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Investigation of the reorientation effect on ^{122}Te, ^{124}Te, ^{126}Te, ^{128}Te, and ^{130}Te†

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Measurements of the Coulomb excitation probabilities of the first 2^+ states in ^{122,124,126,128,130}Te have been made with ^{4}He and ^{16}O projectiles. The values of the reduced transition probabilities $B(E2;0^+\rightarrow 2^+)$ and the static quadrupole moments of the first 2^+ states have been determined. The measurements yield for Q_{2^+} and $B(E2;0^+\rightarrow 2^+)$: (-0.44 ± 0.10) eb or (-0.22 ± 0.10) eb and (0.666 ± 0.011) e^2b^2 for ^{122}Te; (-0.46 ± 0.10) eb or (-0.11 ± 0.10) eb and (0.569 ± 0.011) e^2b^2 for ^{124}Te; (-0.28 ± 0.10) eb or (-0.20 ± 0.10) eb and (0.479 ± 0.011) e^2b^2 for ^{126}Te; (-0.33 ± 0.11) eb or (-0.26 ± 0.11) eb and (0.387 ± 0.011) e^2b^2 for ^{128}Te; (-0.14 ± 0.12) eb or (-0.09 ± 0.12) eb and (0.290 ± 0.011) e^2b^2 for ^{130}Te.

I. INTRODUCTION

The even stable tellurium isotopes with only two protons outside the magic shell of 50 protons and a number of neutrons ranging from 68 to 78 could be expected to be nearly spherical and their level structure should be reasonably well explained by the vibrational model.[1,2] However, measurements of the reorientation effect in ^{122}Te,[3] ^{126}Te, and ^{128}Te[4] showed that the quadrupole moment of the 2^+ levels of these nuclei was appreciably different from zero. In order to explain these large Q_{2^+} values, a considerable amount of theoretical work has been developed. For instance, Lopac[5] calculated the properties of the even tellurium isotopes assuming the protons to be coupled by a quadrupole operator. Sips[6] calculated admixtures of two-phonon into the one-phonon states corresponding to the third-order anharmonicity to determine the Q_{2^+} values. On the other hand, Balbutzev and Jolos,[7] Almoney and Borse,[8] Sorensen (only for ^{122}Te),[9] and more recently Marshalek[10] performed calculations using pairing plus quadrupole-quadrupole forces, based on somewhat different types of boson expansion methods.

The Q_{2^+} values predicted by all these authors are rather contradictory. In fact, Lopac[5] and Sips[6] obtained negative values, whereas Balbutzev and Jolos,[7] Almoney and Borse,[8] Sorensen,[9] and Marshalek[10] predicted large and positive values decreasing from ^{122}Te to ^{130}Te. In view of the above theoretical inconsistencies and in view of the fact that a precise knowledge of the variation of Q_{2^+} with neutron number for the tellurium isotopes bears such a crucial role in our understanding of the structure of these nuclei, we wish to report in this paper a thorough investigation of the reorientation effect on all the available stable even tellurium nuclei (from ^{122}Te to ^{130}Te). It should be noted that preliminary results for $B(E2;0^+\rightarrow 2^+)$ and Q_{2^+} on ^{122}Te and ^{124}Te disagree with the results reported here.[11] This is due to an error found in the analysis of the data which has been subsequently corrected.

II. EXPERIMENTAL PROCEDURE AND RESULTS

Beams of ^{4}He and ^{16}O from the tandem Van de Graaff accelerator of the University of Montreal have been used on thin enriched targets of ^{122,124,126,128,130}Te. The targets having a thickness from 10 to 25 μg/cm^2 were prepared by vacuum evaporation onto a 10-μg/cm^2-thick carbon backing. The excitation probabilities for

TABLE I. Isotope composition of targets in percent.

