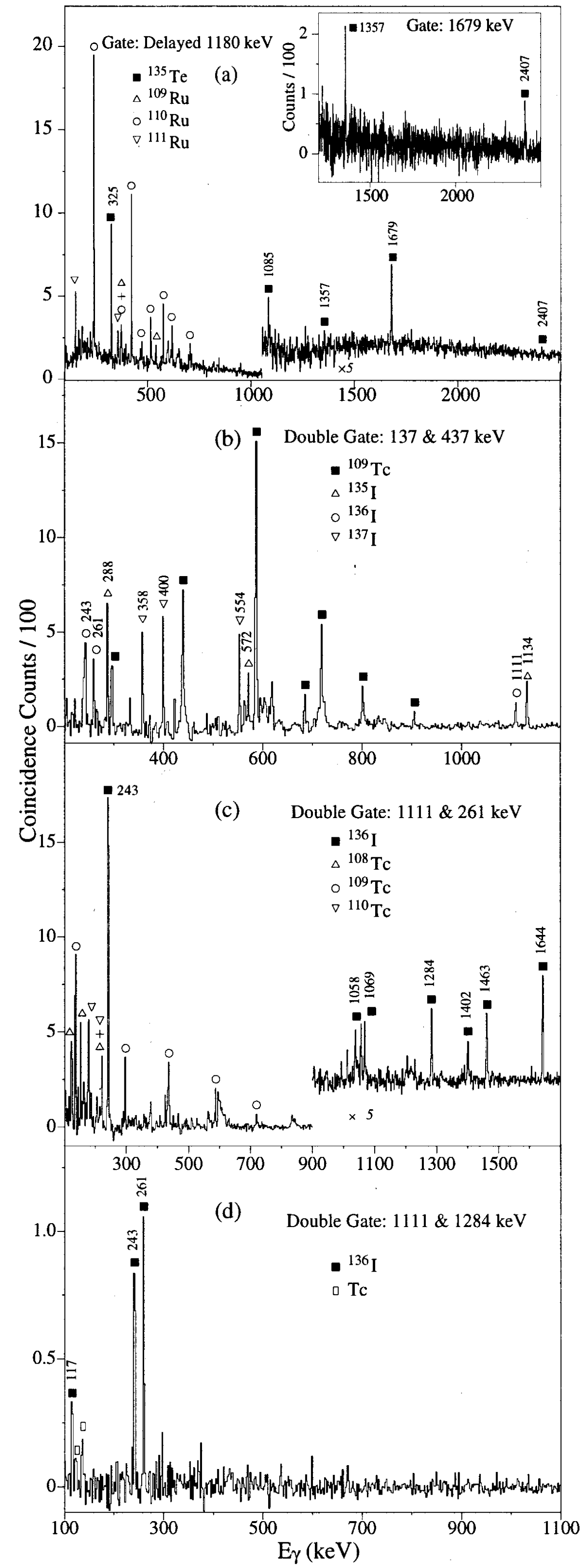

FIG. 1. Key γ-ray coincidence spectra. (a) displays γ rays preceding the 1180 keV ^{135}Te transition, while the inset shows γ rays in prompt coincidence with the 1679 keV transition. (b) displays γ rays coincident with 137 and 437 keV ^{109}Tc transitions. (c) and (d) show γ rays coincident with double gates on the ^{136}I γ rays specified.

