High-spin states in ^{124}Te

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In even-mass Te isotopes with $114 \leqslant A \leqslant 122$ the experimentally observed yrast $I^\pi = 16^+$ states have been interpreted as favored noncollective oblate states based on the fully aligned $\pi[(g_{7/2})^2]_{6^+} \otimes \nu[(h_{11/2})^2]_{10^+}$ configuration. For ^{124}Te the highest-spin positive-parity state known has $I^\pi = 10^+$. An extension of the yrast cascade of ^{124}Te is needed to spin at least 16^+ in order to answer the question of whether this noncollective oblate state lies along the yrast line in this isotope. The level structure of ^{124}Te has been studied via prompt γ-ray spectroscopy. ^{124}Te was produced in the fission of the compound systems formed in two heavy-ion-induced reactions, ^{24}Mg (134.5 MeV) + ^{173}Yb and ^{23}Na (129 MeV) + ^{176}Yb. γ-ray spectroscopy was accomplished with the Gammasphere array. The yrast cascade of ^{124}Te was extended up to 5481-keV excitation energy with a tentative 16^+ assignment for the highest observed state. This state does not exhibit the characteristics of the favored noncollective oblate states with $I^\pi = 16^+$ observed in the lighter doubly even Te isotopes, indicating that such a state is probably no longer yrast in ^{124}Te.

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In the nuclear mass region of 120 with $Z > 50$ various structural effects arise from the interplay between collective and noncollective excitations (see, for instance, Ref. [1]). Shape coexistence in doubly even nuclei in this mass region has been established experimentally and theoretically studied (see, for instance, Ref. [2]). The doubly even Te isotopes in this mass region exhibit vibrational characteristics at low spins, but at higher spins and excitation energies the existence of valence particles or holes can break the spherical symmetry and induce small nuclear deformation. Alignment of a few particles produces a limited total angular momentum and leads to termination of a given configuration. In ^{122}Te [3,4] and ^{114,116,118,120}Te [5] the yrast $I^\pi = 16^+$ states have been interpreted as favored noncollective oblate states based on the fully aligned neutron $(h_{11/2})^2_{10^+}$ configuration coupled to two protons in the $d_{5/2}$ and/or $g_{7/2}$ orbitals with fully aligned $I^\pi = 6^+$.

The shortage of information on high-spin states for the stable ^{124}Te isotope is mainly due to the difficulty in studying this isotope as an evaporation residue in the heavy-ion fusion reactions that could bring in sufficient angular momentum. Indeed, for ^{124}Te the highest spin positive-parity state known has $I^\pi = 10^+$ and the highest spin negative-parity state is 11^-, both observed using an $(\alpha,2n)$ reaction [6]. An alternative way to study high-spin states in stable as well as slightly neutron-rich isotopes is via prompt γ-ray spectroscopy of fragments in fusion-fission reactions that can populate higher spin states close to the yrast line. Such methods have been used several times to collect information on high-spin states of nuclei near the line of stability (see, for instance, Ref. [7] and references therein). Because ^{124}Te is a stable nucleus it can be populated as a fission fragment in such reactions, as was done in the present work. As a consequence, a state in the yrast cascade of ^{124}Te was observed that exhibits a similar decay pattern to the favored noncollective 16^+ oblate state in ^{122}Te [3,4]. However, upon closer investigation, this state does not exhibit the characteristics expected for the favored noncollective oblate 16^+ states in doubly even $^{114-122}$Te isotopes [3–5].

