SHELL-MODEL HIGH-SPIN YRAST STATES OF FISSION PRODUCT NUCLEI ABOVE DOUBLY MAGIC ^{132}Sn * **

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Prompt γ-ray cascades in neutron-rich nuclei around doubly-magic ^{132}Sn have been studied at Eurogam 2 array using a ^{248}Cm fission source. Yrast states to above 5.5 MeV in the two- and three-proton $N = 82$ isotones ^{134}Te and ^{135}I are reported. They are interpreted in terms of valence proton and particle-hole core excitations with the help of shell model calculations employing empirical nucleon–nucleon interactions from both ^{132}Sn and ^{208}Pb regions. A serious inconsistency in the accepted masses of $N = 82$ isotones near ^{132}Sn is discovered but not resolved.

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1. Introduction

The $Z = 50$, $N = 82$ nucleus ^{132}Sn is the most magic of all heavy nuclei, with pronounced shell closures for both protons and neutrons manifested by the absence of excited states below 4.0 MeV excitation energy [1]. The spectroscopy of ^{132}Sn and its neighbors should in many ways resemble that of the well studied region around $Z = 82$, $N = 126$ ^{208}Pb, where a substantial body of empirical nuclear structure information has accrued. The single particle energy gaps in the two cases are comparably large, and the orbitals above and below the gaps are similarly ordered [2]. Several groups [2–5] have discussed the possibility of developing a "universal" theoretical description of shell model properties with some parameter variation in familiar and remote areas of the nuclidic chart, and they have stressed the desirability of detailed comparison between experimental data from the ^{208}Pb and ^{132}Sn regions. Progress along these lines has been hampered by a scarcity of information about simple excitation modes in the ^{132}Sn region. What we know about these nuclei comes mainly from β^- decay studies of short-lived radionuclides produced in the fission of actinides; consequently, our knowledge about simple excitation modes, single particle energies, effective nucleon-nucleon interactions and other basic properties in this region is far from complete.

The development of large multidetector γ-ray arrays with high analyzing power, which can separate the prompt γ-ray cascades within a single fission product nucleus (of moderate yield) from the bulk of prompt γ-rays, has now opened new prospects for detailed studies of yrast excitations in ^{132}Sn and the few valence particle nuclei around it. The findings for only two of these nuclei are presented here, but similar results for many other products around ^{132}Sn will be forthcoming.

2. Analysis of ^{248}Cm fission γ-rays

The experiments were performed at EUROGAM 2 array in Strasbourg, which consists of 52 Compton-suppressed large Ge detectors and four LEPS spectrometers, including 24 four-crystal CLOVER detectors. A ^{248}Cm source of about 5 mg curium oxide was employed, embedded in a 0.5 mm thick pellet of potassium chloride and then delivered $\sim$6.3x10^4 fissions/sec. The fission fragments were stopped in $\sim$ 1ps, and consequently, almost all the de-excitation γ-rays were emitted from nuclei at rest [6]. A total of 2x10^9 threefold or higher-fold coincidence events were collected. The recorded data were primarily sorted into two $\gamma\gamma\gamma$ cubic arrays covering γ-ray energy ranges to above 2 MeV, and into a two-dimensional $\gamma\gamma$ matrix with both axes extending above 4 MeV. The excellent quality and high selectivity of the triple coincidence γ-ray data made it possible to identify even weak transitions in the nuclei of interest, despite the heavy γ-ray background arising from the abundance of fission products.

We embarked on a detailed investigation of valence-particle yrast excitations in the $Z = 50$–54, $N = 80$–84 range of nuclei. Cross coincidences observed between γ-rays from partner light and heavy fission fragments were often of critical importance in establishing isotopic assignments for previously unknown cascades; in other cases, some overlap with the γ-rays known from β-decay studies provided vital first clues. Although the analysis is far from complete, substantial advances have already been made in the spectroscopy of many of the nuclei in the targeted range. In this report, we feature the results for the two and three valence proton $N = 82$ isotones ^{134}Te and ^{135}I which exhibit simple clearcut excitation modes, thus resembling ^{210}Po and ^{211}At, their well studied $N = 126$ counterparts in the ^{208}Pb region.

