Fragmentation of mixed-symmetry excitations in stable even-even tellurium nuclei

S. F. Hicks,[1] J. R. Vanhoy,[2] and S. W. Yates[3,4]

[1]Department of Physics, University of Dallas, Irving, Texas 75062, USA
[2]Department of Physics, United States Naval Academy, Annapolis, Maryland 21402, USA
[3]Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA
[4]Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506-0055, USA

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The lowest six excited 2^+ levels of the even-even $^{122-130}$Te nuclei have been investigated using γ-ray spectroscopy following inelastic neutron scattering. These levels have been identified and their decay properties have been characterized from γ-ray excitation functions and γ-ray angular distributions; additionally, lifetimes of these levels have been deduced using the Doppler-shift attenuation method. Electromagnetic transition rates and $E2/M1$ multipole mixing ratios from the $2^+_x[x = 2–6] \to 2^+_1$ transitions have been examined to identify the lowest mixed-symmetry states in these nuclei. In each nucleus, the mixed-symmetry strength appears to be fragmented between more than one level. The summed $M1$ strength from the $2^+_x[x = 2–6]$ states to the 2^+_1 level agrees rather well with neutron-proton interacting boson model predictions in the U(5) or O(6) limits for these Te nuclei.

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I. INTRODUCTION

The neutron-proton version of the interacting boson model (IBM-2) predicts collective excited levels for vibrational nuclei that result from the neutrons and protons oscillating coherently, or symmetric excitations, and those for which the neutron and proton oscillations are distinguishable, so-called mixed-symmetry (MS) excitations [1]. Low-lying collective levels are obtained within the IBM-2 by coupling valence proton pairs (N_π) and neutron pairs (N_ν) as bosons, and these bosons form collective excitations. Excited levels are characterized by F spin values that range from $F_{\max} = \frac{1}{2}|N_\pi + N_\nu|$ to $F_{\min} = \frac{1}{2}|N_\pi - N_\nu|$. The lowest excited levels have the maximum F spin, the next lowest levels have $F = F_{\max} - 1$, and so on. These isovector excitations are predicted in other collective models as well; see, for example, Refs. [2–4].

For weakly deformed vibrational nuclei, the IBM-2 predicts the lowest MS state to be a 2^+ level at approximately 2 MeV. The state is predicted to decay to the lowest 2^+_1 symmetric state with a large $B(M1; 2^+_{1,\mathrm{MS}} \to 2^+_1) = 0.1–1\ \mu_N^2$ and to exhibit a small $E2/M1$ multipole mixing ratio. The $2^+_{1,\mathrm{MS}}$ state is also expected to decay to the 0^+_1 with a $B(E2)$ value of a few W.u. at most [1,5]. A small $E2/M1$ multipole mixing ratio for a $2^+ \to 2^+_1$ transition, however, is not a sufficient signature of MS character, rather the defining characteristic for the lowest 2^+ MS state in vibrational nuclei is a large $B(M1)$ value for the decay into the lowest symmetric state [5].

The lowest mixed-symmetry states in the nearly spherical Te nuclei have been examined previously both theoretically [3,4,6–8] and experimentally [9–12]. The Cd nuclei, which mirror the Te nuclei across the $Z = 50$ closed shell, also exhibit low-lying MS states [13–15]. Quasiparticle phonon model (QPM) calculations [4] predict that the 2^+_4 state is the lowest mixed-symmetry excitation across the Te isotopic chain with an excitation energy between 2.1 and 2.3 MeV, a $B(M1)$ value between 0.34 and 0.45 μ_N^2, and an $E2/M1$ multipole mixing ratio of $0.01 < \delta < 0.04$. The experimental 2^+_4 states at 2092 and 2184 have been identified previously as MS states in ^{124}Te [3] and ^{126}Te [9,10], respectively, in agreement with QPM calculations. Schauer *et al.* [10], also using the QPM in their study of ^{122}Te, found the calculated 2^+_3 level to be the lowest MS state and suggested the experimental 2099- and 2287-keV states as the best MS candidates in that nucleus. Investigation of the six lowest 2^+ states in ^{122}Te [12] revealed that none of these states decay into the 2^+_1 level with large $M1$ values. Moreover, they concluded that the MS strength is fragmented and weakened, possibly by intruder configurations. Rikovska *et al.* [7] investigated many of the Te isotopes using the IBM-2 and concluded that intruder configurations make the MS strength difficult to identify.

The motivation for this work is to see if a better understanding of the lowest MS strength in the Te nuclei can be obtained by investigating these isotopes in a consistent manner. To identify the lowest $2^+_{1,\mathrm{MS}}$ excitation in each of these nuclei, level spins, parities, branching ratios, multipole mixing ratios, level lifetimes, and transition probabilities must be well determined. As noted in Ref. [5], a complete set of experimental $B(M1)$ values for all 2^+ states in the energy region of interest is important not only for identifying the lowest MS state in each of these nuclei but also for examining fragmentation of MS strength on several levels. The $(n, n'\gamma)$ reaction mechanism provides a means for obtaining all the needed experimental information for identifying MS strength in the nuclei of interest.

II. EXPERIMENTAL METHOD AND DATA ANALYSIS

The six lowest 2^+ states of the even-even $^{122-130}$Te nuclei have been studied using γ-ray spectroscopy following inelastic neutron scattering. The measurements were made using the neutron production and γ-ray detection facilities at the University of Kentucky 7 MV electrostatic accelerator laboratory. The ^{3}H$(p, n)^3$He reaction was used as a neutron source. Samples were hung ≈3 cm from the end of the

TABLE I. The mass and isotopic abundance of each of the scattering samples used in the $(n, n'\gamma)$ measurements. The metallic ingots for the ^{128}Te measurements were non-uniform; the average diameter of the closely packed ingots is given.