	Isotope							
Target	120	122	123	124	125	126	128	130
122	0.4 ± 0.1	73.5 ± 0.1	3.6 ± 0.1	4.9 ± 0.1	3.3 ± 0.1	5.0 ± 0.1	5.6 ± 0.1	3.7 ± 0.1
124	<0.2	<0.2	1.12 ± 0.20	90.97 ± 0.20	3.31 ± 0.20	2.25 ± 0.20	1.40 ± 0.20	0.95 ± 0.20
126	<0.02	<0.02	<0.02	0.05 ± 0.02	0.20 ± 0.05	98.69 ± 0.05	0.81 ± 0.05	0.24 ± 0.05
128	<0.05	<0.05	<0.05	<0.05	<0.05	0.06	99.46 ± 0.1	0.48 ± 0.1
130	<0.02	0.04 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.03 ± 0.01	0.10 ± 0.02	0.30 ± 0.05	99.49 ± 0.05

the ^{4}He and ^{16}O projectiles were obtained by comparing resolved elastically and inelastically scattered particle groups detected in four surface-barrier detectors placed at scattering angles of ±157.5 and ±172.5°. The ^{4}He projectile energy was 10 MeV (8-MeV ^{4}He particles were also employed for ^{122}Te and ^{124}Te), whereas the ^{16}O energy was 42 MeV.[12] The energy resolution varied from 29 to 37 keV for ^{4}He particles and from 160 to 240 keV for ^{16}O particles depending on the target thickness and scattering angles. Some typical spectra are shown in Figs. 1 and 2.

The ratios $R_{exp} = d\sigma_{inel}\,(2^+)/d\sigma_{el}$ were extracted from the data after the contributions from iso-

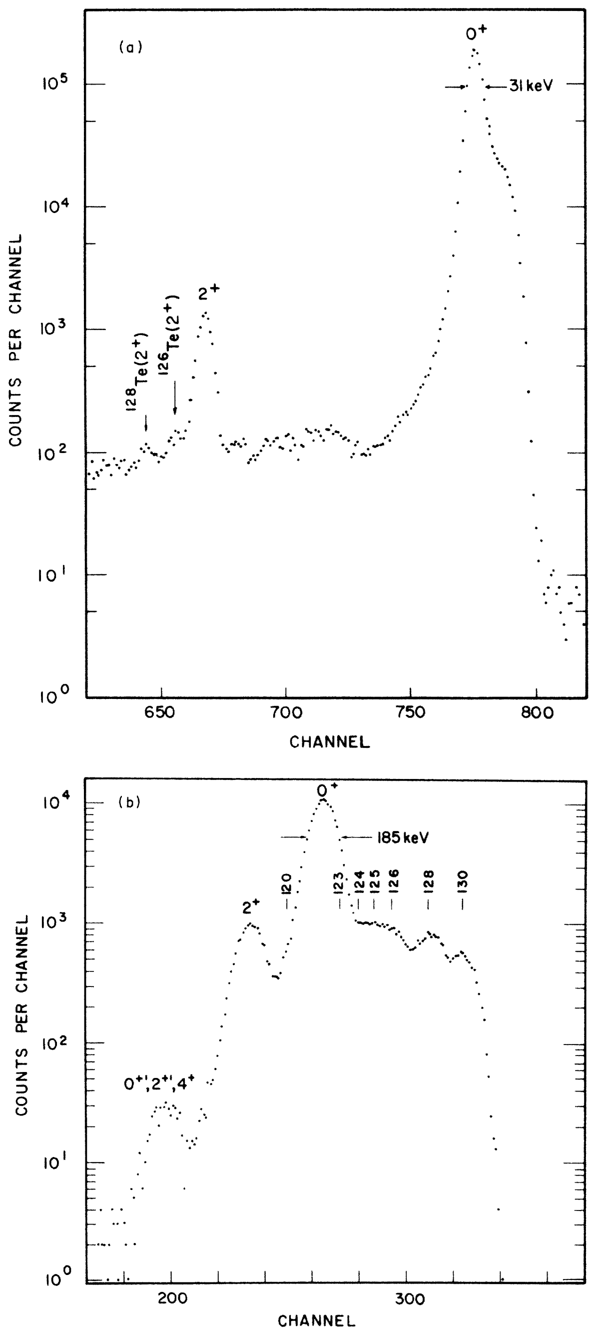

FIG. 1. Spectra from ^{122}Te at a scattering angle $\theta_{lab} = +172.5°$. (a) Spectrum of 10.0-MeV ^{4}He ions. (b) Spectrum of 42.0-MeV ^{16}O ions.

