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One-neutron transfer study of ^{135}Te and ^{137}Xe by particle-γ coincidence spectroscopy: The $\nu 1i_{13/2}$ state at $N = 83$

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Additional information is reported on single-neutron states above the doubly closed-shell nucleus ^{132}Sn. A radioactive ion beam of ^{134}Te($N = 82$) at 565 MeV and a stable ion beam of ^{136}Xe($N = 82$) at 560 MeV were used to study single-neutron states in the $N = 83$ nuclei ^{135}Te and ^{137}Xe, respectively, by (^{13}C, ^{12}Cγ) and (^{9}Be, ^{8}Beγ) direct reactions in inverse kinematics. Particle-γ and particle-γ-γ coincidence measurements using CsI and HPGe arrays allowed determination of decay paths, high-precision level energies, multipolarities of transitions, and relative cross sections. One-neutron transfer with heavy ions is employed to gain selectivity to both low- and high-spin single-neutron states above the $N = 82$ shell closure. Results are presented for the $13/2^+_1$ states in the $N = 83$ nuclei ^{135}Te and ^{137}Xe at 2108.8(9) keV and 1752.6(3) keV, respectively, and for the 3^-_1 collective octupole state observed at 3749(5) keV in ^{134}Te($N = 82$) inelastic scattering, all previously unknown. While the $13/2^+_1$ state (or $\nu 1i_{13/2}$ centroid) in ^{133}Sn($Z = 50$, $N = 83$) remains unknown, the present results provide the best empirical prediction of its energy available to date.

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The nuclear shell model is the leading foundational model of nuclear physics and it predicts a particular number of single-particle and single-hole states outside of each closed proton and/or neutron shell. Experimental energies of single-particle, single-hole, and core-excited states not only challenge microscopic calculations but also serve as empirical input to more realistic calculations and enable one to infer the nature of nucleon-nucleon interactions. While the single-particle, single-hole, and core-excited states near the light (^{16}O, ^{40}Ca) and heavy (^{208}Pb) double-magic nuclei are well known [1], those in the radioactive ^{132}Sn($Z = 50$, $N = 82$) region remain incomplete. With the advent of radioactive ion beams (RIBs), the study of nuclei far from stability, particularly with respect to shell closures, has become a topic of high interest. In this Rapid Communication, experimental results are presented for the $13/2^+_1$ states (i.e., $\nu 1i_{13/2}$ candidates) in the $N = 83$ nuclei ^{135}Te and ^{137}Xe. Results are also presented for the 3^-_1 collective octupole state observed in ^{134}Te($N = 82$) inelastic scattering.

Many of the known levels in the radioactive and double-magic ^{132}Sn region have been determined from β-decay and/or prompt γ-ray studies of actinide fission products (e.g., Refs. [2–7]), which do not offer any particular selectivity to single-particle states. Recently, ^{132}Sn(d, p)^{133}Sn [8], and ^{134}Te(d, p)^{135}Te [9] studies in inverse kinematics have been executed but the momentum matching for $\ell = 6$ transfer did not favor population of the $1i_{13/2}$ single-neutron state with any significant cross section. While the $2f_{7/2}$, $3p_{3/2}$, $3p_{1/2}$, $2f_{5/2}$, and $1h_{9/2}$ systematics are known for the $N = 83$ nuclei at, near, and above ^{133}Sn [1], the $1i_{13/2}$ systematics are incomplete. The $1h_{9/2}$ systematics can also be considered incomplete in that they have never been observed in ^{133}Sn or ^{135}Te by a direct reaction. The $1i_{13/2}$ systematics for the $N = 83, 56 \leqslant Z \leqslant 70$ nuclei are well established in the literature [1]. They are also known to mix with the $13/2^+$, $3^- \otimes 2f_{7/2}$ multiplet member [10–19], which means the observed $13/2^+_1$ energy is different from the unmixed single-neutron energy, $\epsilon_{\text{s.p.}}(1i_{13/2})$. This makes determination of experimental energies in nuclei closer to $Z = 50$ all the more important.