3. Yrast levels of $N = 82$ isotones: ^{134}Te and ^{135}I

In the two-proton nucleus ^{134}Te, most members of the $\pi g_{7/2}^2$, $\pi g_{7/2}d_{5/2}$ and $\pi g_{7/2}h_{11/2}$ multiplets are known from ^{134}Sb β^- decay studies. Recently, Omtvedt *et al.* [7] elucidated the properties of a ^{134}Te $(\pi g_{7/2}h_{11/2})$ 9^- yrast level at 4014 keV, which is strongly populated following β-decay of 10.4 s ^{134}Sb, and which de-excites mainly by an intense 2322 keV E3 transition to the $\pi g_{7/2}^2$ 6^+ isomer at 1691 keV. The present fission product measurements identified two dominant high-energy γ-rays feeding the 1691 keV 6^+ state in ^{134}Te, one the 2322 keV $9^- \to 6^+$ transition mentioned above, the other a 2866 keV γ-ray from a 4557 keV level that was populated weakly (if at all) following the ^{134}Sb β^--decay. Gating on this 2866 keV γ-ray (Fig. 1(a)) revealed many new ^{134}Te γ-rays, and the full $\gamma\gamma\gamma$ coincidence results firmly established the level sequence above 4557 keV shown in the ^{134}Te scheme (Fig. 2), including an important 1608 keV transition connecting to the 4014 keV 9^- level. The data left uncertainty about the ordering of the high-lying 515 and 1040 keV transitions, and the sequence shown in Fig. 2 was chosen to match theoretical expectations. Since the only possible two-proton state with I>9 is $(\pi h_{11/2}^2)$ 10^+, expected in ^{134}Te above 7 MeV, the obvious conclusion is that these new states must involve excitation of the ^{132}Sn core. Later, we interpret them as $\pi g_{7/2}^2 \nu f_{7/2} h_{11/2}^{-1}$ states, with strong support from shell model calculations.

Nothing was known up to now about high-spin states in the $N = 82$ nucleus ^{135}I, but a ^{135}Te β^--decay study [8] has located $11/2^+$ and $9/2^+$ levels at 1134 and 1184 keV respectively above the ^{135}I $\pi g_{7/2}$ ground state.

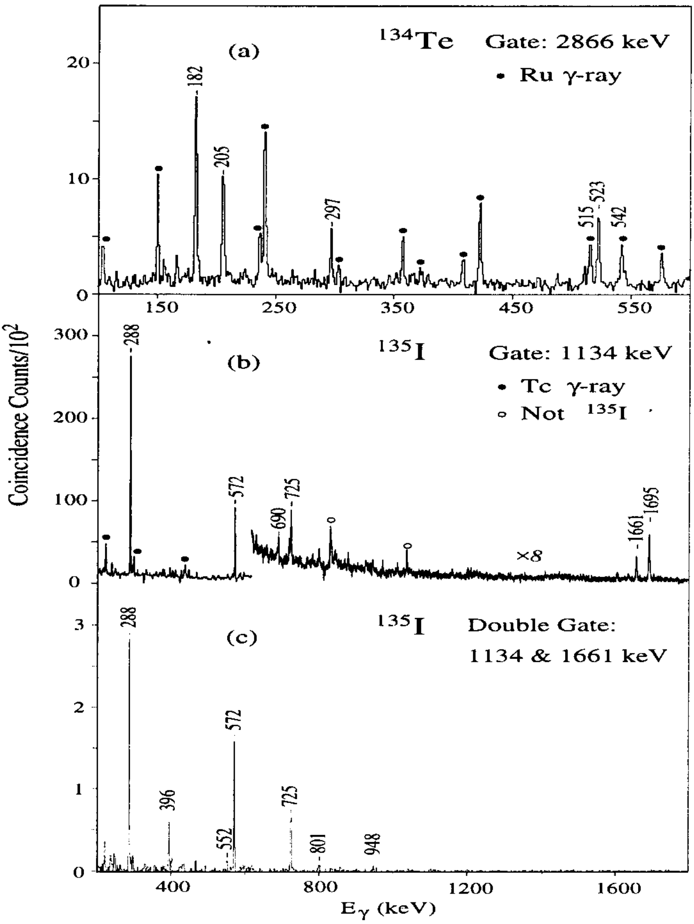

Fig. 1. (a),(b),(c): Representative examples of key γ-ray coincidence spectra. Only ^{134}Te and ^{135}I γ-rays are labelled with energies. The 297 keV ^{134}Te γ-ray appears with diminished intensity in Fig. 1(a) because of the 164 ns 6^+ isomer in that nucleus.

