One-neutron transfer study of $^{135}\text{Te}$ and $^{137}\text{Xe}$ by particle-$\gamma$ coincidence spectroscopy: The $\nu1i_{13/2}$ state at $N = 83$

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Additional information is reported on single-neutron states above the doubly closed-shell nucleus $^{132}\text{Sn}$. A radioactive ion beam of $^{134}\text{Te}(N = 82)$ at 565 MeV and a stable ion beam of $^{136}\text{Xe}(N = 82)$ at 560 MeV were used to study single-neutron states in the $N = 83$ nuclei $^{135}\text{Te}$ and $^{137}\text{Xe}$, respectively, by ($^{13}\text{C},^{12}\text{C}\gamma$) and ($^{8}\text{Be},^{8}\text{Be}\gamma$) direct reactions in inverse kinematics. Particle-$\gamma$ and particle-$\gamma$-$\gamma$ coincidence measurements using CsI and HPGe arrays allowed determination of decay paths, high-resolution 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 $^{135}\text{Te}$ and $^{137}\text{Xe}$ at 2108.8(9) keV and 1752.6(3) keV, respectively, and for the $31/2^+_{1}$ collective octupole state observed at 3749(5) keV in $^{134}\text{Te}(N = 82)$ inelastic scattering, all previously unknown. While the $13/2^+_{1}$ state (or $\nu1i_{13/2}$ centroid) in $^{135}\text{Sn}(Z = 50, N = 83)$ 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 ($^{16}\text{O}$, $^{40}\text{Ca}$) and heavy ($^{208}\text{Pb}$) double-magic nuclei are well known [1], those in the radioactive $^{132}\text{Sn}(Z = 50, N = 82)$ 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., $\nu1i_{13/2}$ candidates) in the $N = 83$ nuclei $^{135}\text{Te}$ and $^{137}\text{Xe}$. Results are also presented for the $31/2^+_{1}$ collective octupole state observed in $^{134}\text{Te}(N = 82)$ inelastic scattering.

Many of the known levels in the radioactive and double-magic $^{132}\text{Sn}$ region have been determined from $\beta$-decay and/or prompt $\gamma$-ray studies of actinide fission products (e.g., Refs. [2–7]), which do not offer any particular selectivity to single-particle states. Recently, $^{132}\text{Sn}(d, p)^{133}\text{Sn}$ [8], and $^{134}\text{Te}(d, p)^{135}\text{Te}$ [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 $2f_{1/2} \
\times 2p_{3/2} \times 2p_{1/2} \times 2f_{5/2}$, and $1h_{9/2}$ systematics are known for the $N = 83$ nuclei at, near, and above $^{133}\text{Sn}$ [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 $^{133}\text{Sn}$ or $^{135}\text{Te}$ by a direct reaction. The $1i_{13/2}$ systematics for the $N = 83$, $56 \leq Z \leq 70$ nuclei are well established in the literature [1]. They are also known to mix with the $13/2^+, 3^+ \otimes 2f_{1/2}$ multiplet member [10–19], which means the observed $13/2^+_1$ energy is different from the unmixed single-neutron energy, $E_{\text{n}}(1i_{13/2})$. 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-$\gamma$ coincidence spectroscopy, using ($^{13}\text{C},^{12}\text{C}\gamma$) and ($^{8}\text{Be},^{8}\text{Be}\gamma$) 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 $^{8}\text{Be}$ is unbound ($T_{1/2} = 8.2 \times 10^{-17}$ s [1]), two correlated $\gamma$-rays are detected. Scattered target nuclei were measured at forward laboratory angles relative to the beam direction (corresponding

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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 13C target, with a ν1p1/2 (Jc = l − 1/2) ground state, and the 9Be target, with a ν1p3/2 (Jc = 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 134Te RIB at 565 MeV was used on two targets: a 13C target with a thickness of 1.2 mg/cm² and a 9Be target with a thickness of 2.37 mg/cm². The 134Te RIB provided by the Holifield Radioactive Ion Beam Facility (HRIBF) had an intensity of approximately 3 × 10⁸ 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 136Xe beam at 560 MeV was used on two targets: a 13C target with a thickness of 1 mg/cm² and a 9Be target with a thickness of 1.25 mg/cm². 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⁻ ground state for the 135Te and 137Xe nuclei is through the 11/2⁻, 2⁺ ⊗ 2 f7/2 states at 1179.88(9) keV and 1220.07(15) keV, respectively. These 11/2⁻ states are well known in both 135Te and 137Xe from their part in a 15/2⁻ → 11/2⁻ → 7/2⁻ yrast transition sequence following de-excitation of an 19/2⁻ isomer [1,7,30–33]. Carbon-gated γ-γ coincidence data from the 13C(134Te,12Cγγ)135Te and 13C(136Xe,12Cγγ)137Xe 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⁺ ⊗ 2 f7/2 state of 135Te; the 929-keV γ-ray coincidence data from the 13C(134Te,12Cγγ)135Te and 13C(136Xe,12Cγγ)137Xe direct reaction shows 1180- and 929-keV γ-ray decays from the previously known 11/2⁻, 2⁺ ⊗ 2 f7/2 state at 1179.88(9) keV [1].
The 400-keV $^{15}$ level previously observed but unassigned level in the selectivity of a direct reaction. The level is identified as a $^{1752.56 (15)}$ keV level [cf. the present value of $^{1752.6 (3)}$ keV $^{15}$ level].