One-neutron transfer is employed here in conjunction with particle-γ coincidence spectroscopy, using (^{13}C, ^{12}Cγ) and (^{9}Be, ^{8}Be$\rightarrow 2\alpha\gamma$) direct reactions in inverse kinematics ($A_{\text{beam}} > A_{\text{target}}$), to gain selectivity to the single-neutron states above the $N = 82$ shell closure. Because ^{8}Be is unbound ($T_{1/2} = 8.2 \times 10^{-17}$ s [1]), two correlated αs are detected. Scattered target nuclei were measured at forward laboratory angles relative to the beam direction (corresponding

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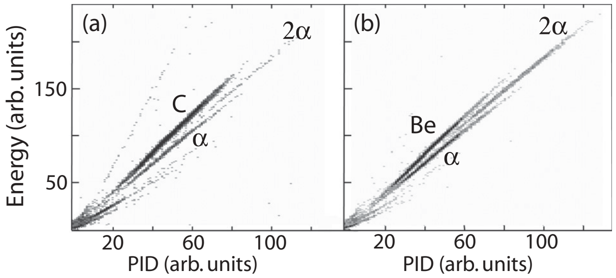

FIG. 1. CsI particle identification (PID) maps from the ^{134}Te RIB experiment, where the PID parameter on the x axis is established by integrating the tail of the energy signal (cf. Ref. [26]). (a) ^{13}C target data. (b) ^{9}Be target data.

to backward angles in the center-of-mass frame) to provide a clean trigger for selecting the γ-ray transitions emitted from the beamlike reaction products. The ^{13}C target, with a $\nu 1p_{1/2}$ ($J_< = l - 1/2$) ground state, and the ^{9}Be target, with a $\nu 1p_{3/2}$ ($J_> = l + 1/2$) ground state, provide different selective populations of single-neutron states (cf. Ref. [20] for a discussion on selective populations of high-J states with heavy-ion reactions). The difference in ground-state Q values for one-neutron transfer reactions on these two targets provide further differences in selectivity; this provides a mechanism for assigning observed levels to specific single-neutron configurations. Preliminary results have been reported using this technique in Refs. [21–25].

A ^{134}Te RIB at 565 MeV was used on two targets: a ^{13}C target with a thickness of 1.2 mg/cm^2 and a ^{9}Be target with a thickness of 2.37 mg/cm^2. The ^{134}Te RIB provided by the Holifield Radioactive Ion Beam Facility (HRIBF) had an intensity of approximately 3×10^5 ions/s. Recoiling target nuclei were detected in the "bare" HyBall (BareBall) array [26] (cf. Fig. 1) using the first four rings (laboratory angles 7°–14°, 14°–28°, 28°–44°, and 44°–60°, relative to the beam direction, with 6, 10, 12, and 12 CsI(Tl) crystals, respectively). Coincident γ rays were detected by 11 HPGe segmented clover detectors of the CLARION array [27] (cf. Fig. 2) at angles of 90°(5 clovers), 132°(4 clovers), and 154°(2 clovers) at a distance of 21.75 cm from the target with a total efficiency of 2.94(5)% at 1 MeV. The left, middle, and right side channels of these segmented clover detectors were used to effectively give 8 segments per clover (2×4 "leaves"). The experimental trigger required either a scaled-down particle singles event or a particle-γ coincidence event.

In a second experiment, a stable ^{136}Xe beam at 560 MeV was used on two targets: a ^{13}C target with a thickness of 1 mg/cm^2 and a ^{9}Be target with a thickness of 1.25 mg/cm^2. The Gammasphere [28] and Microball [29] arrays were used for this experiment at the Argonne Tandem Linear Accelerator System (ATLAS) facility.

