$2\pi 1\nu$ states populated in ^{135}Te from ^{9}Be-induced reactions with a ^{132}Sn beam

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γ-ray transitions in ^{134}Te, ^{135}Te, and ^{136}Te were measured from ^{9}Be-induced reactions with a radioactive ^{132}Sn beam at a sub-Coulomb barrier energy of 3 MeV per nucleon using particle-γ coincidence spectroscopy. The transitions were selected by gating on alpha-like particles in a CsI detector following a combination of (^{9}Be,$\alpha 1n$), (^{9}Be,$\alpha 2n$), and (^{9}Be,$\alpha 3n$) incomplete fusion-evaporation reactions. Distorted-wave Born approximation calculations suggest little to no contribution from the (^{9}Be,^{7}He), (^{9}Be,^{6}He), and (^{9}Be,^{5}He) direct reactions.γ-ray transitions from previously known $2^+ \otimes \nu 2f_{7/2}$ and $4^+ \otimes \nu 2f_{7/2}$ multiplet members in ^{135}Te are observed. A new γ ray is observed, assigned to the third-excited state in ^{135}Te, and new $2^+ \otimes \nu 2f_{7/2}$ multiplet members are suggested. In addition, spin assignments are made by using recent one-neutron transfer data. The updated experimental data for ^{135}Te are compared to shell-model calculations for a relatively complete set of states up to the yrast $15/2^-$,$4^+ \otimes \nu 2f_{7/2}$ multiplet member at 1505 keV.

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The tellurium isotopes ^{134,135,136}Te have two protons and zero, one, and two valence neutrons, respectively, outside of the double-magic nucleus ^{132}Sn. Such nuclei provide relatively simple laboratories for exploring nucleon-nucleon interactions. Recently, we reported electromagnetic moments of the 2_1^+ state in ^{134}Te from Coulomb excitation [1] and single-neutron states in ^{135}Te ($N = 83$) from (^{13}C, ^{12}C) and (^{9}Be, ^{8}Be) direct reactions [2], which support the simple scenario of only a few active nucleons. In the present study, γ-ray transitions in ^{134,135,136}Te are reported from ^{9}Be-induced reactions with a radioactive ^{132}Sn beam and the updated experimental data are compared with shell-model calculations.

A ^{132}Sn beam of 1×10^5 ions/s ($\geqslant$96% pure [3,4]) was provided by the Holifield Radioactive Ion Beam Facility for five days at a sub-Coulomb barrier energy of 3 MeV per nucleon on a 1.57 (8) mg/cm^2 monoisotopic ^{9}Be target. Charged particles were detected in the "bare" HyBall (BareBall) CsI(Tl) array [5], covering laboratory angles 7°–60° relative to the beam direction. Coincident γ rays were detected in the Clover Array for Radioactive Ion beams (CLARION) of 11 Compton-suppressed, segmented HPGe Clover detectors [6] with a total efficiency of 3.00 (5)% at 1 MeV. The experimental trigger required either a scaled-down particle event or a particle-γ coincidence event. In the process of studying the one-neutron transfer reaction ^{132}Sn(^{9}Be, ^{8}Be)^{133}Sn [7], γ rays from ^{134,135,136}Te were observed in coincidence with single alpha-like particles; see Fig. 1. Additional experimental details for the present study can be found in Ref. [7]. The observed γ-ray intensities in the tellurium isotopes were two to three orders of magnitude less intense than those from the one-neutron transfer reaction into ^{133}Sn.

A summary of the observed γ-ray transitions is given in Table I and illustrated by partial level schemes in Fig. 2. The majority of the transitions and states were previously known from fission and decay studies [8–11] and can be found in the Evaluated Nuclear Structure Data File (ENSDF) [12]. In particular, transitions from the 2_1^+ states in ^{134,136}Te and $11/2^-$,$2^+ \otimes \nu 2f_{7/2}$ and $15/2^-$,$4^+ \otimes \nu 2f_{7/2}$ multiplet members in ^{135}Te are observed. The relatively low-lying, low-spin $p_{1/2}$ and $p_{3/2}$ candidates in ^{135}Te are also observed. A new 1122-keV transition is observed, which is likely a member of the $2^+ \otimes \nu 2f_{7/2}$ multiplet based on the energy and shell-model calculations (see below); the previously known 1380-keV transition may also be a member. There is also weak evidence for the previously known 1127- and 1442-keV γ rays.