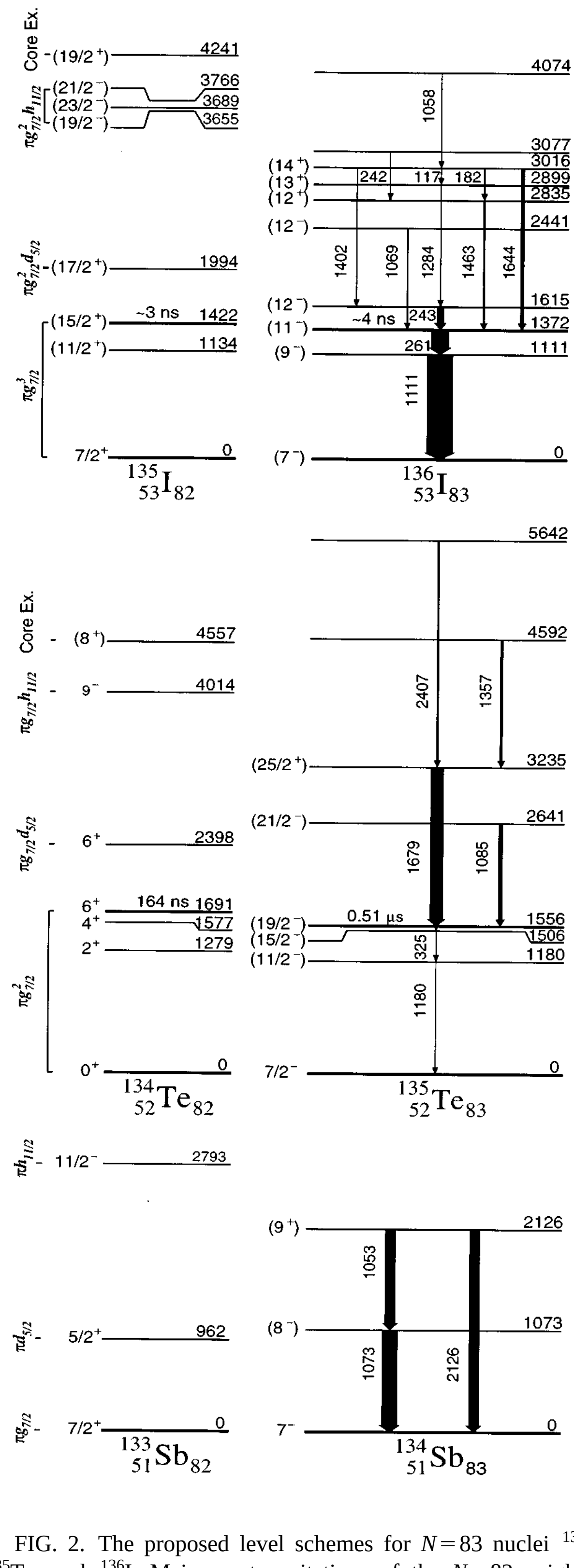

FIG. 2. The proposed level schemes for $N=83$ nuclei ^{134}Sb, ^{135}Te, and ^{136}I. Main yrast excitations of the $N=82$ neighbors ^{133}Sb, ^{134}Te, and ^{135}I are shown to the left.

cross over transition, as shown in the ^{134}Sb scheme of Fig. 2. The non-observation of transitions feeding the 2126 keV level is not so surprising, since the estimated neutron separation energy for ^{134}Sb is only 3.1 MeV [13].

The two-particle nucleus ^{134}Sb has two β-decaying isomers with $I^{\pi}=0^{-}$ and 7^{-}, both assigned the configuration $\pi g_{7/2}\nu f_{7/2}$ [14,15]. It is natural to identify the ^{134}Sb level populated by the 2126 keV γ ray (Fig. 2) as the $(\pi g_{7/2}\nu f_{7/2})7^{-}$ state. In ^{133}Sb the $\pi d_{5/2}$ and $\pi h_{11/2}$ single particle states are located 962 and 2793 keV above the $\pi g_{7/2}$ ground state [1], and in ^{133}Sn the $\nu h_{9/2}$ and $\nu i_{13/2}$ states lie 1561 keV and ~ 3 MeV, respectively, above the $\nu f_{7/2}$ ground state [7]. There are not many possibilities for yrast two-particle states in ^{134}Sb with $I>7$, and the most likely assignments appear to be $(\pi g_{7/2}\nu h_{9/2})8^{-}$ and $(\pi h_{11/2}\nu f_{7/2})9^{+}$ for the 1073 and 2126 keV levels. Approximate excitation energies for these states could be calculated using the single particle energies together with estimates of $(\pi g_{7/2}\nu f_{7/2})7^{-}$, $(\pi g_{7/2}\nu h_{9/2})8^{-}$, and $(\pi h_{11/2}\nu f_{7/2})9^{+}$ proton-neutron interaction energies obtained from the $\pi\nu$ interactions known in ^{210}Bi for the analogous $(\pi h_{9/2}\nu g_{9/2})9^{-}$, $(\pi h_{9/2}\nu i_{11/2})10^{-}$, and $(\pi i_{13/2}\nu g_{9/2})11^{+}$ states [2], with scaling as $A^{-1/3}$ to take account of the nuclear size variation [1,4]. The results, $1561-441=1120$ keV for the $(\pi g\nu h)8^{-}$ excitation energy and $2793-653=2140$ keV for the $(\pi h\nu f)9^{+}$ state, agree rather well with experiment, and lend forceful support to this interpretation of the sparse ^{134}Sb data. Moreover, they encouraged us to proceed with truncated shell model calculations for all three $N=83$ nuclei using a single set of input parameters.