From the $N = 83$ systematics [1], the most likely decay path (i.e., the only $E1$ or/and $E2$ path) of the $13/2_1^+$ state to the $7/2_1^-$ ground state for the ^{135}Te and ^{137}Xe nuclei is through the $11/2^-, 2^+ \otimes 2f_{7/2}$ states at 1179.88(9) keV and 1220.07(15) keV, respectively. These $11/2^-$ states are well known in both ^{135}Te and ^{137}Xe from their part in a $15/2^- \rightarrow 11/2^- \rightarrow 7/2^-$ yrast transition sequence following de-excitation of an $19/2^-$

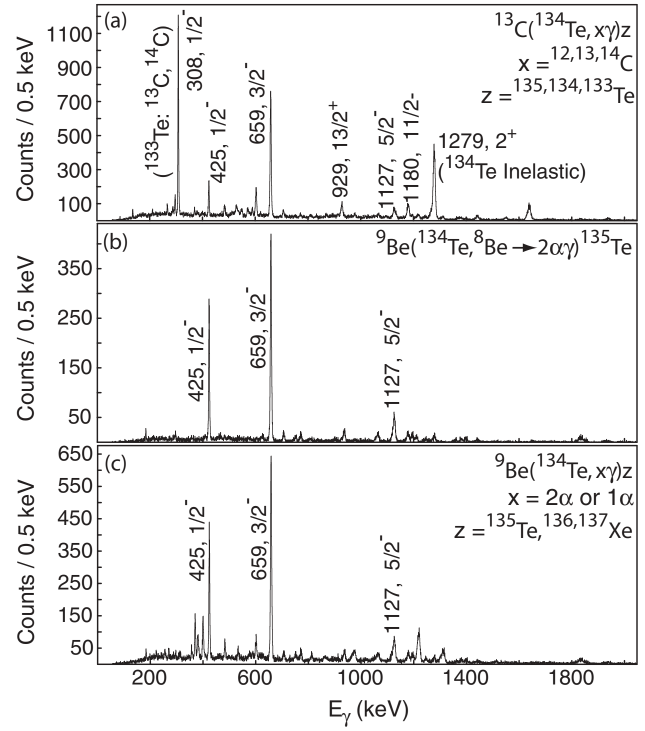

FIG. 2. The particle-gated γ-ray spectra related to ^{135}Te from the ^{134}Te RIB experiment. The gating conditions and residual nuclei are indicated in the figure and the peak labels, unless stated otherwise, pertain to transitions in ^{135}Te.

isomer [1,7,30–33]. Carbon-gated γ-γ coincidence data from the ^{13}C(^{134}Te,^{12}C$\gamma\gamma$)^{135}Te and ^{13}C(^{136}Xe,^{12}C$\gamma\gamma$)^{137}Xe direct reactions are shown in Figs. 3 and 4, respectively. Figure 3 shows a strong 928.9(9)-keV γ-ray transition in coincidence with the $11/2^-, 2^+ \otimes 2f_{7/2}$ state of ^{135}Te; the 929-keV γ ray

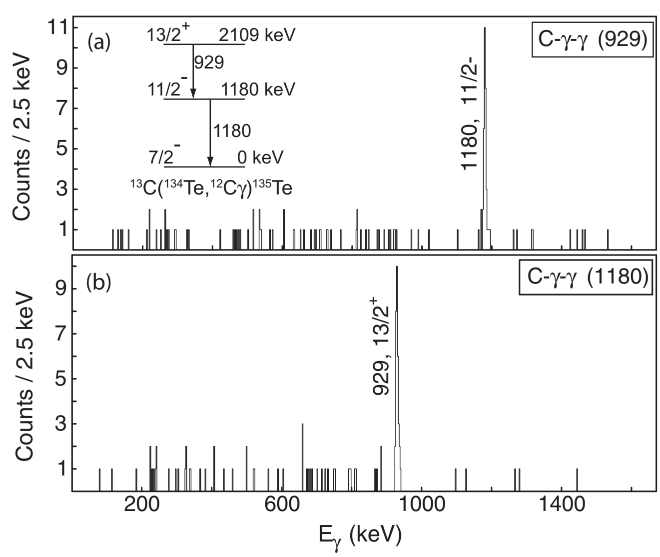

FIG. 3. The carbon-gated γ-γ coincidence data from the ^{13}C(^{134}Te,^{12}C$\gamma\gamma$)^{135}Te direct reaction shows 1180- and 929-keV γ rays in coincidence with each other. The 1180-keV γ ray decays from the previously known $11/2^-, 2^+ \otimes 2f_{7/2}$ state at 1179.88(9) keV [1].