The population of the states in ^{135}Te appears dominated by the (^{9}Be,$\alpha 2n$) incomplete fusion-evaporation reaction [i.e., from ^{9}Be breakup followed by fusion of 1 α or

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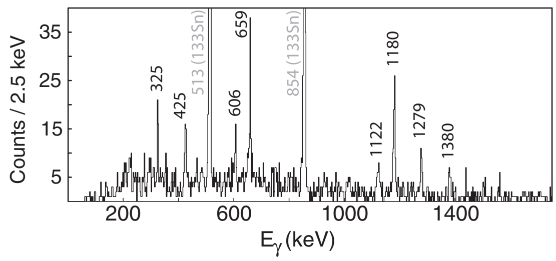

FIG. 1. γ-ray spectrum from single alpha-like particle gate. Transitions labeled in gray are contaminants from ^{132}Sn(^{9}Be, ^{8}Be $\rightarrow 2\alpha$)^{133}Sn.

(^{9}Be, ^{8}Be $\rightarrow 2\alpha$) one-neutron transfer followed by fusion of 1 α], which explains the population of both high- and low-spin states [13–15]; the largest γ-ray intensity is from the yrast $11/2^-, 2^+ \otimes \nu\, 2f_{7/2}$ state in ^{135}Te and the second-largest transition is from the first-excited state in ^{135}Te, i.e., the $p_{3/2}$ candidate. Distorted wave Born approximation (DWBA) calculations were attempted with the code PTOLEMY [16] assuming a (^{9}Be,^{6}He) direct reaction. All of the direct-reaction cross sections were predicted to be sub mb. Furthermore, the DWBA calculations failed to describe the population patterns observed in the data. In particular, the DWBA calculations predict that the $i_{13/2}$ candidate at 2109 keV [2], which decays to the $11/2^-_1$ state at 1180 keV by a 929-keV γ ray, should be the most strongly populated state following the (^{9}Be,^{6}He) direct reaction. However, there is no evidence for a 929-keV γ-ray transition. Furthermore, the DWBA calculations predict that the $3/2^-_1$ state ($p_{3/2}$ candidate) should have a larger cross section than the $1/2^-_1$ state ($p_{1/2}$ candidate). However, the opposite is observed when the $3/2^-_1$ state is corrected for the feeding from the $1/2^-_1$ state. The discrepancy between the DWBA predictions and experimental data suggest little to no contribution from the (^{9}Be,^{6}He) direct reaction.

In order to assess the proposed $2^+ \otimes \nu\, 2f_{7/2}$ multiplet-member assignments of the 1122- and 1380-keV states observed in the present study, shell-model calculations for ^{134,135,136}Te were performed with the NUSHELLX@MSU code [17]. The basis included all proton single-particle orbits in the $Z = 50$–82 shell ($\pi 1g_{7/2}, 2d_{5/2}, 2d_{3/2}, 3s_{1/2}, 1h_{11/2}$) and all neutron orbits in $N = 82$–126 shell ($\nu 1h_{9/2}, 2f_{7/2}, 2f_{5/2}, 3p_{3/2}, 3p_{1/2}, 1i_{13/2}$). The interactions for the proton-proton space were based on the CD Bonn

TABLE I. Summary of γ-ray energies and relative intensities.

Nuclide	E_x (keV)	E_γ (keV)	J^π [a]	$I_\gamma^{\rm rel}$
^{136}Te	606.1 (6)	606.1 (6)	2^+	19 (4)
^{135}Te	658.9 (2)	658.9 (2)	$3/2^-$	65 (16)
^{135}Te	1083.6 (7)	424.6 (7)	$1/2^-$	40 (14)
(^{135}Te)	1122.3 (24)	1122.3 (24) [b]	$(7/2^-)$	31 (8)
^{135}Te	1180.4 (5)	1180.4 (5)	$11/2^-$	100 (12)
^{134}Te	1278.6 (9)	1278.6 (9)	2^+	40 (9)
^{135}Te	1380.0 (12)	1380.0 (12)	$9/2^-$	28 (8)
^{135}Te	1505.2 (6)	324.8 (4)	$15/2^-$	30 (8)

[a] J^π from Refs. [2,11,12] and present study.
[b] Possible 1127-keV component [12].