In the present work, we started a search for other ^{135}I transitions by setting a single coincidence gate on 1134 keV γ-rays (Fig. 1(b)). Strong 288, 572, 690, 725, 1661, 1695 and 2247 keV coincident γ-rays were identified, and by generating a series of double gated γ-ray spectra including these transitions, they were all confirmed as ^{135}I γ-rays. Other peaks in Fig. 1(b) were found to arise from fission partner Tc nuclei or from extraneous contaminants. A compilation of many doubly gated γ-ray spectra, such as the one shown in

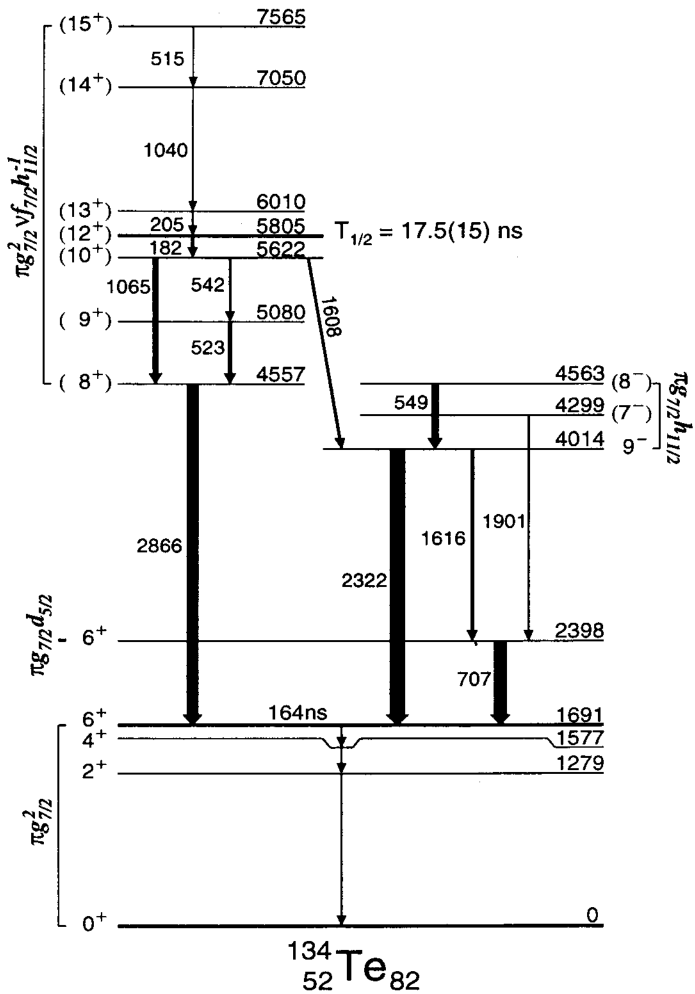

Fig. 2. The ^{134}Te yrast levels established from ^{248}Cm fission γ-ray coincidences. Widths of the transition arrows are proportional to the observed γ-ray intensities, except for transitions below the 164 ns isomer in ^{134}Te. Configuration assignments are also shown.

Fig. 1(c), then established the ^{135}I level scheme presented in Fig. 3. Since no information about transition multipolarities was derived from the data, the spin-parity assignments and the interpretation of the ^{135}I levels below 4 MeV as $\pi g^3_{7/2}$, $\pi g^2_{7/2}d_{5/2}$ and $\pi g^2_{7/2}h_{11/2}$ states are based in part on the results of the shell model calculations described below. It is no surprise that the yrast excitations of ^{135}I are found to resemble closely those of the other three-proton nucleus ^{211}At, which has low-lying states of $\pi h^3_{9/2}$, $\pi h^2_{9/2} f_{7/2}$ and $\pi h^2_{9/2} i_{13/2}$ character.