The 88-Inch Cyclotron Facility at Lawrence Berkeley National Laboratory was used to populate compound nuclei in two similar experiments henceforth referred to as experiments I and II. The Gammasphere array was used for subsequent γ-ray spectroscopy. In experiment I the Gammasphere array comprised 92 Compton-suppressed large volume HPGe detectors. A ^{197}Pb compound nucleus (CN) was formed in the ^{24}Mg + ^{173}Yb reaction at 134.5 MeV. The target consisted of 1 mg/cm^2 isotopically enriched ^{173}Yb, evaporated on a 7 mg/cm^2 gold backing. Reactions of the beam in the backing produced a ^{221}Pa CN. In experiment II, with 100 Gammasphere detectors, a ^{199}Tl CN was formed in the ^{23}Na + ^{176}Yb reaction at a beam energy of 129 MeV. The target consisted of approximately 1 mg/cm^2 isotopically enriched ^{176}Yb on a 10 mg/cm^2 Au backing. Reactions of the beam in the backing produced a ^{220}Th CN. About 2.3×10^9 triple, and 10^9 quadruple γ-ray events were collected in experiments I and II, respectively. Symmetrized, three-dimensional cubes were constructed in all cases to investigate the coincidence relationships between the γ rays. Additional information for both experiments in the present work can be found in Refs. [8,9].

The level scheme of ^{124}Te deduced in the present work is shown in Fig. 1 where intensities of the transitions obtained in experiment I are quoted. The yrast cascade of ^{124}Te, previously known up to 3154-keV excitation energy [6,10], is extended up to 5481 keV with a tentative 16^+ assignment for the highest

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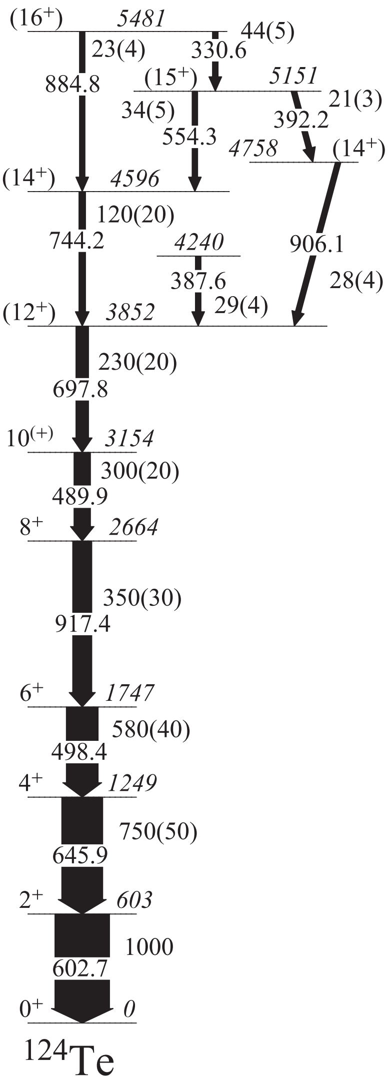

FIG. 1. Level scheme assigned to ^{124}Te in the present work. Transition and excitation energies are given in keV. The width of the arrows is representative of the quoted intensity of the transitions from experiment I. The uncertainty on the γ-ray energies varies from 0.4 to 0.9 keV.