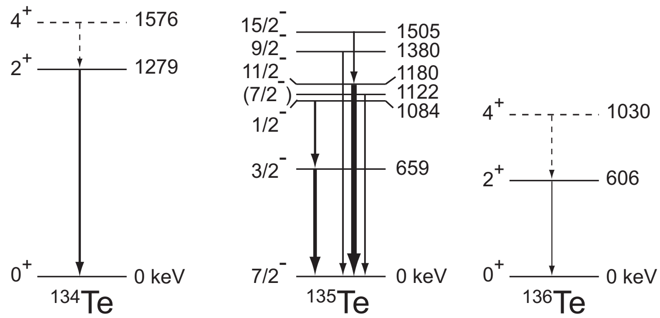

FIG. 2. Partial level diagram for ^{134,135,136}Te. The dashed lines represent unobserved states and transitions.

potential as described by Brown *et al.* [18]. The proton-neutron and neutron-neutron interactions were obtained from the N^3LO potential [19], with a ^{132}Sn core and 4 $\hbar\omega$ harmonic oscillator basis. These interactions are designated $jj56pnb$. Electromagnetic decays were evaluated with the bare $M1$ operator and standard effective charges of $e_p = 1.5e$ and $e_n = 0.5e$. The results for excitation energies and wave functions are presented in Table II and Fig. 3. For completeness, all

TABLE II. Shell-model energies, wave functions, and spectroscopic factors for ^{135}Te. See text for details.

J^π (theor.)	E_x (theor.) (MeV)	E_x (expt.) (MeV)	Config.	Probability (%)	S(theor.) [a]
$7/2^-_1$	0	0	$\pi 0^+ \otimes \nu f_{7/2}$	81.9	0.817
$3/2^-_1$	0.635	0.659	$\pi 0^+ \otimes \nu p_{3/2}$	52.8	0.523
			$\pi 2^+ \otimes \nu f_{7/2}$	26.6	
$5/2^-{}_1$ [b]	0.917	1.127	$\pi 6^+ \otimes \nu f_{7/2}$	46.3	0.102
			$\pi 4^+ \otimes \nu f_{7/2}$	15.3	
			$\pi 0^+ \otimes \nu f_{5/2}$	10.3	
$1/2^-_1$	0.972	1.083	$\pi 2^+ \otimes \nu f_{7/2}$	40.8	0.359
			$\pi 0^+ \otimes \nu p_{1/2}$	36.5	
			$\pi 2^+ \otimes \nu f_{5/2}$	14.8	
$11/2^-_1$	1.170	1.180	$\pi 2^+ \otimes \nu f_{7/2}$	53.5	0.000
			$\pi 4^+ \otimes \nu f_{7/2}$	20.8	
			$\pi 6^+ \otimes \nu f_{7/2}$	11.2	
$9/2^-_1$	1.225	1.246	$\pi 2^+ \otimes \nu f_{7/2}$	38.1	0.248
			$\pi 0^+ \otimes \nu h_{9/2}$	24.8	
			$\pi 4^+ \otimes \nu f_{7/2}$	14.2	
$9/2^-_2$	1.242	1.380	$\pi 2^+ \otimes \nu f_{7/2}$	32.4	0.299
			$\pi 0^+ \otimes \nu h_{9/2}$	29.9	
$7/2^-_2$	1.260	(1.122)	$\pi 2^+ \otimes \nu f_{7/2}$	67.5	0.103
			$\pi 4^+ \otimes \nu f_{7/2}$	12.2	
			$\pi 0^+ \otimes \nu f_{7/2}$	10.7	
$7/2^-_3$	1.455	1.442	$\pi 6^+ \otimes \nu f_{7/2}$	56.4	0.003
			$\pi 4^+ \otimes \nu f_{7/2}$	22.2	
			$\pi 2^+ \otimes \nu f_{7/2}$	13.6	
$5/2^-{}_2$ [b]	1.527		$\pi 2^+ \otimes \nu f_{7/2}$	46.7	0.005
			$\pi 6^+ \otimes \nu f_{7/2}$	31.7	
$15/2^-_1$	1.544	1.505	$\pi 4^+ \otimes \nu f_{7/2}$	64.0	0.000
			$\pi 6^+ \otimes \nu f_{7/2}$	26.0	