The shell model calculations for ^{134}Sb, ^{135}Te, and ^{136}I included the $\pi g_{7/2}$, $\pi d_{5/2}$, $\pi h_{11/2}$, $\nu f_{7/2}$, and $\nu h_{9/2}$ orbitals, and considered only yrast and near-yrast states having pure configurations. The input consisted of the single particle energies cited earlier, proton-proton interactions taken directly from the ^{134}Te level spectrum as in Ref. [4], and the proton-neutron interactions specified in Table I. These $\pi\nu$ matrix elements were estimated from known ^{210}Bi interactions in the manner described above, except for the three values marked with asterisks, which have been slightly modified (by 40 keV or less) to achieve near-perfect agreement with the ^{134}Sb data. Table I compares the experimental and calculated excitation energies for the three $N=83$ nuclei. For the ^{135}Te levels up to and including the 0.51 μs isomeric state, the agreement between theory and experiment is fair. There is not much doubt that they are dominantly $\pi g^{2}_{7/2}\nu f_{7/2}$ states, but with appreciable admixed contributions from other configurations, especially $\pi g_{7/2}d_{5/2}\nu f_{7/2}$. The calculations support the interpretation of the 2641 and 3235 keV levels 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. This $25/2^{+}$ state is closely related to the $(\pi h_{11/2}\nu f_{7/2})9^{+}$ state in ^{134}Sb and the $(\pi g_{7/2}h_{11/2})9^{-}$ state in ^{134}Te [15], but the second much weaker $E3$ branch expected from the ^{135}Te 3235 keV level to a $(\pi g_{7/2}d_{5/2}\nu f_{7/2})19/2^{-}$ level at about 2100 keV could not be detected. The weakly fed level at 4592 keV may be either $(\pi g_{7/2}h_{11/2}\nu h_{9/2})27/2^{+}$ or $(\pi g^{2}_{7/2}\nu i_{13/2})25/2^{+}$, both of which are predicted around 4.6 MeV. The topmost level at 5642 keV is probably a state of $(\pi g^{2}_{7/2}\nu f^{2}_{7/2}h^{-1}_{11/2})$ type directly related to the core-excited states identified in ^{134}Te at similar excitation energy [4].

The known 47 s β-decaying isomer of the odd-odd nucleus ^{136}I has been assigned $I^{\pi}=(6^{-})$ [16], but the $(\pi g^{3}_{7/2}\nu f_{7/2})7^{-}$ state must be low lying; here we make the

TABLE I. The shell model calculations for $N=83$ isotones. Empirical proton-proton interactions were adopted from the ^{134}Te spectrum, and the proton-neutron interactions used are given below. Level energies calculated for the specified states are compared with the experimental energies.