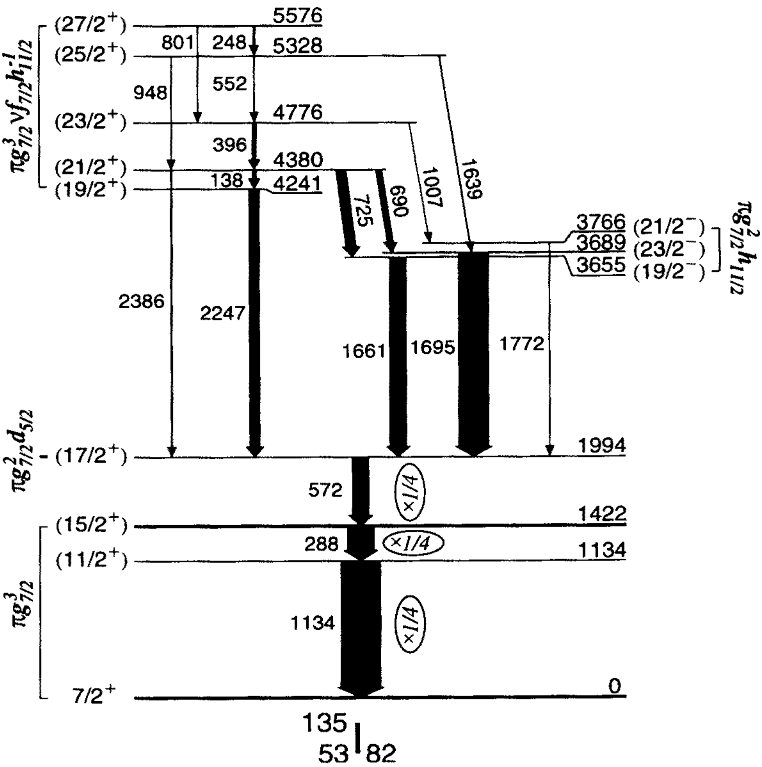

Fig. 3. The yrast states established for ^{135}I(*c.f.* caption to Fig. 2). For three low-lying transitions, the fractional numbers in the ellipsoids indicate that their observed γ-ray intensities are four times larger than shown in the figure.

Many years ago, John *et al.* [9] studied γ-rays emitted in isomeric decays of ^{252}Cf fission fragments, and there is some overlap between their findings and ours. In retrospect, the 182.4 keV γ-ray de-exciting an $A = 134$ 15 ns isomer and the 288.5 keV γ-ray de-exciting an $A = 136$ or 135 3 ns isomer, as reported in Ref. [9], are almost certainly identical to the ^{134}Te $12^+ \rightarrow 10^+$ and ^{135}I $15/2^+ \rightarrow 11/2^+$ transitions placed in Fig. 2 and Fig. 3. In the recent experiment [10] at GAMMASPHERE array, the yrast states of ^{134}Te were weakly populated in the deep-inelastic reaction of ^{232}Th thick-target bombarded with 833 MeV ^{136}Xe, and the half-life of 12^+ yrast isomer was determined to be 17.5(15) ns, from the time distribution of 182 keV and 1065 keV transitions with respect to the cyclotron beam bursts.

4. Shell model analysis

The energies of $\pi g^3_{7/2}$, $\pi g^2_{7/2}d_{5/2}$ and $\pi g^2_{7/2}h_{11/2}$ states in ^{135}I were calculated with nucleon-nucleon interactions taken directly from the ^{134}Te level spectrum, where the few missing matrix elements of $\pi g_{7/2}$-$\pi h_{11/2}$ interactions could be estimated accurately. The results for ^{135}I agree satisfactorily with experiment (Table I),

TABLE I

A comparison of ^{135}I yrast level energies below 4 MeV with those calculated for the specified three-proton states using empirical proton-proton interactions taken from ^{134}Te. Calculated energies are normalized to match the experimental value of 1422 keV for the aligned $(\pi g^3_{7/2})$ 15/2$^+$ state. As noted in text, our interpretation of the experimental levels is largely based on the energy comparison shown here.