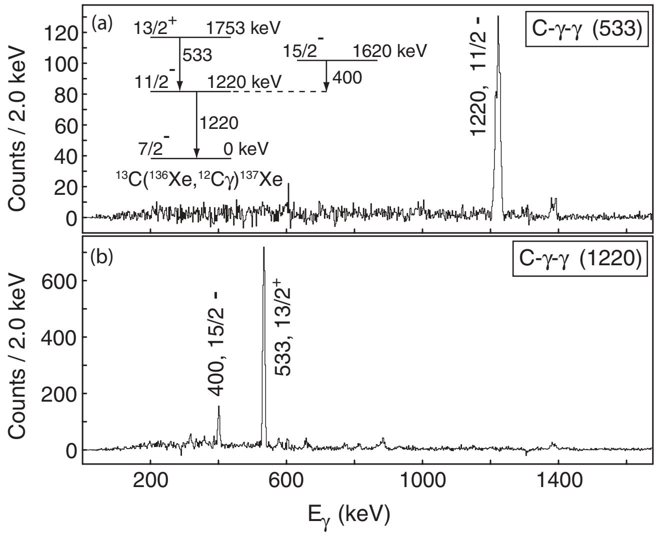

FIG. 4. The carbon-gated γ-γ coincidence data from the ^{13}C(^{136}Xe,^{12}C$\gamma\gamma$)^{137}Xe direct reaction shows 1220- and 533-keV γ rays in coincidence with each other; a narrow 533-keV gate is used to remove leakage of neighboring γ-ray transitions. The 1220-keV γ ray decays from the previously known $11/2^-, 2^+ \otimes 2f_{7/2}$ state at 1220.07(15) keV [1]. The 400-keV γ ray is the previously known $15/2^- \rightarrow 11/2^-$ yrast transition [1,7,30–32].

originates from a state at 2108.8(9) keV. Figure 4 shows a strong 532.5(3)-keV γ-ray transition in coincidence with the $11/2^-, 2^+ \otimes 2f_{7/2}$ state of ^{137}Te; the 533-keV γ ray originates from a state at 1752.6(3) keV.

The 2108.8(9) and 1752.6(3) keV states in ^{135}Te and ^{137}Xe, respectively, are likely the $13/2^+_1$ states (i.e., $1i_{13/2}$ candidates). Recently, a $13/2^+$ state in ^{137}Xe has been reported in an inverse kinematics $(d,p)^{137}$Xe study (particles only, no γ rays) by Kay *et al.* [34]; they report a weak $\ell = 6$ transfer component at ∼1751 keV with a spectroscopic factor of 0.84. This identification, as acknowledged by the authors in Ref. [34], was guided by preliminary results of the present study through a private communication. The excitation energy is reported here with high precision (in combination with the selectivity of a direct reaction). The level is identified as a previously observed but unassigned level in the β decay of ^{137}I$(7/2^+)$ [35], which reported a 532.49(10)-keV γ ray from a 1752.56(15)-keV level [cf. the present value of 1752.6(3) keV] in coincidence with a 1220.07(15)-keV γ ray.