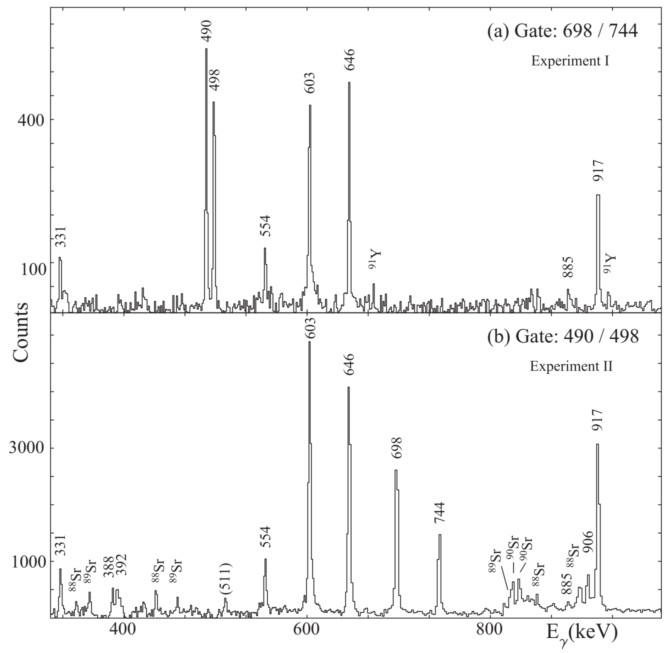

FIG. 2. Background-subtracted γ-ray spectra of ^{124}Te double gated on (a) the 697.8- and 744.2-keV transitions in data obtained in experiment I, and (b) the 489.9- and 498.4-keV transitions in data obtained in experiment II. The peaks from Sr and Y complementary fission fragments [11–14] are indicated. Unlabeled peaks are most likely contaminants, for example, the 511-keV transition is indicated.

observed state. Eight new transitions and six new levels were added to the previously known level scheme. The 3154-keV level was assigned a spin-parity of 10^+ in Ref. [6] but an $I^\pi = 10^{(+)}$ was adopted in the latest evaluation [10]. The tentative parity assignment was adopted also in the present work. The quality of the data obtained in experiment I can be seen in the gated spectrum in Fig. 2(a). Data of similar quality were obtained in experiment II as can be seen in the gated spectrum in Fig. 2(b). All transitions of ^{124}Te in Fig. 1 are present in the spectra in Fig. 2. Transitions from the complementary Sr and Y fragments [11–14], from the ^{220}Th and ^{221}Pa compound nuclei, are also indicated. Spin and parity assignments of all new levels reported in this work are difficult to deduce experimentally due to the lack of directional correlation information with respect to the beam for the fission products. However, based on comparison with assignments for the yrast excited states in the neighboring even-mass Te isotopes, spin and parity assignments for the four new levels assigned to ^{124}Te in the present work have been tentatively suggested.

In Fig. 3 partial level schemes from Refs. [15–19] and the present work show the yrast level sequences in the even-mass $^{120-128}$Te isotopes up to the (16^+) levels. For ^{126,128}Te the known yrast sequence reaches only the (14^+) states. The similarity in the sequences deexciting the (16^+) levels in ^{122,124}Te, which lead to the tentative spin-parity assignment proposed in this work for the new levels of ^{124}Te, is highlighted by including the transitions down to the (10^+) states. The off-yrast second (14^+) state is observed in both cases, but the weak $(14^+_2) \rightarrow (14^+_1)$ transition was observed only in ^{122}Te [3,4,17]. In ^{120}Te [16] the off-yrast second 14^+ state is observed but the 15^+ state was not observed, most likely because it is off-yrast and lies above the 16^+ state.

While the excitation energy of the 8^+ states remains relatively flat in Fig. 3, the excitation energy of the (10^+) levels gradually decreases with increasing mass, and eventually the (10^+) level becomes an isomer in ^{128,130,132}Te [19–21]. Similar (10^+) isomers identified in the neighboring Sn isotopes, as summarized in Ref. [22], may be interpreted to arise from the neutron $h^2_{11/2}$ configuration and their excitation energy drops smoothly with mass number. The (12^+_1) states in those Sn isotopes also behave smoothly with mass number following the lower (10^+_1) states [7], and the ratios of the $(12^+_1) \rightarrow (10^+_1)$ and the $2^+_1 \rightarrow 0^+_1$ transition energies are large ($\sim$1) suggesting collectivity for the (12^+_1) states similar to that of