Confign.	I^π	Ex(keV) Exp.	Ex(keV) Calc.
$\pi g^3_{7/2}$	7/2$^+$	0	−26
	9/2$^+$	1184	1149
	11/2$^+$	1134	1089
	15/2$^+$	1422	1422
$\pi g^2_{7/2}d_{5/2}$	17/2$^+$	1994	2089
$\pi g^2_{7/2}h_{11/2}$	19/2$^-$	3655	3704
	21/2$^-$	3766	3753
	23/2$^-$	3689	3687

although the agreement is not quite as good as similar calculations for ^{211}At excitations based on two proton interactions from ^{210}Po. However, we have found that in both ^{135}I and ^{211}At, the remaining discrepancies between calculated energies and experiment can be removed by allowing a moderate amount of configuration mixing. Since a high-lying $(\pi h^3_{11/2})$ 27/2$^-$ state (close to 7 MeV) is the only expected three-proton excitation with $I > 23/2$, the sequence of levels above 4241 keV in ^{135}I must involve core excitations, and we naturally interpret them as $\pi g^3_{7/2}\nu f_{7/2}h^{-1}_{11/2}$ states directly related to the core-excited states in ^{134}Te above 4.5 MeV. Particle-hole states of $\nu f_{7/2}h^{-1}_{11/2}$ character having I^π=2$^+$ to 8$^+$ are known [1] in ^{132}Sn in the 4–5 MeV energy range; their energies (together with estimates for two missing multiplet members) provided some of the two-body interactions needed for calculating $\pi g^n_{7/2}\nu f_{7/2}h^{-1}_{11/2}$ states. In addition, $\pi g_{7/2}\nu h^{-1}_{11/2}$ and $\pi g_{7/2}\nu f_{7/2}$ interactions were also needed, but since ^{132}Sb and ^{134}Sb excitations are still poorly known, these matrix elements had to be estimated from the $\pi h_{9/2}\nu i_{13/2}^{-1}$ and $\pi h_{9/2}\nu g_{9/2}$ multiplets in ^{208}Bi and ^{210}Bi, respectively, with scaling as $A^{-1/3}$ to take account of nuclear size variation [2]. Calculations of $\pi g_{7/2}^{n}\nu f_{7/2}h_{11/2}^{-1}$ energies were performed using the angular momentum recoupling part of OXBASH shell model code [11, 12], with no adjustment of input parameters to fit the data. The results are displayed in Fig. 4 with the calculated energies normalized to 6010 keV for the ^{134}Te 13^{+} level, and to 5576 keV for the ^{135}I $27/2^{+}$ level. The excellent overall agreement with experiment in both cases provides persuasive support for the proposed interpretations. It is apparent that, while lower spin $\pi g_{7/2}^{n}\nu f_{7/2}h_{11/2}^{-1}$ levels are available in the two $N = 82$ nuclei, they receive negligible population because the yrast 8^{+} and $19/2^{+}$ states both de-excite preferentially by favorable > 2 MeV transitions.

The shell model calculations described above yielded relative excitation energies only, because the appropriate ground state nuclear masses were not included in the supplied input, for reasons that will become obvious. Mezilev *et al.* [4] recently revised the Audi-Wapstra 1993 masses [13] for nuclei around ^{132}Sn by precision β-decay endpoint determinations; updated mass excesses for the $N = 82$ isotones ^{132}Sn, ^{133}Sb, ^{134}Te, and ^{135}I are $-76.620(29)$, $-78.984(32)$, $-82.399(34)$, and $-83.787(23)$ MeV [4, 13]. The present results enabled us to check the consistency of these $N = 82$ mass values by shell model reduction techniques [14]. The aligned $\pi g_{7/2}^{3}$ $15/2^{+}$ state in ^{135}I may be decomposed into simpler configurations with fewer valence particles, which correspond to known levels in ^{134}Te (4^{+}, 6^{+}), ^{133}Sb ($7/2^{+}$) and ^{132}Sn (0^{+}). As previously shown for similar decompositions [14, 15], a mass "window" W, comprising a specific combination of $N = 82$ ground state masses, can thus be related to experimental energies by the equation:

$$\begin{aligned} W &= M(^{132}\mathrm{Sn}) - 3M(^{133}\mathrm{Sb}) + 3M(^{134}\mathrm{Te}) - M(^{135}\mathrm{I}) \\ &= E(15/2^{+}) - 3\,(\mathrm{c.f.p.})^{2}\,E(4^{+},\,6^{+})\,. \end{aligned} \quad (1)$$