A $13/2^+$ assignment of a level decaying to an $11/2^-$ state suggests an $E1$ decay. Figure 5 shows the particle-γ $\Delta\phi$ angular correlations for three different decays: (a) a stretched $E2$ decay from the Coulomb excitation of 2^+_1 in ^{134}Te and subsequent $2^+_1 \rightarrow 0^+_1$ decay, (b) a relatively isotropic $E2$ decay from the direct and indirect population of the $3/2^-_1$ level and subsequent decay to the $7/2^-$ ground state, and (c) a nonisotropic decay from the direct population of a level at 2108.8(9) keV and subsequent decay to the $11/2^-_1$ state. The particle-γ angular correlation, cf. Fig. 5(c), is consistent with an $E1$ decay and a $13/2^+$ assignment; a $M1$ decay and $13/2^-$ assignment are also consistent but very unlikely since no $13/2^-$ state is expected to be strongly populated in these direct reactions.

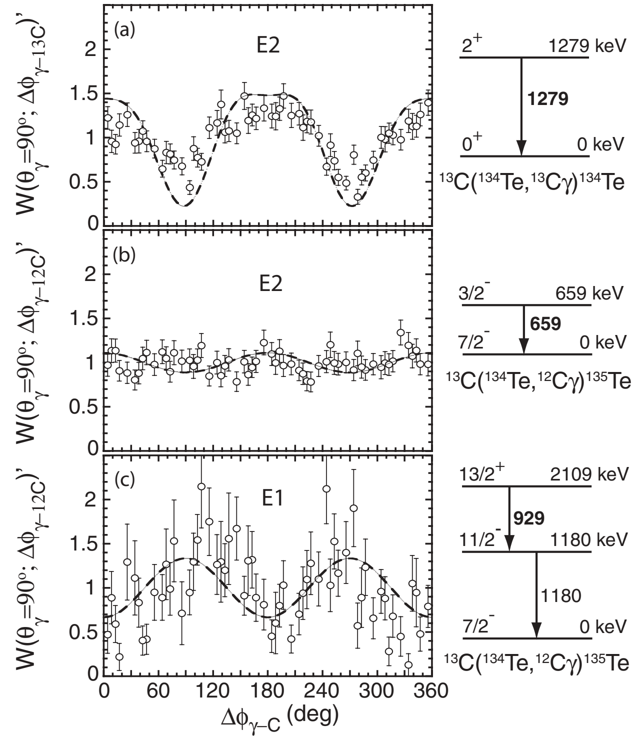

FIG. 5. The carbon-γ $\Delta\phi$ angular correlations, $W(\theta_\gamma,\theta_C;\Delta\phi_{\gamma-C})' = W(\theta_\gamma,\theta_C;\Delta\phi_{\gamma-C})/W(\theta_\gamma,\theta_C)$, where $\theta_C = 28^\circ$ to 60° and $\theta_\gamma = 90^\circ$ in the laboratory frame, show (a) a stretched $E2$ decay, (b) a relatively isotropic $E2$ decay, and (c) a stretched $E1$ decay. The dashed curves were calculated (cf. Ref. [36]) assuming full alignment.

A summary of previously unknown levels and γ-ray energies which are observed in the present study is given in Table I. In addition to the $13/2^+_1$ levels in ^{135}Te and ^{137}Xe, levels at 1854.8(8), 2021.5(10), and 2483.2(12) keV in ^{135}Te are reported (cf. Fig. 6 for their γ-ray transitions).

TABLE I. Levels and γ-ray energies from particle-γ-γ coincidence measurements which were previously unknown.

E_x (keV)	J^π	E_γ (keV)	I_γ^{branch}	E_f (keV)[a]	J_f^π [a]
134Te					
3749(5)	(3^-)	2470(5)[b]	100	1279.11(10)	2^+
135Te					
1854.8(8)	$1/2^\pm, 3/2^\pm, 5/2^-$	772.1(9)	58(5)	1083.3(4)	$(\frac{1}{2}^-)$
		1195.7(9)	100(7)	658.65(10)	$(\frac{3}{2}^-)$
2021.5(10)	$1/2^\pm, 3/2^\pm, 5/2^-$	938.2(9)	100	1083.3(4)	$(\frac{1}{2}^-)$
2108.8(9)	$(13/2^+)$	928.9(9)	100	1179.88(9)	$(\frac{11}{2}^-)$
2483.2(12)	$1/2^\pm, 3/2^\pm, 5/2^-$	1399.9(11)	100	1083.3(4)	$(\frac{1}{2}^-)$
137Xe					
1752.6(3)[c]	$(13/2^+)$	532.5(3)[c]	100	1220.07(15)	$(\frac{11}{2}^-)$