[a] Theoretical spectroscopic factors (single-neutron purity).
[b] $2f_{5/2}$ components measured near 1.8 MeV [2,20].

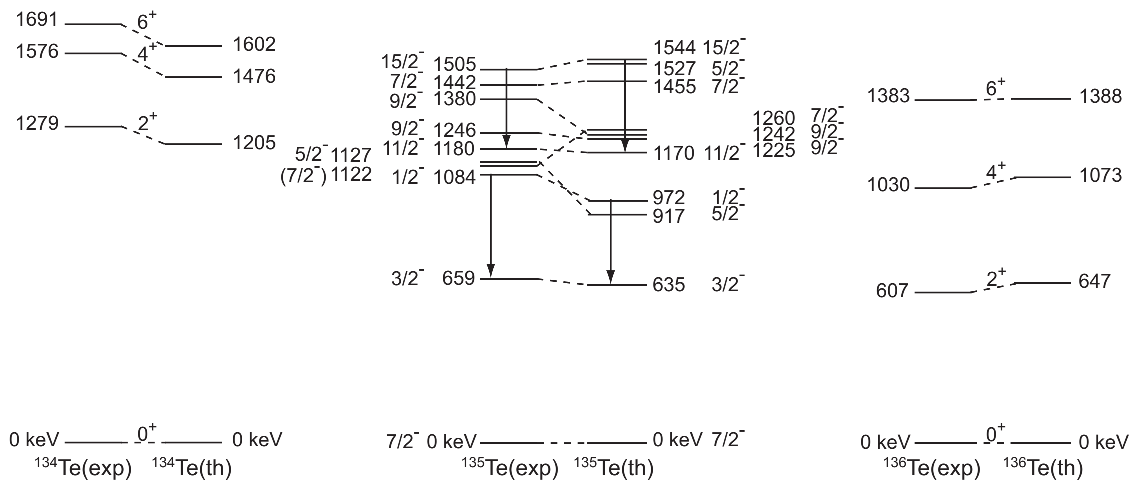

FIG. 3. Comparison between experimental and theoretical states in ^{134,135,136}Te. For ^{135}Te, the transitions are included if the strongest branch is not to the $7/2^-$ ground state.

of the known states up to 1505 keV in ^{135}Te and up to 6_1^+ in ^{134,136}Te are included, which are from the present study and Refs. [2,11,12]. Table II indicates the dominant components in the wave functions. The spin decomposition for the proton and neutron parts is indicated for contributions that exceed 10% probability. The theoretical spectroscopic factor, S(theor), follows the single-neutron-component probability of the wave function.

As indicated in Fig. 3, the agreement between the theoretical and experimental levels is good for the two even isotopes ^{134,136}Te. In the intermediate odd-A isotope ^{135}Te, including the ground state, there are nine experimental states up to the yrast $15/2^-$ level and ten shell-model states. An attempt was made to associate each experimental state with a theoretical counterpart, taking account of the present data, one-neutron transfer data [2], and ENSDF [12]. It is immediately apparent from the wave function compositions shown in Table II that the excited states have mixed configurations and thus it is not possible to speak quantitatively about multiplets of states associated with coupling the odd neutron to a particular two-proton state. It is evident, however, that the observed states are dominated by neutron occupation of the $2f_{7/2}$ orbit. Even the states identified with occupation of the neutron $3p_{3/2}$, $2f_{5/2}$, $3p_{1/2}$, and $1h_{9/2}$ orbits [2] have strong admixtures of the type $J_p \otimes \nu 2f_{7/2}$, where J_p represents the total proton spin.