Sample	Mass (g)	Enrichment (%)	Diameter (cm)	Height (cm)	Composition
^{122}Te	5.1	97.12	1.42	2.45	Powdered
^{124}Te	19.3	93.74	1.85	2.90	Powdered
^{126}Te	47.6	99.00	2.2	4.0	Metallic
^{128}Te	38.6	99.08	18.5	4.3	Metal ingots
^{130}Te	50	99.47	2.2	4.0	Metallic

tritium-filled gas cell, and the γ-ray detector was located about 1 m from the scattering samples; the geometry varied slightly from experiment-to-experiment because of the differences in the sizes of the scattering samples. The mass and isotopic enrichment of each of the scattering samples is given in Table I. Details of the measurements on ^{122}Te [12] and ^{126}Te [11] have been published previously, as has information on the neutron scattering facilities, TOF neutron background suppression, neutron monitoring, and data reduction techniques [16,17].

The γ rays emitted following inelastic neutron scattering were detected in the singles configuration with a Compton-suppressed n-type HPGe detector with a relative efficiency of 51–55% and an energy resolution of ≈2.1 keV FWHM at 1.33 MeV depending on the nucleus studied. A BGO annular detector surrounded the HPGe detector to provide Compton suppression and to serve as an active shield. The gain stability of the system was monitored with ^{56}Co and ^{152}Eu radioactive sources, and the energy calibration of the detector was achieved with these two sources as well as a ^{226}Ra source.

Excitation functions were measured for incident neutron energies between 2.0 and 3.3 MeV for each nucleus in appoximately 100-keV steps. The maximum incident neutron energy is well above the excitation energy expected for the lowest $2^+_{1,\mathrm{MS}}$ states in these nuclei. The thresholds and shapes of the γ-ray excitation functions were used to identify the lowest 2^+ levels and transitions originating from these levels, because all transitions from a given state should have a similarly shaped excitation function. Yields from the γ-ray excitation function measurements were corrected for γ-ray detection efficiency and were normalized to yields from the neutron monitor whose yields were corrected for efficiency as a function of neutron energy to obtain relative γ-ray production cross sections. These relative cross sections were then compared to theoretical values calculated with the statistical model code CINDY [18], using optical model parameters for this mass and energy region [19] to evaluate the consistency of the spin assignments and branching ratios determined from the angular distribution measurements.

The γ-ray angular distributions and Doppler shifts were measured for each Te nucleus at the incident neutron energies given in Table II. Information on a given level was obtained from the measurement with the lowest incident neutron energy exciting that level. The spins and parities of most of the levels considered here were determined unambiguously by an observed $E2$ transition to the ground state. For states

TABLE II. Incident neutron energies at which γ-ray angular distributions and Doppler-shift measurements were performed for each of the Te nuclei. Decay properties determined for each level are from the lowest-energy angular distribution from which the information can be obtained, thus minimizing the effects of feeding from higher-lying levels.

Sample	Incident neutron energy (MeV)
^{122}Te	1.7, 2.8, 3.3
^{124}Te	2.4, 3.3
^{126}Te	2.4, 2.8, 3.3
^{128}Te	2.2, 2.8, 3.3
^{130}Te	2.2, 3.4

without ground-state decays and to determine multipole mixing ratios, the measured angular distributions were compared with calculations from the statistical model code CINDY [18], as discussed previously [11,12]. The transition shown in Fig. 1(a) is of mixed $E2$ and $M1$ multipolarity. Figure 1(b) is an example of the χ^2 versus $\tan^{-1}(\delta)$ used to determine the multipole mixing ratio for this transition. The two minima with nearly identical χ^2 values are common for $2^+ \rightarrow 2^+$ transitions in $(n, n'\gamma)$ measurements. Both values are listed in Table III when two nearly identical minima are observed. The value with the lower χ^2 is listed first. The γ-ray angular distributions observed for ground-state transitions from the 2190.2-keV and 2282.4-keV levels in ^{130}Te are shown in Figs. 1(c) and 1(d), respectively.

Level lifetimes were extracted using the Doppler-shift attenuation method (DSAM) following inelastic neutron scattering. At the recoil velocities present in this experiment, the γ-ray peaks have centroids with the angular dependence

$$E_\gamma(\theta) = E_o\,[1 + F(\tau)\beta\cos\langle\theta\rangle]\,, \tag{1}$$

where E_o is the unshifted γ-ray energy, $F(\tau)$ is the Doppler-shift attenuation factor, $\beta = v_{\mathrm{cm}}\,c, \theta$ is the γ-ray emission angle with respect to the incident neutrons, and $E_\gamma(\theta)$ is the γ-ray energy measured at angle θ. Lifetimes were determined by comparing experimental and theoretical Doppler-shift attenuation factors. Theoretical values of $F(\tau)$ were calculated using the theory of Winterbon [20], because this method has been shown to yield reliable lifetimes with oxide and metal targets [21]. Mean lifetimes in the range of a few fs to approximately 2 ps were determined in this experiment. The Doppler-shifts for two transitions observed in ^{128}Te are shown in Fig. 2.

III. DISCUSSION

Level energies, transition energies, branching ratios, multipole mixing ratios, lifetimes, $B(M1)$ and $B(E2)$ values for the lowest six 2^+ states in ^{124,128,130}Te are given in Table III. Similar information for ^{122}Te [12] and ^{126}Te [11] has been published previously. The 2^+_3-2^+_6 states in these nuclei are observed to have energies between 1.85 and 2.55 MeV, which

TABLE III. Experimental information for the lowest six 2^+ levels in ^{124,128,130}Te observed in these $(n, n'\gamma)$ measurements. Similar information has previously been published for ^{122,126}Te [11,12]. Uncertainties are in the least significant digit(s). Multipole mixing ratios for the 713.8-keV and 1436.6-keV transitions from the 2039-keV level in ^{124}Te could not be determined because of the doublet nature of each of these decays. The $B(M1)$ and $B(E2)$ values listed for these two decays are upper limits calculated by assuming pure $M1$ and $E2$ transitions. For some $2^+ \rightarrow 2^+$ transitions two solutions for $\tan^{-1}(\delta)$ are obtained with nearly identical χ^2 values. In these situations, both solutions are given with the value of $\tan^{-1}(\delta)$ having the smaller χ^2 value, and the associated $B(M1)$ and $B(E2)$ values, listed immediately above those for the solution with the larger χ^2 value.