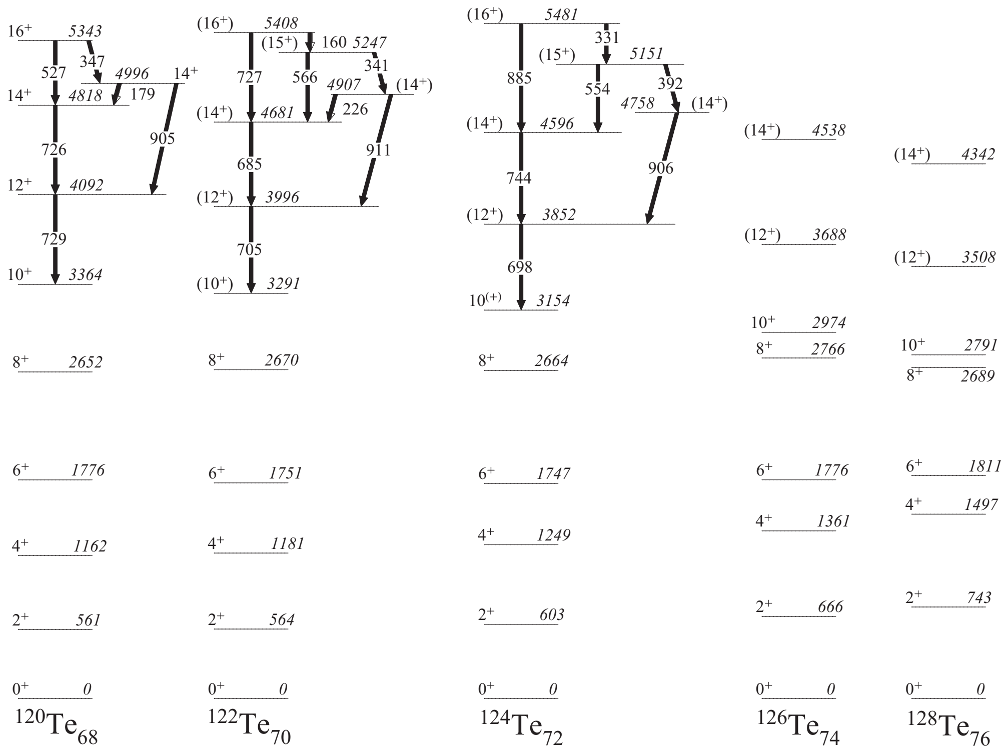

FIG. 3. Partial level schemes of $^{120-128}$Te even-mass isotopes. Data taken from the present work and Refs. [15–19].

the 2^+ states. Similar conclusions can be drawn for the Te isotopes from Table I, where the energies of the $(12_1^+) \rightarrow (10_1^+)$ and $2_1^+ \rightarrow 0_1^+$ transitions are summarized together with their respective ratios. An increased collectivity at the middle of the $N = 50$–82 shell, which gradually disappears by $N = 78$, is noted for the lighter Te isotopes, with two extra protons outside the Sn proton closed shell.

All states in Fig. 3 above the 10_1^+ behave smoothly with mass number, and the excitation energies of all of them, except for the (16^+) states, gradually decrease with increasing mass. In contrast, the excitation energy of the (16^+) states increases smoothly with mass number. In Fig. 4 a rigid-rotor plot for yrast cascades up to the 16^+ levels of the even-mass $^{118-126}$Te isotopes is shown with a rotating liquid-drop energy reference subtracted and the rigid-body moment of inertia normalized to ^{158}Er, exactly as was done in Refs. [3–5] for the even-mass $^{114-122}$Te isotopes. The yrast 16^+ states in the even-mass $^{114-120}$Te [5] isotopes are at a minimum in these rigid-rotor plots. In ^{122}Te [3,4] the 14^+ and 16^+ states have similar values in this plot and in ^{124}Te the value for the 16^+ state is clearly higher. This pattern is due to the excitation energy smoothly increasing for the yrast 16^+ states and smoothly decreasing for the yrast 14^+ states with mass number, as was shown in Fig. 3. In Refs. [3,5] the presence of the decrease in the rigid-rotor plot for the yrast 16^+ states is associated with the favored noncollective oblate states from

TABLE I. γ-ray energies of the $12_1^+ \rightarrow 10_1^+$ transitions and the $2_1^+ \rightarrow 0_1^+$ transitions and their ratios in even-mass $^{116-128}$Sn (data from Refs. [7,23]) and $^{118-130}$Te isotopes (data from Refs. [15,17–20,24,25] and the present work).