Of the two predicted $9/2^-$ levels, we assign the first one to the experimental level at 1246 keV and the second one to the experimental level at 1380 keV. These two assignments are made on the basis that these states have large $\nu 1h_{9/2}$ components, consistent with the one-neutron transfer measurements [2]. We note here that the previous spin assignment for the 1380-keV state was $(7/2^-,9/2)$ [2,12]. However, the one-neutron transfer results report (^{13}C, ^{12}C) and (^{9}Be, ^{8}Be) cross sections for the 1380-keV state that are consistent with $J = \ell - 1/2$ [2], leaving $9/2^-$ of $(7/2^-,9/2)$ as the favored spin assignment; unlike the (^{9}Be, ^{8}Be) reaction, the (^{13}C, ^{12}C) reaction heavily suppresses direct population of $J = \ell - 1/2$ states. In recent shell-model calculations using a somewhat different set of interactions, Coraggio *et al.* [21] reported similar assignments with spectroscopic factors that agree with our determination that the first $9/2^-$ level is mainly $2^+ \otimes \nu 2f_{7/2}$ and the second one has the dominant $0^+ \otimes \nu 1h_{9/2}$ component. However, it is unclear why the 1380-keV transition is observed in the present (^{9}Be,$\alpha 2n$) study but not the 1246 keV transition.

We propose that the new state at 1122 keV and the previously known $7/2^-$ state at 1442 keV most likely correspond to the theoretical $7/2_2^-$ and $7/2_3^-$ states, which are predicted to show a decay to the $5/2_1^-$ state together with a dominant decay to the ground state. In this part of the level scheme, these states alone are predicted to show such decay branches. The decay branches for the experimental 1442-keV state [12] are consistent with this prediction. Furthermore, the one-neutron transfer results report (^{13}C, ^{12}C) and (^{9}Be, ^{8}Be) cross sections for the 1442-keV state that are consistent with $J = \ell + 1/2$ [2], leaving $7/2^-$ of $(5/2^-,7/2,9/2^-)$ [12] as the favored spin assignment. The shell-model $7/2_2^-$ state, which has a predominant $2^+ \otimes \nu 2f_{7/2}$ configuration, is the only remaining plausible candidate for the 1122-keV state. However, the fact that the 1122-keV state is seen in the present (^{9}Be,$\alpha 2n$) study but not in the one-neutron transfer study [2] suggests that the shell-model calculations overpredict the $0^+ \otimes \nu 2f_{7/2}$ component in the $7/2_2^-$ state and underpredict it in the $7/2_3^-$ state.

We suggest that the shell-model $5/2_2^-$ state, predicted at 1527 keV, might correspond to a state that has yet to be observed, potentially above or below the $15/2_1^-$ state. Beyond the experimental $5/2^-$ state at 1127 keV, the next known $5/2^-$ state is at 1654 keV. However, the decay branches for the experimental $5/2^-$ state at 1654 keV are well described by a $5/2_3^-$ shell model state at 1602 keV. Preliminary (d,p) results [20] report a strong $2f_{5/2}$ component near 1.8 MeV. The heavy-ion-induced one-neutron transfer results report relatively large (^{13}C, ^{12}C) and (^{9}Be, ^{8}Be) cross sections for a 1837-keV state that are consistent with $J = \ell - 1/2$ [2], leaving $5/2^-$ of $(3/2^-,5/2^-)$ [12] as the favored spin assignment. However, these higher-lying $5/2^-$ states do not likely correspond to the $5/2_2^-$ shell-model state at 1527 keV, supporting the initial

TABLE III. Comparison of experimental (relative) [2] and theoretical spectroscopic factors for ^{135}Te. See the text for details.