J^π	E_x (keV)	E_γ (keV)	E_f (keV)	BR (%)	$\tan^{-1}(\delta)$	τ (fs)	$B(M1)$ (μ_N^2)	$B(E2)$ (W.u.)
				^{124}Te				
2_1^+	602.73(1)	602.73(1)	0	100		8900^{+100}_{-100} [a]		31.5^{+7}_{-7}
2_2^+	1325.52(6)	722.79(4)	603	87(1)	-0.53^{+6}_{-3}	850^{+170}_{-130}	$1.14^{+4}_{-7} \times 10^{-1}$	29.9^{+17}_{-12}
					-1.44^{+3}_{-3}		$2.6^{+1}_{-1} \times 10^{-3}$	114^{+4}_{-4}
		1325.51(5)	0	13(1)				$8.3^{+8}_{-8}E$-1
2_3^+	2039.29(8)	382.29(5)	1657	<1		880^{+110}_{-110}		<31
		713.78(5)	1326	2(1)			$<3.5^{+25}_{-19} \times 10^{-3}$	$<2.7^{+19}_{-15}$
		790.71(2)	1249	1(1)				$8.1^{+100}_{-81}E$-1
		1436.56(9)	603	61(1)			$<1.3^{+2}_{-2} \times 10^{-2}$	$<2.5^{+4}_{-3}E$-2
		2039.30(7)	0	36(1)				$2.6^{+4}_{-4}E$-1
2_4^+	2092.03(9)	766.33(10)	1326	1(1)	0.66^{+88}_{-101}	740^{+120}_{-100}	$1.1^{+20}_{-13}E$-3	$4.3^{+71}_{-43}E$-1
		1489.03(9)	603	92(1)	1.13^{+3}_{-3}		$3.9^{+7}_{-6}E$-3	3.1^{+6}_{-5}
					0.06^{+3}_{-3}		$2.1^{+4}_{-3}E$-2	$1.4^{+2}_{-2}E$-2
		2091.75(7)	0	7(1)				$5.3^{+17}_{-14}E$-2
2_5^+	2323.25(8)	997.00(6)	1326	2(1)	-0.38^{+19}_{-28}	85^{+7}_{-7}	$1.2^{+8}_{-7}E$-2	$7.4^{+47}_{-41}E$-1
		1720.30(7)	603	96(2)	-0.03^{+9}_{-3}		$1.3^{+2}_{-2}E$-1	$1.5^{+2}_{-2}E$-2
		2323.10(32)	0	2(1)				$7.8^{+49}_{-42}E$-2
2_6^+	2453.83(5)	1128.27(3)	1326	12(1)	-1.00^{+44}_{-38}	360^{+40}_{-40}	$3.8^{+17}_{-15}E$-3	2.9^{+14}_{-10}
		1205.54(12)	1249	7(1)				1.7^{+5}_{-4}
		1851.50(5)	603	64(1)	0.16^{+19}_{-13}		$1.6^{+3}_{-2}E$-2	$4.6^{+8}_{-6}E$-2
					1.00^{+13}_{-16}		$4.7^{+11}_{-8}E$-3	1.3^{+3}_{-3}
		2454.40(10)	0	17(1)				$1.2^{+3}_{-2}E$-1
				^{128}Te				
2_1^+	743.20(5)	743.20(5)	0	100		4780^{+40}_{-40} [b]		19.7^{+4}_{-4}
2_2^+	1519.96(6)	776.73(5)	743	96.9(1)	1.26^{+6}_{-9}	2400^{+1100}_{-600}	$4.6^{+18}_{-9}E$-3	27.7^{+100}_{-94}
					-0.09^{+12}_{-7}		$4.9^{+17}_{-16}E$-2	0.25^{+23}_{-25}
		1520.00(9)	0	3.1(1)				$3.4^{+13}_{-12}E$-2
2_3^+,3^+	1968.51(7)	448.7(3)	1520	⩽0.9		301^{+25}_{-22}		
		1225.30(5)	743	⩾99.1	1.32^{+6}_{-6}		$6.7^{+6}_{-6}E$-3	23.9^{+24}_{-23}
					0.13^{+13}_{-7}		$1.0^{+1}_{-1}E$-1	0.42^{+5}_{-6}
2_4^+	2193.46(7)	1450.24(5)	743	91.2(1)	-0.03^{+9}_{-6}	72^{+2}_{-2}	$2.4^{+1}_{-1}E$-1	$3.8^{+15}_{-8}E$-2
					1.19^{+6}_{-9}		$3.3^{+3}_{-2}E$-2	36.4^{+21}_{-26}
		2193.52(14)	0	8.8(1)				$5.1^{+2}_{-2}E$-1
2_5^+	2352.34(7)	1608.88(6)	743	86.8(2)	-0.19^{+10}_{-9}	198^{+14}_{-10}	$5.8^{+5}_{-5}E$-2	$3.0^{+3}_{-3}E$-1
				13.2(2)	1.35^{+9}_{-9}		$2.9^{+2}_{-3}E$-3	8.3^{+7}_{-8}
		2353.25(14)	0	13.2(2)				$2.0^{+2}_{-2}E$-1
2_6^+	2508.14(7)	1764.88(6)	743	73.5(4)	0.56^{+22}_{-18}	528^{+91}_{-69}	$1.0^{+3}_{-3}E$-2	$4.9^{+15}_{-12}E$-1
		2508.30(13)	0	26.5(4)				$1.1^{+2}_{-2}E$-1