The 2108.8(9) and 1752.6(3) keV states in $^{135}$Te and $^{137}$Xe, respectively, are likely the $^{13}$ Te and $^{137}$Xe states of $^{137}$Xe; the 533-keV $^{15}$ level originates from a state at 1752.6(3) keV. Figure 4 shows a strong 532.5(3)-keV $^{15}$ γ-ray transition in coincidence with the 11/2$^+$, 2$^+ \otimes 2 f_{7/2}$ state of $^{137}$Te; the 533-keV $^{15}$ γ-ray originates from a state at 1752.6(3) keV.

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$^+$ 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.

<table>
<thead>
<tr>
<th>$^{134}$Te</th>
<th>$^{135}$Te</th>
</tr>
</thead>
<tbody>
<tr>
<td>3749(5)</td>
<td>1854.8(8)</td>
</tr>
<tr>
<td>(3$^-$)</td>
<td>1/2$^-$, 3/2$^+$, 5/2$^-$</td>
</tr>
<tr>
<td>2470(5)$^b$</td>
<td>772.1(9)</td>
</tr>
<tr>
<td>100</td>
<td>58(5)</td>
</tr>
<tr>
<td>1083.3(4) ($^1_2$)</td>
<td>1195.7(9)</td>
</tr>
<tr>
<td>100(7)</td>
<td>658.65(10) ($^1_2$)</td>
</tr>
<tr>
<td>2021.5(10)</td>
<td>2108.8(9)</td>
</tr>
<tr>
<td>1/2$^-$, 3/2$^+$, 5/2$^-$</td>
<td>(13/2$^+$)</td>
</tr>
<tr>
<td>938.2(9)</td>
<td>928.9(9)</td>
</tr>
<tr>
<td>100</td>
<td>1179.88(9) ($^1_2$)</td>
</tr>
<tr>
<td>1083.3(4) ($^1_2$)</td>
<td>2483.2(12)</td>
</tr>
<tr>
<td>1/2$^-$, 3/2$^+$, 5/2$^-$</td>
<td>1399.9(11)</td>
</tr>
<tr>
<td>100</td>
<td>1083.3(4) ($^1_2$)</td>
</tr>
</tbody>
</table>

$^{a}$Taken from the literature [1].

$^{b}$Strongly observed in γ-ray singles spectrum as 2467.5(8) keV but could be contaminated with $E_\gamma (2^+ \rightarrow 0_1^+) = 2465.3(2)$ keV [1].

$^{c}$Exists in the literature [1] as an unassigned state from $^{131}$I decay [35] with $E_\gamma = 1752.56(16)$ keV and $E_\gamma = 532.49(10)$ keV.
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-$\gamma$ angular correlations. More importantly, the $3^+_1$ collective octupole excitation at 3749(5) keV in $^{134}\text{Te}$ is observed; cf. Fig. 7. The $(^{13}\text{C},^{13}\text{C})$ and $(^9\text{Be},^8\text{Be})$ 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 $\gamma$-ray transition in the $^{134}\text{Te}$ and $^{136}\text{Xe}$ inelastic-scattering channels; the $3^+_1$ level in $^{136}\text{Xe}$ was previously known in the literature [1]. The observation of the $3^+_1$ level in $^{134}\text{Te}$ completes the systematics for $N = 82$, $50 \leq Z \leq 72$ nuclei and the observation of $13/2^+_1$ in $^{135}\text{Te}$ and $^{137}\text{Xe}$ completes the systematics for all but $^{133}\text{Sn}$ of the $N = 83$, $50 \leq Z \leq 70$ 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, $\sigma^{rel} \approx \Sigma I_{out} - \Sigma I_{in}$) 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.