E_x (keV)	J^π	$\sigma_{expt}/\sigma_{theor} \propto S^{rel}$ (expt.)[a]	S (theor.)
0.659	$3/2^-$	0.52 (1)	0.52
1.084	$1/2^-$	0.34 (2)	0.36
1.127	$5/2^-$	0.33 (3)	0.10
1.246	$9/2^-$	0.44 (5)	0.25
1.380	$9/2^-$	0.60 (6)	0.30
1.837	$5/2^-$	0.28 (2)	0.20[b]
2.109	$13/2^+$	0.42 (2)	0.64

[a]Relative spectroscopic factors [2] normalized to $3/2^-$ theory.
[b]Two $5/2^-$ states near 2 MeV are predicted with $S \sim 0.2$.

suggestion that there remains an unobserved $5/2^-$ state above or below the $15/2^-_1$ state.

The relative spectroscopic factors from the (^{13}C, ^{12}C) and (^{9}Be, ^{8}Be)^{135}Te direct reactions [2] are averaged and compared to the shell-model calculations in Table III. The relative spectroscopic factors were determined from the relative ratios of the experimental (γ-ray intensity balance) and theoretical (PTOLEMY [16]) cross sections in Table 2 of Ref. [2]. The experimental values have been normalized to the $3/2^-$ theoretical spectroscopic factor of 0.52 to aid comparison. The theoretical spectroscopic factors in Table III are taken from Table II; two additional values are now given. Relative to the $3/2^-$ state, the theoretical spectroscopic factor for the $1/2^-$ state is in excellent agreement with the transfer data. However, the shell model predicts more fragmentation of $f_{5/2}$ and $h_{9/2}$ and less fragmentation of $i_{13/2}$ than what is experimentally observed. The transfer data also show relatively large populations of other states between 1.8 and 2.5 MeV, mostly $J = \ell - 1/2$, which likely carry much of the remaining single-neutron strength. While the precision of spectroscopic factors from heavy-ion-induced transfer reactions is complicated by potential multistep processes and execution of a γ-ray intensity balance, which is subject to systematic uncertainties from decay branches and unobserved feeding (cf. discussion in Ref. [2]), spectroscopic factors from the recent (^{9}Be, ^{8}Be)^{133}Sn study [7] largely followed those from $(d,p)^{133}$Sn [22]. Therefore, the relative spectroscopic factors of ^{135}Te determined from the (^{13}C, ^{12}C) and (^{9}Be, ^{8}Be) heavy-ion-induced transfer reactions should provide a good first-order indication of the relative single-particle strength; no spectroscopic factors from $(d,p)^{135}$Te have been published to date.

A future report of absolute spectroscopic factors from the preliminary (d,p) study [20] would be valuable in accessing the magnitude of single-neutron components. In addition, a future Coulomb excitation study of ^{135}Te could potentially evaluate the predicted mixing of the nominal $2^+ \otimes \nu 2f_{7/2}$ multiplet structure. Based on the current comparison of experimental data to shell-model expectations, an improved description is needed for the nucleon-nucleon interactions, particularly the proton-neutron interactions.

In summary, states in ^{134,135,136}Te were populated by the (^{9}Be,$\alpha 3n$), (^{9}Be,$\alpha 2n$), and (^{9}Be,$\alpha 1n$) incomplete fusion-evaporation reactions, respectively, using a radioactive ^{132}Sn beam at a sub-Coulomb barrier energy of 3 MeV per nucleon. A new γ ray is observed, assigned to the third-excited state in ^{135}Te, and new $2^+ \otimes \nu 2f_{7/2}$ multiplet members are suggested. The observed γ-ray intensities from the (^{9}Be,αxn) channels were two to three orders of magnitude smaller than those from the one-neutron transfer channel. The (^{9}Be,αxn) reactions with a neutron-rich ^{132}Sn beam resulted in less neutron-rich nuclei due to the large number of neutrons evaporated even at sub-Coulomb barrier energies. The present (^{9}Be,αxn) incomplete fusion-evaporation data, combined with previous data, provide a complete set of states up to the $15/2^-$ yrast state at 1505 keV. However, there likely remains an unobserved $5/2^-$ state above or below the $15/2^-$ yrast state. Relatively good agreement between experimental data and shell-model calculations is demonstrated but an improved description is needed for the proton-neutron interactions.

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