TABLE III. *(Continued.)*

^{130}Te								
J^{π}	E_x (keV)	E_{γ} (keV)	E_f (keV)	BR (%)	$\tan^{-1}(\delta)$	τ (fs)	$B(M1)$ (μ_N^2)	$B(E2)$ (W.u.)
2_1^+	839.49(4)	839.49(4)	0	100		3320^{+70}_{-70}[c]		15.1^{+3}_{-3}
2_2^+	1588.17(8)	748.76(4)	839	98.1(3)	1.00^{+6}_{-6}	<3000	$<1.3^{+1}_{-1}E$-2	$<21^{+1}_{-1}$
					0.16^{+10}_{-13}		$<4.3^{+2}_{-1}E$-2	$<7.3^{+2}_{-2}E$-1
		1588.09(2)	0	1.9(1)				$<1.3^{+1}_{-1}E$-2
2_3^+	1885.60(4)	1046.11(2)	839	98.5(4)	1.38^{+6}_{-6}	470^{+40}_{-30}	$3.7^{+3}_{-4}E$-3	34^{+3}_{-3}
					-0.25^{+10}_{-3}		$9.7^{+8}_{-11}E$-2	2.2^{+3}_{-2}
		1885.60(2)	0	1.5(1)				$2.8^{+4}_{-4}E$-2
2_4^+	2190.21(4)	1350.98(3)	839	44.2(4)	1.41^{+6}_{-6}	590^{+50}_{-50}	$4.4^{+5}_{-4}E$-4	3.4^{+4}_{-4}
					-0.28^{+9}_{-9}		$1.6^{+2}_{-2}E$-2	0.27^{+4}_{-3}
		2190.48(3)	0	55.8(6)				$3.9^{+4}_{-4}E$-1
2_5^+	2282.43(4)	1442.95(3)	839	79.3(6)	1.29^{+13}_{-6}	150^{+10}_{-10}	$7.7^{+8}_{-9}E$-3	16^{+2}_{-2}
					-0.13^{+13}_{-13}		$9.8^{+10}_{-9}E$-2	$2.9^{+3}_{-3}E$-1
		2282.42(3)	0	20.7(5)				$4.7^{+5}_{-4}E$-1
(2_6^+)	2300.14(7)	1460.58(3)	839	96.3(8)	1.44^{+6}_{-6}	660^{+60}_{-50}	$4.5^{+4}_{-4}E$-4	4.5^{+5}_{-5}
					-0.28^{+7}_{-6}		$2.5^{+3}_{-3}E$-2	$3.6^{+4}_{-4}E$-1
		2300.20(6)	0	3.7(4)				$1.8^{+4}_{-4}E$-2

[a]Reference [22].
[b]Reference [23].
[c]Reference [24].

is the energy region predicted by the IBM-2 for the lowest 2^+ MS excitations in vibrational nuclei [1].

Lifetimes for the first six 2^+ levels in $^{122-130}$Te are given in Table IV. The lifetimes of the 2_1^+ states are well established for these nuclei [22–26] and are longer than can be obtained using the Doppler-shift attenuation method; however, lifetimes, or at least limits, were obtained for the other states considered. Lifetimes were previously available for only a few of these states, and these values are also listed in Table IV. The agreement is rather good between $(n, n'\gamma)$ values and those obtained using other methods.

The decays of these 2^+ levels to the 2_1^+ states are observed to be of mixed $E2/M1$ multipolarity. Multipole mixing ratios are presented in Table V, along with previously adopted values. The doublet nature of the 2039-keV state in ^{124}Te precludes a determination of $\delta(2_3^+ \rightarrow 2_1^+)$ for that nucleus. In Table V the

TABLE IV. Lifetimes in fs for the $2_x^+[x = 2–6]$ levels in $^{122-130}$Te from $(n, n'\gamma)$ measurements. The adopted lifetimes for the 2_1^+ states are included, as are values previously measured for the other 2^+ states.

Level	^{122}Te		^{124}Te		^{126}Te		^{128}Te		^{130}Te	
	$(n, n'\gamma)$	Previous	$(n, n'\gamma)$	Previous	$(n, n'\gamma)$	Previous	$(n, n'\gamma)$	Previous	$(n, n'\gamma)$	Adopted
2_1^+		10800^{+100}_{-100}[a]		8900^{+100}_{-100}[b]		6520^{+170}_{-170}[d]		4780^{+40}_{-40}[e]		3320^{+70}_{-70}[f]
2_2^+	1140^{+840}_{-360}	1000^{+200}_{-200}[a]	850^{+170}_{-130}	600^{+300}_{-300}[b]	1800^{+200}_{-200}	1000^{+300}_{-300}[d]	2400^{+1100}_{-600}		>2900	
				2200^{+400}_{-300}[c]						
2_3^+	540^{+80}_{-60}		880^{+110}_{-110}	1000^{+700}_{-100}[c]	1100^{+100}_{-100}		300^{+30}_{-20}		470^{+40}_{-30}	
2_4^+	380^{+30}_{-30}		740^{+120}_{-100}	600^{+100}_{-100}[c]	95^{+2}_{-2}		72^{+2}_{-2}		590^{+50}_{-50}	
2_5^+	210^{+10}_{-10}		85^{+7}_{-7}		41^{+2}_{-2}		200^{+10}_{-10}		152^{+2}_{-2}	
2_6^+	1200^{+500}_{-300}		360^{+40}_{-40}		300^{+20}_{-20}		530^{+90}_{-70}		650^{+60}_{-50}	

[a]Reference [25].
[b]Reference [22].
[c]Reference [26].
[d]Reference [26].
[e]Reference [23].
[f]Reference [24].