[a]Taken from the literature [1].
[b]Strongly observed in γ-ray singles spectrum as 2467.5(8) keV but could be contaminated with $E_\gamma(2^+_2 \rightarrow 0^+_1) = 2465.3(2)$ keV [1].
[c]Exists in the literature [1] as an unassigned state from ^{137}I decay [35] with $E_x = 1752.56(16)$ keV and $E_\gamma = 532.49(10)$ keV.

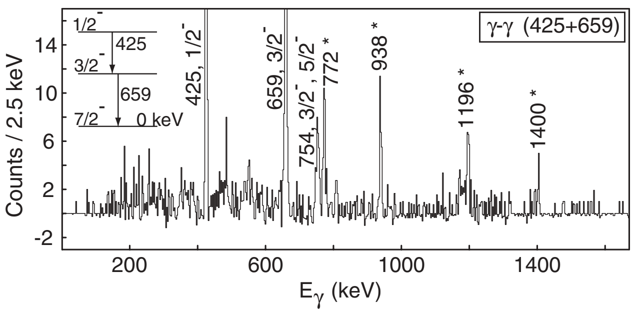

FIG. 6. The 425 + 659-keV γ-gated γ-ray spectrum of ^{135}Te from the sum of the carbon and beryllium target data show four transitions (marked by asterisks). The 1196-keV transition is observed only in the 659-keV gate component.

These levels are likely members of multiplets expected from single-neutron-core coupling. The spin assignments of these levels assume $E1$, $M1$, or $E2$ decay; the statistics of these states are too low to determine multipolarities through particle-γ angular correlations. More importantly, the 3_1^- collective octupole excitation at 3749(5) keV in ^{134}Te is observed; cf. Fig. 7. The (^{13}C, ^{13}C′) and (^{9}Be, ^{9}Be′) inelastic scattering channels are highly selective of 2_1^+ quadrupole and 3_1^- octupole states [13,14]. Indeed, the 3_1^- decay to the 2_1^+ level is the second strongest γ-ray transition in the ^{134}Te and ^{136}Xe inelastic-scattering channels; the 3_1^- level in ^{136}Xe was previously known in the literature [1]. The observation of the 3_1^- level in ^{134}Te completes the systematics for $N = 82$, $50 \leqslant Z \leqslant 72$ nuclei and the observation of $13/2_1^+$ in ^{135}Te and ^{137}Xe completes the systematics for all but ^{133}Sn of the $N = 83$, $50 \leqslant Z \leqslant 70$ nuclei.

The relative cross sections are deduced by performing an intensity balance (i.e., total intensity out of a level less the total intensity feeding that level, $\sigma^{\rm rel} \approx \Sigma I_{\rm out} - \Sigma I_{\rm in}$) and normalization to the $3/2_1^-$ level ($3p_{3/2}$ candidate); unobserved side feeding could reduce the accuracy of this method. Absolute cross sections can be obtained by normalizing to Rutherford scattering, but this was not possible in the present study due to the fact that scattered particles were only measured at "nonsafe" backward center-of-mass angles. The relative cross sections are compared to distorted wave Born approximation (DWBA) calculations performed with the finite-range PTOLEMY code [37], assuming a one-step process and pure single-neutron configurations.