The $11/2^+_2$ cross section for the $(^{13}\text{C},^{12}\text{C})$ reaction is expected to be large compared to the $(^9\text{Be},^8\text{Be})$ reaction. The $13/2^+_1$ to $3/2^+_1$ cross-section ratio in $^{135}\text{Te}$ is measured as 0.238(12) (cf. 0.294 from DWBA calculations) for the $(^{13}\text{C},^{12}\text{C})$ reaction but only 0.046(10) (cf. 0.054 from DWBA calculations) for the $(^9\text{Be},^8\text{Be})$ reaction; a $13/2^+_1$, $0^+_1 \otimes 1r_{13/2}$ assignment is supported by the DWBA calculations. A summary of the experimental and calculated relative cross sections for the $^{13}\text{C}$($^{13}\text{Te},^{12}\text{C}$)$^{135}\text{Te}$ and $^{9}\text{Be}$($^{13}\text{Te},^{8}\text{Be}$)$^{135}\text{Te}$ 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 $(d,p)^{135}\text{Te}$ study [9] report a $2f_{5/2}$ candidate at $\approx 1.8$ MeV. While the present data are more consistent with the predominant $2f_{5/2}$ component being located at 1207 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 $^{133}\text{Sn}$ 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 $^{135}\text{Te}$

<table>
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<tr>
<th>$E_x$</th>
<th>$J^\pi$</th>
<th>$^{13}\text{C}$($^{13}\text{Te},^{12}\text{C}$)$^{135}\text{Te}$</th>
<th>$^9\text{Be}$($^{13}\text{Te},^{8}\text{Be}$)$^{135}\text{Te}$</th>
<th>$\sigma^{rel}$</th>
<th>$\sigma^{rel}$</th>
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</thead>
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<tr>
<td></td>
<td></td>
<td>$^{13}\text{C}$($^{13}\text{Te},^{12}\text{C}$)$^{135}\text{Te}$</td>
<td>$^9\text{Be}$($^{13}\text{Te},^{8}\text{Be}$)$^{135}\text{Te}$</td>
<td>DWBA</td>
<td>DWBA</td>
</tr>
<tr>
<td>0.00</td>
<td>7/2^-</td>
<td>1.391</td>
<td>0.333</td>
<td></td>
<td></td>
</tr>
<tr>
<td>658.65(10)</td>
<td>3/2^-</td>
<td>1.000(21)</td>
<td>1.000(58)</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>1083.3(4)</td>
<td>1/2^-</td>
<td>0.145(11)</td>
<td>0.185</td>
<td>0.478(39)</td>
<td>0.832</td>
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<tr>
<td>1127.06(8)</td>
<td>5/2^-</td>
<td>0.153(52)</td>
<td>0.152</td>
<td>0.436(39)</td>
<td>0.711</td>
</tr>
<tr>
<td>1179.88(9)</td>
<td>11/2^-</td>
<td>0.095(20)</td>
<td>0.190</td>
<td>0.095(20)</td>
<td>0.190</td>
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<tr>
<td>1246.18(10)</td>
<td>9/2^-</td>
<td>0.035(8)</td>
<td>0.018</td>
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<td>0.056(7)</td>
<td>0.106(12)</td>
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<tr>
<td>1442.22(10)</td>
<td>1/2^+</td>
<td>0.129(9)</td>
<td>0.078(10)</td>
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<td>1837.19(10)</td>
<td>3/2^-, 5/2^-</td>
<td>0.064(8)</td>
<td>0.152(12)</td>
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<td>0.152(12)</td>
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<td>2339.07(22)</td>
<td>1/2^-</td>
<td>0.131(13)</td>
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<td>2483.2(12)</td>
<td>1/2^-</td>
<td>0.029(5)</td>
<td>0.116(14)</td>
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*a Calculated for $2f_{5/2}$, $3p_{3/2}$, $3p_{1/2}$, $2f_{5/2}$, $1h_{9/2}$, and $1f_{13/2}$.

*b Preliminary $(d,p)^{135}\text{Te}$ results [9] report $2f_{5/2}$ at $\approx 1.8$ MeV.

c Level energies from present study; other energies from Evaluated Nuclear Structure Data File [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 $I_{13/2}$ single-neutron states are known to mix with the $13/2^+$ member of the $3^- \otimes 2 f_{7/2}$ multiplet [10–19,34], which means the observed $13/2_2^+$ energy is different from the unmixed single-neutron energy, $\epsilon_{s.p.}(1/13/2)$. 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 $3^- \otimes 2 f_{7/2}$ multiplet is not known or observed in the present study, which makes an empirical determination of the unmixed single-neutron energy, $\epsilon_{s.p.}(1/13/2)$, 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 $I_{13/2}$ single-neutron energy.

In summary, the $13/2_1^+$ state ($I_{13/2}$ 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-$\gamma$ coincidence spectroscopy with CsI-HPGe arrays; this technique provides an invaluable tool for future direct-reaction studies of RIBs in inverse kinematics. While the $13/2^+_2$ state (or $I_{13/2}$ 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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