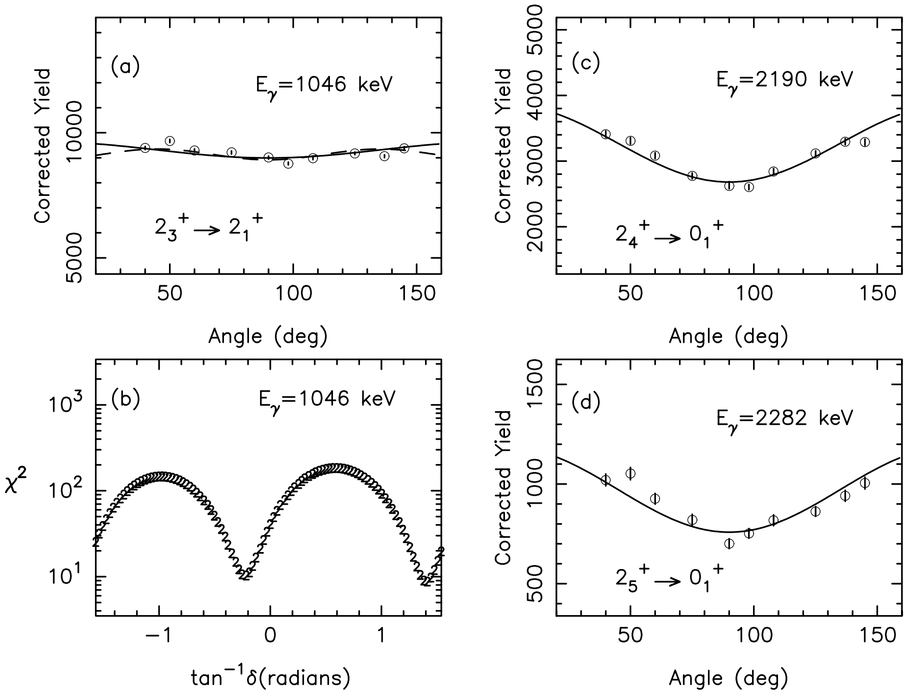

FIG. 1. The γ-ray angular distribution with Legendre polynomial fits to the data for the 1046.1-keV transition from the 1885.6-keV level in ^{130}Te to the 2_1^+ state, panel (a). In panel (b), the χ^2 vs $\tan^{-1}\delta$ curve used to obtain the multipole mixing ratio for this transition is shown. Two solutions for the multipole mixing ratio are determined from the curve. The γ-ray angular distributions for ground-state transitions from the 2_4^+ level at 2190.2 keV and from the the 2_5^+ level at 2282.4 keV in ^{130}Te are shown in panels (c) and (d).

value of δ with the lower absolute χ^2 value is listed first for transitions with two possible solutions, although the difference in χ^2 is sometimes very small, as is shown in Fig. 1(b). For several transitions, the existing δs are from previous $(n, n'\gamma)$ measurements, which also listed two values of δ [25,28,29]. The agreement between previously adopted values and the new values for δ is generally quite good. Table V shows there are many transitions in these nuclei that have small, nearly zero, multipole mixing ratios, consistent with predictions of the IBM-2 [1] and QPM [4] models for the lowest 2^+ MS states in vibrational nuclei. These small $E2/M1$ multipole mixing ratios, however, are not a sufficient signature for the assignment of MS character to a nuclear state [5].

Electromagnetic transition rates are needed to identify most clearly the lowest 2^+_{MS} level in vibrational nuclei and to look for the fragmentation of the MS strength in more than one level. The experimental $B(E2)$ and $B(M1)$ values for transitions from the $2_x^+[x = 2\text{–}6]$ states to the 0_1^+ and

TABLE V. Comparison of measured multipole mixing ratios for decays from the $2_x^+[x = 2\text{–}6]$ states to the 2_1^+ levels in the even-mass $^{122-130}$Te nuclei with previous values.

Transition	^{122}Te		^{124}Te		^{126}Te		^{128}Te		^{130}Te	
	δ[a]	δ^{new}	δ[b]	δ^{new}	δ[c]	δ^{new}	δ[d]	δ^{new}	δ[e]	δ^{new}
$2_2^+ \rightarrow 2_1^+$	−3.7(4)	-1.46^{+47}_{-84}	−3.4(3)	-0.59^{+8}_{-4}	-4.25^{+15}_{-1}	-4.5^{+10}_{-17}	4.7(2)	3.11^{+79}_{-75}	0.65(15)	1.56^{+23}_{-19}
				-7.6^{+14}_{-23}		-0.78^{+14}_{-5}		-0.09^{+12}_{-7}		0.16^{+10}_{-10}
$2_3^+ \rightarrow 2_1^+$	0.04(3)	2.7^{+24}_{-12}	Doublet		−0.04(3)	-0.03^{+9}_{-6}	−0.210(11)	3.90^{+127}_{-79}	−0.175(10)	5.2^{+24}_{-13}
		−0.03(19)			2.84(24)			0.13^{+14}_{-7}		-0.26^{+10}_{-3}
$2_4^+ \rightarrow 2_1^+$	2.6(2)	2.3(2)	0.10(23)	2.12^{+18}_{-15}	0.002^{+18}_{-2}	0.00^{+13}_{-3}	−0.116(13)	-0.03^{+9}_{-6}	−0.27(2)	6.2^{+37}_{-17}
		0.00^{+6}_{-3}		0.06(3)		2.0^{+9}_{-3}		2.50^{+51}_{-53}		−0.29(10)
$2_5^+ \rightarrow 2_1^+$	1.7(2)	1.3(3)	0.18(20)	-0.03^{+9}_{-3}	3.02(18)	-0.40^{+18}_{-15}	−0.230(14)	-0.19^{+10}_{-10}	−0.10(2)	3.5^{+31}_{-6}
		0.3^{+2}_{-1}				$-11 < \delta < 11$				-0.13^{+13}_{-14}
$2_6^+ \rightarrow 2_1^+$		-11.0^{+44}_{-54}	−0.02(4)	0.16^{+19}_{-13}	1.54(9)	0.68^{+45}_{-32}	−0.230(14)	-0.19^{+10}_{-10}	−0.20(2)	7.6^{+65}_{-24}
		−0.55(8)	2.1(3)	1.56^{+56}_{-44}						-0.29^{+7}_{-7}

[a]Reference [25].
[b]Reference [22].
[c]Reference [26].
[d]Reference [23].
[e]Reference [24].