$\pi\nu$ interaction energies (keV)

$\pi g_{7/2}\nu f_{7/2}$		$\pi g_{7/2}\nu h_{9/2}$		$\pi d_{5/2}\nu f_{7/2}$		$\pi h_{11/2}\nu f_{7/2}$	
7^-	-420*	8^-	-910*	6^-	-760	9^+	-1090*
6^-	-100	7^-	+40			8^+	0
5^-	-300	6^-	-300			7^+	-150
4^-	-140					6^+	-20
3^-	-300						
2^-	-400						
1^-	-680						
0^-	-720						

Results

Nucleus	I^π	Configuration	Expt. (keV)	Theor. (keV)
$^{134}_{51}Sb_{83}$	7^-	$\pi g\nu f$	0	0
	8^-	$\pi g\nu h$	1073	1071
	9^+	$\pi h\nu f$	2126	2123
$^{135}_{52}Te_{83}$	$7/2^-$	$\pi g^2\nu f$	0	0
	$11/2^-$	$\pi g^2\nu f$	1180	1341
	$15/2^-$	$\pi g^2\nu f$	1505	1626
	$19/2^-$	$\pi g^2\nu f$	1555	1684
	$21/2^-$	$\pi g^2\nu h$	2641	2640
	$25/2^+$	$\pi gh\nu f$	3234	3176
$^{136}_{53}I_{83}$	7^-	$\pi g^3\nu f$	0	0
	9^-	$\pi g^3\nu f$	1111	1162
	11^-	$\pi g^3\nu f$	1372	1472
	12^-	$\pi g^2 d\nu f$	1615	1607
	12^-	$\pi g^3\nu h$	2441	2412
	15^+	$\pi g^2 h\nu f$	-	2875
	12^+	$\pi g^2 h\nu f$	2835	2889
	13^+	$\pi g^2 h\nu f$	2899	2941
	14^+	$\pi g^2 h\nu f$	3016	2981

assumption that the yrast γ-ray cascade in ^{136}I feeds this 7^- state, which subsequently deexcites by a low-energy transition. (The 6^- state is calculated 57 keV below the 7^-.) Accordingly, the ^{136}I excitation energies in Fig. 2 and Table I are expressed relative to zero for the 7^- state. The calculations support the interpretation of the ^{136}I levels up to 1615 keV as members of the $\pi g^3_{7/2}\nu f_{7/2}$ and $\pi g^2_{7/2} d_{5/2}\nu f_{7/2}$ multiplets. Associating the $\sim$4 ns half-life with the 1372 keV level leads to a $B(E2;\, 11^-\rightarrow 9^-)$ of about 3 W.u., which is in good accord with the $B(E2)$ values determined for the $\pi g^3_{7/2}$ $15/2^+\rightarrow 11/2^+$ transition in ^{135}I [9], and for the analogous $15^-\rightarrow 13^-$ $E2$ transition in the counterpart nucleus ^{212}At [17,18]. The cluster of ^{136}I levels around 2.9 MeV lies in an energy region where $\pi g^2_{7/2} h_{11/2}\nu f_{7/2}$ yrast states are expected, and the low-energy transitions between them suggest that they are structurally related. The observed decay properties of the 2835, 2899, and 3016 keV levels are consistent with I^π assignments of 12^+, 13^+, and 14^+, respectively, and the calculated energies fully support these assignments. There remains a question about the aligned 15^+ multiplet member, which is calculated to be lowest. The 2899 keV level might be considered an $I^\pi = 15^+$ candidate, with the 1284 keV an $E3$ transition to the yrast 12^- level. However, even though the $\pi h_{11/2}\rightarrow \pi d_{5/2}$ $E3$ involved is fast, the half-life of the parent level would be around 25 ns. The data on the other hand indicate that none of the excited states in Fig. 2 can have $t_{1/2}>10$ ns. We conclude that the 15^+ state must be weakly populated in ^{248}Cm fission, and that it is not placed in the present work.

This investigation has shown that information about prompt γ rays in the largely unexplored $N=83$ nuclei ^{134}Sb, ^{135}Te, and ^{136}I can be obtained from fission product $\gamma\gamma$ measurements using a multidetector Ge array. The results have been interpreted in the shell model, with a close eye on earlier findings for the counterpart nuclei around ^{208}Pb. The limited progress made here should stimulate more detailed and focused spectroscopic studies of the fission product nuclei around ^{132}Sn.

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