Here, the excitation energy $E(15/2^{+})$ in ^{135}I is 1422 keV, and $E(4^{+}, 6^{+})$ are energies of $\pi g_{7/2}^{2}$ states in ^{134}Te, weighted by appropriate coefficients of fractional parentage (c.f.p.). The result from spectroscopy is $W = -3570$ keV. This differs by almost 500 keV from the value $W = -3080(150)$ keV obtained directly from the $N = 82$ masses given above. [In contrast, for the analogous mass window in the $N = 126$ isotones, the W value from decomposition of the ^{211}At $\pi h_{9/2}^{3}$ $21/2^{-}$ state agrees <u>within 5 keV</u> with the one computed from Audi-Wapstra masses]. We are forced to the conclusion that

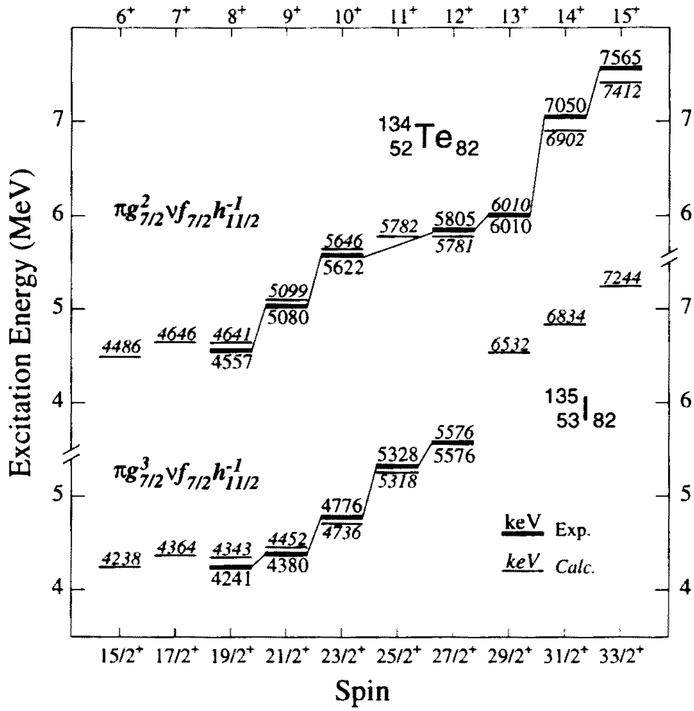

Fig. 4. A comparison of observed levels energies in ^{134}Te and ^{135}I with those calculated for $\pi g^{n}_{7/2} \nu f_{7/2} h^{-1}_{11/2}$ yrast states using empirical nucleon-nucleon interactions. The calculated energies are normalized to match the experimental 13^{+} 6010 keV level in ^{134}Te and $27/2^{+}$ 5576 keV level in ^{135}I. In both nuclei, the experimental levels are connected to guide the eye.

one or more of the accepted $N = 82$ masses is inaccurate by considerably more than the estimated errors. The ^{134}Te and/or ^{133}Sb masses appear the most likely suspects since they are weighted heavily in the W expression: possibly the β-decay schemes adopted for these nuclei may not be entirely correct.

5. Summary

In summary, neutron-rich fission product nuclei around doubly magic ^{132}Sn have now become accessible for detailed study by prompt γ-ray measurements using multidetector arrays. Yrast excitations to above 5.5 MeV excitation energy in the two- and three-proton nuclei ^{134}Te and ^{135}I have been established and interpreted with the help of precise shell model calculations using empirical nucleon-nucleon interactions. These results open possibilities for exploring simple excitation modes in the ^{132}Sn region under conditions that are comparable with but not identical to those in the well-studied ^{208}Pb region.

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