N	Sn				Te			
	A	$12_1^+ \rightarrow 10_1^+$ $E_{\gamma 12}$ (keV)	$2_1^+ \rightarrow 0_1^+$ $E_{\gamma 2}$ (keV)	$E_{\gamma 12}/E_{\gamma 2}$	A	$12_1^+ \rightarrow 10_1^+$ $E_{\gamma 12}$ (keV)	$2_1^+ \rightarrow 0_1^+$ $E_{\gamma 2}$ (keV)	$E_{\gamma 12}/E_{\gamma 2}$
66	116	1335.2	1293.5	1.032	118	812.1	605.7	1.341
68	118	1237.8	1229.7	1.007	120	728.6	560.4	1.300
70	120	1190.1	1171.3	1.016	122	705.3	564.1	1.250
72	122	1103.3	1140.5	0.967	124	697.8	602.7	1.158
74	124	1046.8	1131.7	0.925	126	713.5	666.3	1.071
76	126	1030.2	1141.1	0.903	128	717.4	743.2	0.965
78	128	1061	1169	0.908	130	718	839.5	0.855

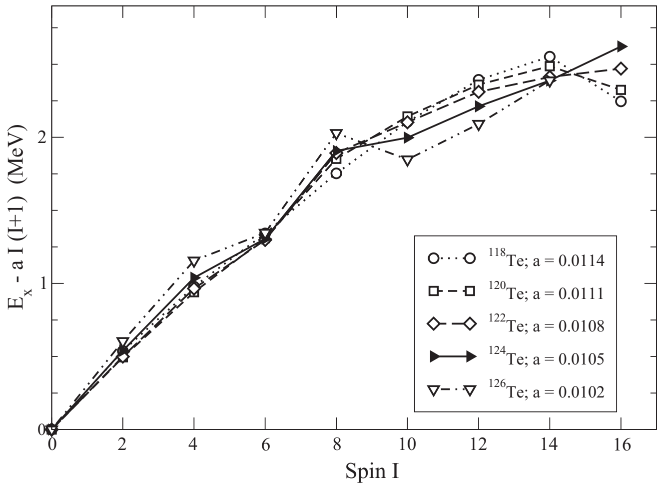

FIG. 4. Rigid-rotor plots for even-mass $^{118-126}$Te isotopes. Data taken from the present work and Refs. [3–5,15–18,25].

the fully aligned $\pi[(g_{7/2})^2]_{6^+} \otimes \nu[(h_{11/2})^2]_{10^+}$ configuration, predicted by deformed self-consistent cranking calculations based on the total Routhian surface formalism. The change in the pattern in the rigid-rotor plot for ^{124}Te indicates that this interpretation is probably no longer valid for the (16^+) state in this isotope. From Fig. 4 the (16^+) state appears to be part of a weakly deformed collective structure, together with the yrast $10^{(+)}$, (12^+), and (14^+) states in Fig. 1. It would be interesting to search for this state in future experiments in the heavier even-mass Te isotopes. At even higher spins in ^{120,122}Te [4,16] the 22^+ state has being identified as the next fully aligned state. No change in the pattern in the rigid-rotor plots for ^{120,122}Te is observed for this level [4,16], indicating that the 22^+ level becomes the prominent noncollective state in ^{122}Te. Due to the population of ^{124}Te in the present experiments as a fission fragment such a high-spin state was not observed.

In summary, ^{124}Te was studied as a fragment in the fission of the compound systems formed in two heavy-ion-induced reactions using Gammasphere. The yrast cascade of ^{124}Te was extended to a state at ~5.5 MeV excitation energy and tentative spin-parity 16^+. This highest yrast state does not exhibit the characteristics of the favored noncollective oblate states with $I^\pi = 16^+$ observed in the lighter doubly even Te isotopes. Such a state is probably no longer yrast in ^{124}Te. The new yrast states assigned to ^{124}Te in the present work behave as members of a weakly deformed collective structure.

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