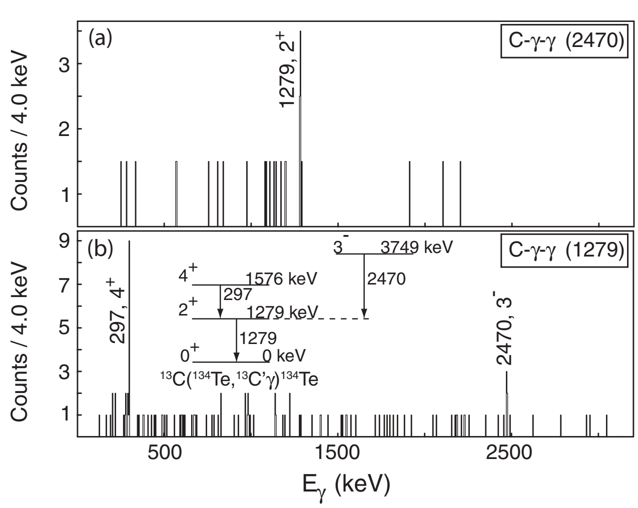

FIG. 7. The carbon-gated γ-γ coincidence data from ^{13}C(^{134}Te,^{13}C′$\gamma\gamma$)^{134}Te inelastic scattering shows 1279- and 2470-keV γ rays in coincidence with each other.

The $1i_{13/2}$ cross section for the (^{13}C, ^{12}C) reaction is expected to be large compared to the (^{9}Be, ^{8}Be) reaction. The $13/2_1^+$ to $3/2_1^-$ cross-section ratio in ^{135}Te is measured as 0.238(12) (cf. 0.294 from DWBA calculations) for the (^{13}C, ^{12}C) reaction but only 0.046(10) (cf. 0.054 from DWBA calculations) for the (^{9}Be, ^{8}Be) reaction; a $13/2_1^+, 0^+ \otimes 1i_{13/2}$ assignment is supported by the DWBA calculations. A summary of the experimental and calculated relative cross sections for the ^{13}C(^{134}Te,^{12}C)^{135}Te and ^{9}Be(^{134}Te,^{8}Be)^{135}Te reactions are given in Table II. The measured and calculated relative cross sections are in fairly good agreement for the carbon target data but not for the beryllium target data, which could be, in part, due to significant two-step processes from Coulomb excitation, unobserved side feeding, and/or breakup. Preliminary results from a recent $(d, p)^{135}$Te study [9] report a $2f_{5/2}$ candidate at ≈1.8 MeV. While the present data are more consistent with the predominant $2f_{5/2}$ component being located at 1127 keV, which is also the adopted assignment in the literature [1], the present data are not inconsistent with a strong $2f_{5/2}$ component at 1837 and/or 1855 keV. A future report of spectroscopic factors from the recent (d, p) study [9] or a future $(d, p\gamma)$ study may be able to clarify this further.

The $7/2_1^-$ ($N = 83$), $13/2_1^+$ ($N = 83$), and 3^- ($N = 82$) core-excited octupole systematics from the present study and literature [1] are shown in Fig. 8. The $13/2_1^+$ level in ^{133}Sn is the only outstanding unknown, which was predicted [6]

TABLE II. Measured relative cross sections and DWBA calculations (see text) for the one-neutron transfer study of ^{135}Te.

E_x	J^π	^{13}C(^{134}Te,^{12}C)^{135}Te		^{9}Be(^{134}Te,^{8}Be)^{135}Te	
		$\sigma^{\rm rel}$	DWBA[a]	$\sigma^{\rm rel}$	DWBA[a]
0.00	$7/2^-$		1.391		0.333
658.65(10)	$3/2^-$	1.000(21)	1.000	1.000(58)	1.000
1083.3(4)	$1/2^-$	0.145(11)	0.185	0.478(39)	0.832
1127.06(8)	$5/2^-$	0.153(52)	0.152	0.436(39)	0.711
1179.88(9)	$11/2^-$	0.095(20)		0.190(20)	
1246.18(10)	$9/2^-$	0.035(8)	0.018	0.085(10)	0.108
1380.14(9)	$(7/2^-, 9/2)$	0.056(7)		0.106(12)	
1442.22(10)		0.129(9)		0.078(10)	
1837.19(10)	$(3/2^-, 5/2^-)$	0.064(8)	(0.152)[b]	0.478(42)	(0.711)[b]
1854.8(8)[c]		0.083(8)	(0.152)[b]	0.302(19)	(0.711)[b]
2017.88(15)				0.192(17)	
2021.5(10)[c]				0.185(18)	
2108.8(9)[c]	$13/2^+$	0.238(12)	0.294	0.046(10)	0.057
2193.80(13)		0.084(9)		0.157(19)	
2339.07(22)				0.131(13)	
2483.2(12)[c]		0.029(5)		0.116(14)	