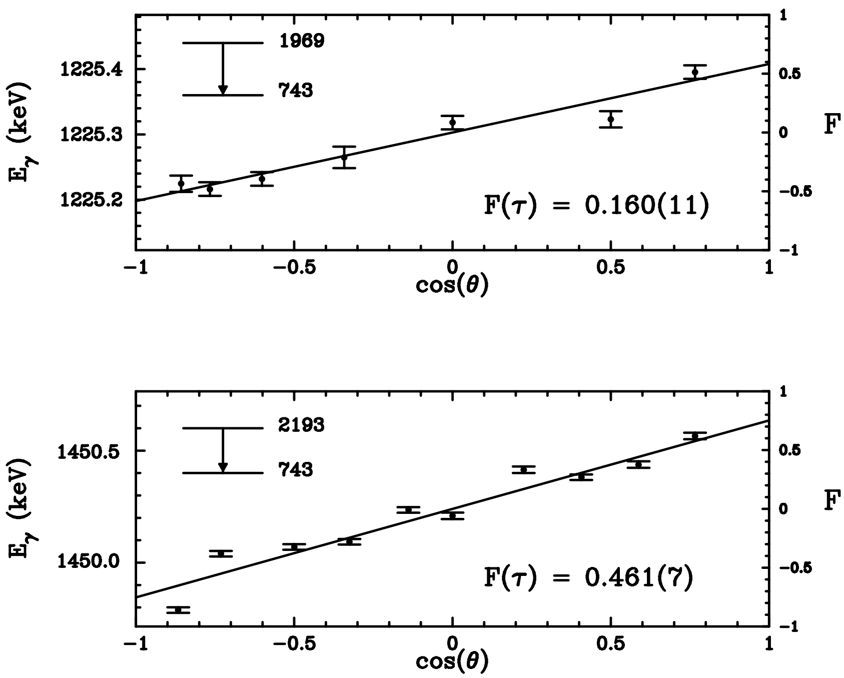

FIG. 2. Doppler shifts for the 1125.3-keV transition from the 2_3^+ level and for the 1450.2-keV transition from the 2_4^+ level in ^{128}Te. Experimental $F(\tau)$ values are shown for each transition.

2_1^+ states, respectively, are given in Table III for ^{124,128,130}Te and in Ref. [12] for ^{122}Te and in Ref. [11] for ^{126}Te. For comparison, the reduced transition probabilities are shown in Fig. 3 and Fig. 4 for $E2$ and $M1$ transitions, respectively.

The lowest-energy MS excitations in vibrational nuclei are predicted to have weak $E2$ transitions to the ground state [1,30]. The $B(E2; 2_x^+ \rightarrow 0_1^+)$ values shown in Fig. 3 are all <1 W.u. consistent with model predictions, except for transitions from the 2_2^+ and 2_3^+ levels in ^{122}Te.

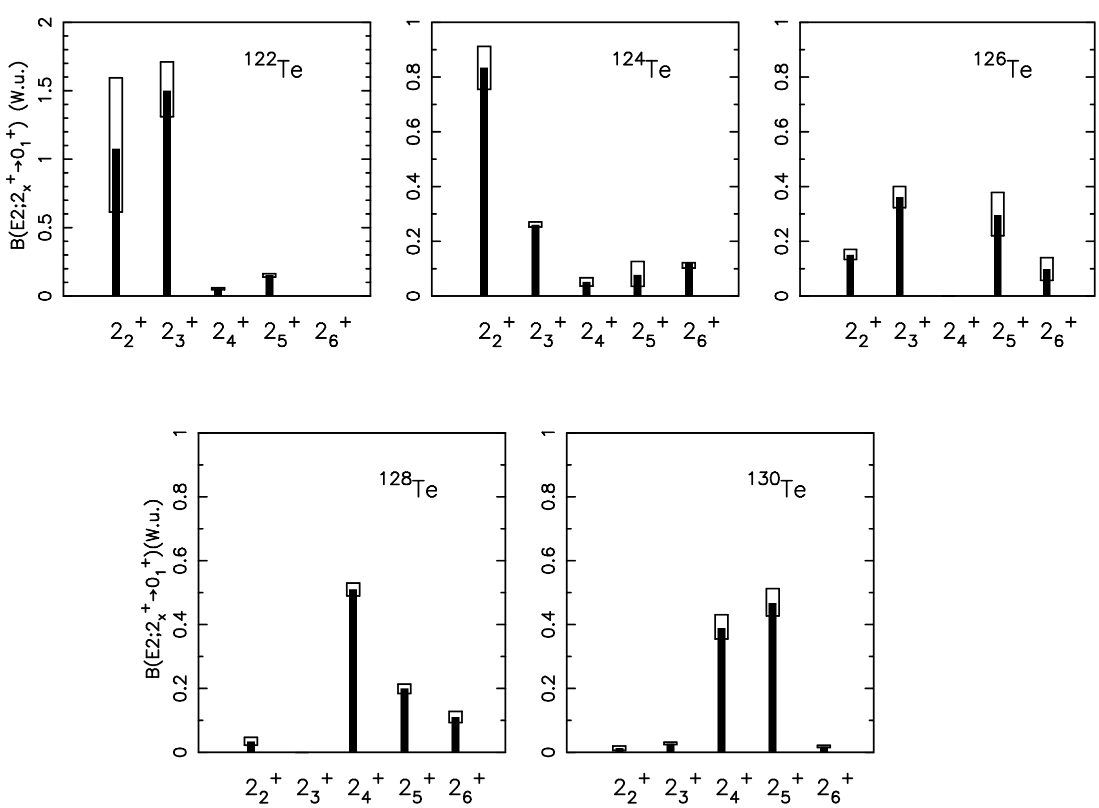

FIG. 3. $B(E2; 2_x^+ \rightarrow 0_1^+)[x = 2\text{–}6]$ values for each of the tellurium nuclei studied. The vertical scale for the ^{122}Te panel differs by a factor of two from the panels for each of the other nuclei studied.