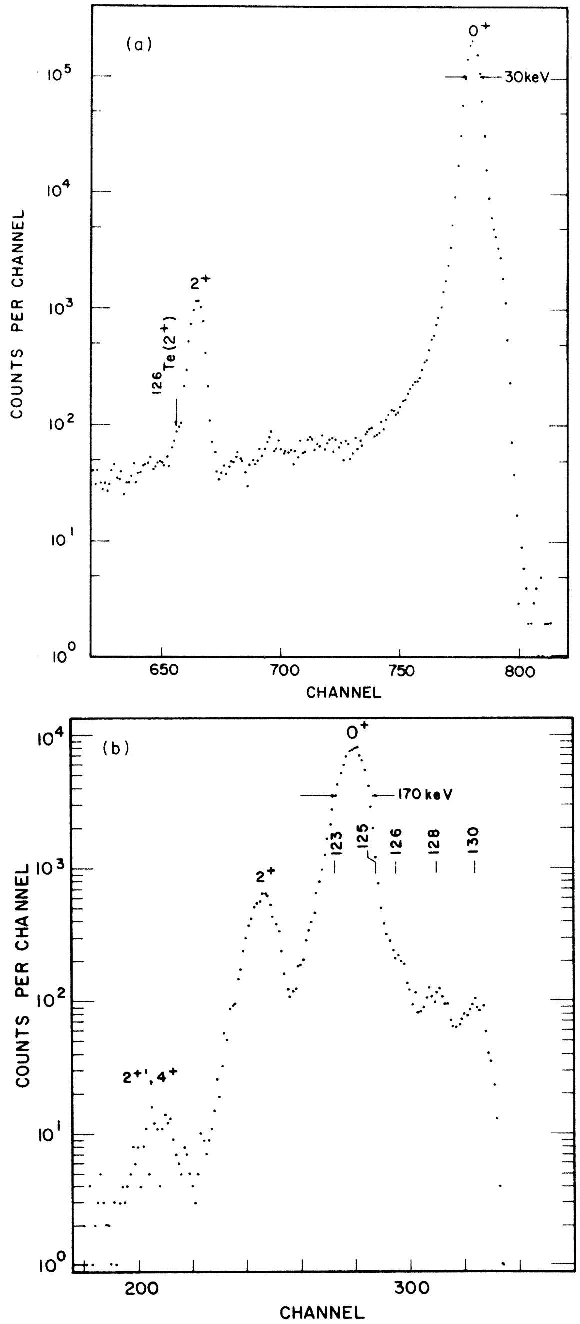

FIG. 2. Spectra from ^{124}Te at scattering angle $\theta_{lab} = +172.5°$. (a) Spectrum of 10.0-MeV ^{4}He ions. (b) Spectrum of 42.0-MeV ^{16}O ions.