[a]Calculated for $2f_{7/2}$, $3p_{3/2}$, $3p_{1/2}$, $2f_{5/2}$, $1h_{9/2}$, and $1i_{13/2}$.
[b]Preliminary $(d, p)^{135}$Te results [9] report $2f_{5/2}$ at ≈ 1.8 MeV.
[c]Level energies from present study; other energies from Evaluated Nuclear Structure Data File [1].

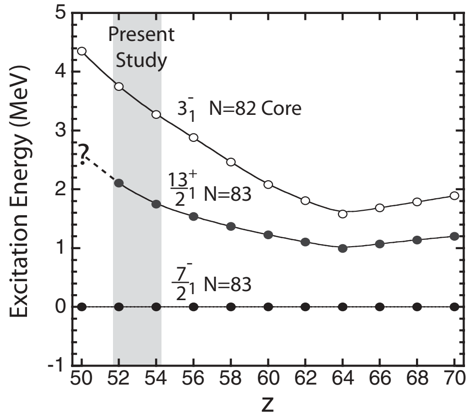

FIG. 8. The $7/2^-_1$ ($N = 83$), $13/2^+_1$ ($N = 83$), and 3^- ($N = 82$) core-excited octupole systematics from the present study and literature [1].

to be unbound at an excitation energy of 2694 keV (the neutron-separation threshold is $S_n = 2370(24)$ [1]); this is consistent with the extrapolated systematics in Fig. 8, which now include the ^{135}Te and ^{137}Xe data. The $1i_{13/2}$ single-neutron states are known to mix with the $13/2^+$ member of the $3^- \otimes 2f_{7/2}$ multiplet [10–19,34], which means the observed $13/2^+_1$ energy is different from the unmixed single-neutron energy, $\epsilon_{\rm s.p.}(1i_{13/2})$. The presence of this mixing, as evident in Fig. 8, highlights the importance in obtaining the experimental energies in nuclei closer to $Z = 50$, such as ^{135}Te and ^{137}Xe.

The higher lying $13/2^+$ member of the $3^- \otimes 2f_{7/2}$ multiplet is not known or observed in the present study, which makes an empirical determination of the unmixed single-neutron energy, $\epsilon_{\rm s.p.}(1i_{13/2})$, and the two-state mixing strength out of reach for ^{135}Te and ^{137}Xe. A future experiment with higher statistics could resolve this. Lifetime or g-factor measurements of the first $13/2^+$ state would be of similar value [11,12] in determining the two-state mixing strength and unmixed single-neutron energy, as would spectroscopic factors from a (d, p) reaction study. Nevertheless, the present data provide valuable constraints on the unmixed $1i_{13/2}$ single-neutron energy.

In summary, the $13/2^+_1$ state ($1i_{13/2}$ candidate) in ^{135}Te($Z = 52$, $N = 83$) and the 3^-_1 collective octupole state in ^{134}Te($Z = 52$, $N = 82$) have been observed by using a ^{134}Te RIB with ^{13}C and ^{9}Be targets. Furthermore, the $13/2^+_1$ state in ^{137}Xe ($Z = 54$, $N = 83$) has been identified with high-precision energy. These results were achieved by employing particle-γ coincidence spectroscopy with CsI-HPGe arrays; this technique provides an invaluable tool for future direct-reaction studies of RIBs in inverse kinematics. While the $13/2^+_1$ state (or $1i_{13/2}$ centroid) in ^{133}Sn ($Z = 50$, $N = 83$) remains unknown, the present results provide the best empirical measure of its energy available to date and a path towards a more complete determination in the future.

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