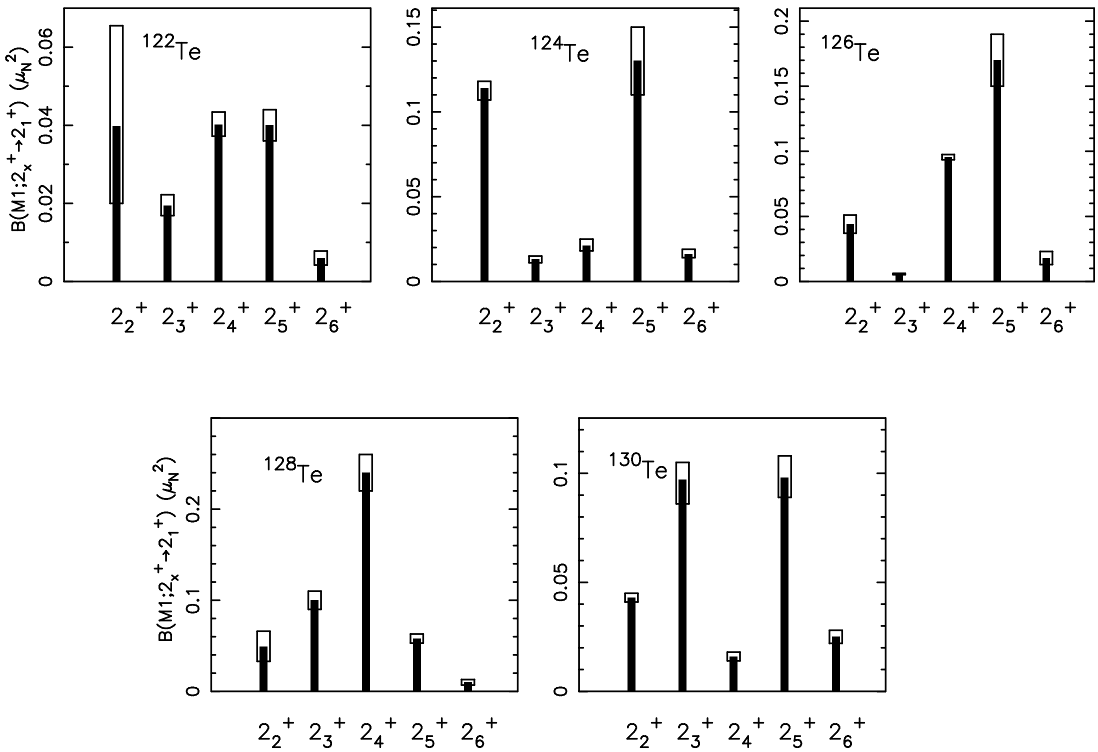

FIG. 4. $B(M1;2_x^+\rightarrow 2_1^+)[x=2\text{–}6]$ values for each of the tellurium nuclei studied. All $B(M1)$ values shown were calculated using the smaller multipole mixing ratio when two unique values of δ with similar χ-squared values resulted from statistical model calculations. No mixing ratio was obtained for the 2_3^+ level in ^{124}Te because of the doublet nature of that level, so what is shown represents an upper limit on the $B(M1)$ value for this level. Uncertainties are shown with the open boxes, and the vertical scale differs for each panel.

The most definitive MS signature is the observation of strong $M1$ decays into the lowest symmetric level [5]. To calculate the $M1$ strength depicted in Fig. 4, the smaller of the two observed multipole mixing ratios was used in cases where more than one δ is listed for a single level. This procedure was found to represent best the data for ^{114}Cd [14]. From Fig. 4, the observed $M1$ strength into the 2_1^+ state in ^{122}Te is found to be fragmented between decays from the 2_2^+, 2_4^+, and 2_5^+ levels and has a relatively weak value of $\approx 0.04\ \mu_N^2$ for each of these transitions. This fragmentation and weakness for any individual level has been discussed previously and may be due to mixing with intruder configurations [7,12]. (The ^{122}Te figure reflects a scale correction over Fig. 9 of Ref. [12], although the values in Table I of that reference are correct.) The best single candidate for the lowest $2_{\rm MS}^+$ state in ^{122}Te is the 2_4^+ level because it has a nearly zero multipole mixing ratio for its decay into the 2_1^+ level and a small $B(E2)$ to ground which agrees with QPM calculations [4], but the $B(M1)$ value is almost an order of magnitude smaller than that predicted in the same calculations. The 2_4^+ states at 2092 and 2184 keV have been identified previously as MS states in ^{124}Te [3] and ^{126}Te [4,9], respectively, in agreement with QPM calculations. The ^{124}Te 2_4^+ state, however, is not observed to decay with a large $B(M1)$ value in this work, as can be seen in Fig. 4. The decay characteristics observed for the 2_5^+ level in ^{124}Te indicate it is the best MS candidate in this nucleus. The 2_2^+ state has an $M1$ value of magnitude comparable to that of the 2_5^+ state in ^{124}Te, but its mixing ratio is larger than predicted for a MS level in a vibrational nucleus, and its $B(E2)$ into the 2_1^+ is $\approx$30 W.u., which is indicative of symmetric two-phonon collectivity. For ^{126}Te the $M1$ strength into the 2_1^+ level is rather large for the decays from both the 2_4^+ level at 2184 keV and the 2_5^+ state at 2421 keV and the $B(E2)$ values for the decays into the 0_1^+ level are small for both levels. The $M1$ strength appears to be fragmented between these two levels in ^{126}Te, rather than isolated only in the 2_4^+ state, although 2_4^+ has best overall characteristics in agreement with Refs. [9,10] because $\delta(2_4^+\rightarrow 2_1^+)$ decay is closer to zero. In ^{128}Te, the lowest QPM $2_{1,\rm MS}^+$ state is calculated at 2.142 MeV with $\delta(2_{1,\rm MS}^+\rightarrow 2_1^+)=0.023$, and $B(M1;2_{1,\rm MS}^+\rightarrow 2_1^+)=0.38\ \mu_N^2$ [4]. The observed $\delta(2_4^+\rightarrow 2_1^+)=-0.03^{+0.09}_{-0.06}$, the excitation energy of the 2_4^+ level, and the observed $M1$ strength from this level are consistent with the QPM calculations [4]. The 2_3^+ state at 1968.5 keV also has a rather large $B(M1;2_3^+\rightarrow 2_1^+)=0.10\ \mu_N^2$, which indicates that the MS strength may also be fragmented in ^{128}Te. Some care should be taken with this level, as the 2^+ spin assignment is preferred but not completely certain. The 2_3^+ and the 2_5^+ levels at 1886 and 2282 keV, respectively, in ^{130}Te exhibit similar $M1$ strengths of about 0.1 μ_N^2. Mixing ratios do not clearly eliminate one of these states as a MS candidate, so again the MS strength appears to be fragmented in this nucleus.

It is interesting to compare the summed $M1$ strength for each of the Te nuclei with the strength predicted for the lowest MS state within the U(5) vibrational and O(6) γ-soft limits of the IBM-2. The $M1$ strengths predicted within the IBM-2 for

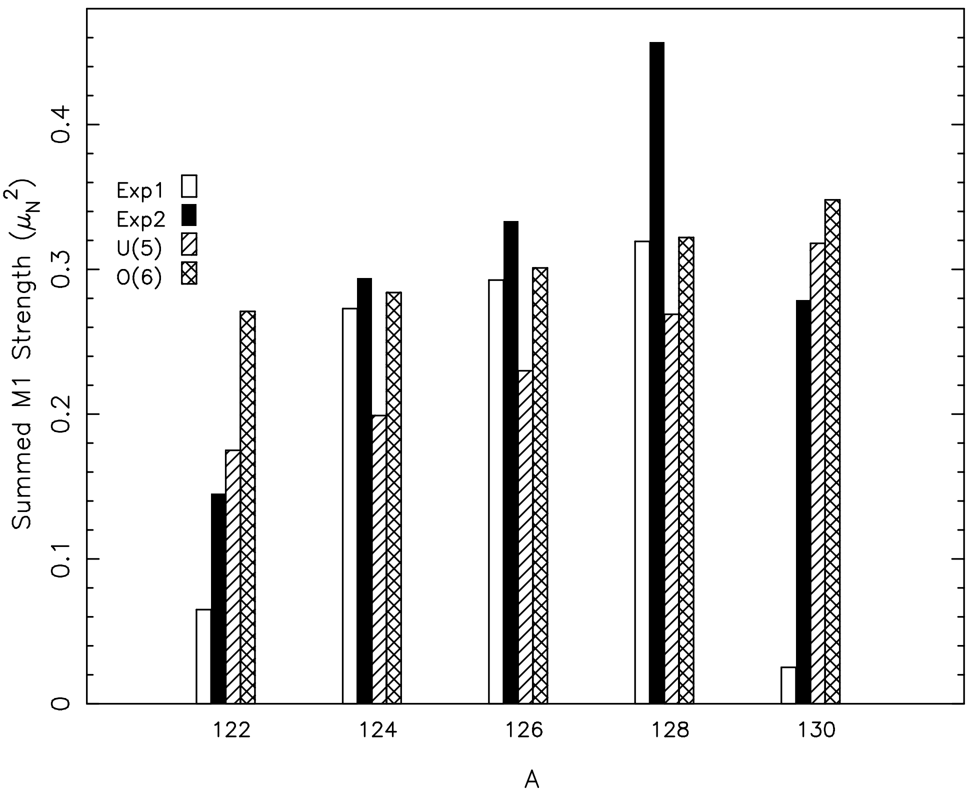

FIG. 5. The summed strength from $M1$ transitions from the $2_x^+[x = 2\text{–}6]$ levels into the 2_1^+ state along with calculated $M1$ strengths within the U(5) and O(6) limits of the IBM-2. The label "Exp2" represents the summed strength when the smaller multipole mixing ratio is used, while the label "Exp1" represents the sum when the multipole mixing ratio with the smaller χ^2 value is used.

the U(5) and O(6) limits [5,30,31], respectively, are given by

$$B(M1; 2^+_{\rm MS} \rightarrow 2^+_1) = \frac{3}{4\pi}{\mu_N}^2 \frac{6N_\pi N_\nu}{N^2}(g_\pi - g_\nu)^2 \qquad (2)$$

$$B(M1; 2^+_{\rm MS} \rightarrow 2^+_1) = \frac{3}{4\pi}{\mu_N}^2 \frac{3(N+2)(N+4)N_\pi N_\nu}{4N^2(N+1)} \times (g_\pi - g_\nu)^2. \qquad (3)$$

The tellurium isotopes with two protons beyond the closed $Z = 50$ shell are considered to have $N_\pi = 1$ and $N_\nu = [6\text{–}2]$ for $^{[122-130]}$Te, respectively. The boson g factors used in the calculations are the standard values of $g_\pi = 1$ and $g_\nu = 0$. Comparisons of the predicted $M1$ strengths within these limits, as well as the summed experimental $B(M1; 2_x^+ \rightarrow 2_1^+)[x = 2\text{–}6]$ values, are pictured in Fig. 5. The data respresented by "Exp2" are the sum of the $M1$ transitions shown in Fig. 4, while "Exp1" represents the summed $M1$ strengths if the lower χ^2 multipole mixing ratios are used to calculate $B(M1)$ values for transitions where two possible mixing ratios were obtained and should serve as a lower limit on the summed values. Uncertainties on the summed strengths are under 8% except for ^{122}Te which has an uncertainty of about 40%. The observed "Exp2" $M1$ strength is in rather good agreement with the U(5) model limits of the IBM-2 for ^{122}Te and ^{130}Te. The observed strength appears closer to O(6) limits for ^{124}Te and ^{126}Te, while for ^{128}Te the observed strength is larger than predicted by either model limit. This may indicate that the assumption of the smaller multipole mixing ratio when evaluating the MS strength is not completely justified.

IV. SUMMARY

Inelastic neutron scattering experiments have been performed on the even-even $^{122-130}$Te nuclei to investigate the mixed-symmetry characteristics of the lowest 2^+ excited levels. Excitation and decay energies, spins, parities, multipole mixing ratios, and lifetimes have been determined through γ-ray excitation functions, angular distributions, and Doppler shifts. The deduced transition rates into the ground state and $M1$ rates to the 2_1^+ level were used to evaluate the MS characteristics of low-lying 2^+ states in each of these nuclei. The $M1$ strength is found to be highly fragmented in each of these nuclei; although, if all MS characteristics are considered, then it is possible to label a best MS candidate in all of these nuclei except ^{130}Te. The 2_4^+ level is predicted to be the best MS candidate across the Te isotopic chain within the QPM [4] and, experimentally, this level is observed to be the best candidate in ^{122}Te, ^{126}Te, and ^{128}Te. However, in ^{124}Te the 2_5^+ level is the best MS candidate and in ^{130}Te no single best candidate can be identified. Comparisons of the summed experimental $M1$ strength from the observed 2^+ levels to the 2_1^+ states with the U(5) and O(6) limits indicate that the observed strength in ^{122}Te and ^{130}Te agrees well with the calculated U(5) limit. For $^{124-128}$Te the experimental values appear to be represented better by the O(6) model limits.

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