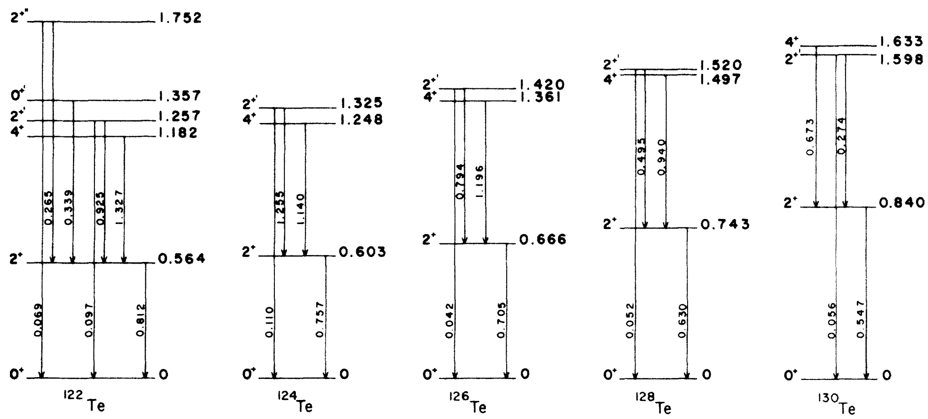

FIG. 3. Level structures of ^{122}Te, ^{124}Te, ^{126}Te, ^{128}Te, and ^{130}Te as deduced from the Coulomb-excitation measurements. The determined $E2$ matrix elements are given in units of eb for each transition. These values are in good agreement with those given by Lagrange (see Ref. 19). The δ value obtained by J. Kock, F. Münnich, and V. Schötzig [Nucl. Phys. A103, 300 (1967)] for the 692.8-keV γ ray in ^{122}Te has been used to calculate the $B(E2)$ values of the transitions deexciting the 1257-keV level. The δ value obtained by P. H. Stelson [Phys. Rev. 157, 1098 (1967)] for the 722.8-keV γ ray in ^{124}Te has been used to calculate the $B(E2)$ values of the transitions deexciting the 1325-keV level. All the other $2^{+\prime} \to 2^+$ (and $2^{+\prime\prime} \to 2^+$ only for ^{122}Te) γ rays have been considered as pure $E2$ transitions.

topic impurities were subtracted from the spectra. The subtractions were made employing the Oak Ridge isotopic analysis which is given in Table I.

Details regarding analysis methods, computer fitting procedures, and target contaminants are presented elsewhere.[13]

To derive the static quadrupole moment and the reduced transition probability $B(E2; 0^+ \to 2^+)$ of

TABLE II. Values of the experimental and least-squares-fitted ratios.

Isotope	Beam energy (MeV)	Lab angle (deg)	$10^3 R_{exp}$ [a]	$10^3 R_{fit}$ [b]
122	8 (^{4}He)	157.5	2.231 ± 0.019	2.164
		172.5	2.235 ± 0.016	2.236
	10 (^{4}He)	157.5	6.930 ± 0.064	6.971
		172.5	7.107 ± 0.055	7.267
	42 (^{16}O)	157.5	93.2 ± 0.6	92.9
		172.5	95.8 ± 0.6	95.9
124	8 (^{4}He)	157.5	1.625 ± 0.019	1.617
		172.5	1.670 ± 0.018	1.665
	10 (^{4}He)	157.5	5.470 ± 0.049	5.502
		172.5	5.723 ± 0.046	5.725
	42 (^{16}O)	157.5	74.2 ± 0.5	74.3
		172.5	76.8 ± 0.6	76.6
126	10 (^{4}He)	157.5	4.094 ± 0.033	4.025
		172.5	4.105 ± 0.032	4.176
	42 (^{16}O)	157.5	55.1 ± 0.6	55.6
		172.5	57.5 ± 0.6	57.2
128	10 (^{4}He)	157.5	2.690 ± 0.017	2.705
		172.5	2.815 ± 0.017	2.800
	42 (^{16}O)	157.5	37.2 ± 0.4	37.8
		172.5	39.2 ± 0.4	38.8
130	10 (^{4}He)	157.5	1.595 ± 0.011	1.599
		172.5	1.649 ± 0.011	1.645
	42 (^{16}O)	157.5	23.4 ± 0.3	23.8
		172.5	24.9 ± 0.4	24.4

[a] The experimental errors quoted for R_{exp} are statistical only.

[b] The fitted ratios are those obtained for a positive value of $P_3 = M_{02'} M_{2'2} M_{02}$ and $P_3' = M_{02''} M_{2''2} M_{02}$.

TABLE III. Summary of results for $B(E2;0^+\rightarrow 2^+)$ and Q_{2^+} values for the even tellurium nuclei.

			$B(E2;0^+\rightarrow 2^+)$ (e^2b^2)					Q_{2^+} $(e\,b)$			
			Present work		Other works			Present	Other works		
Isotope	P_3	P_3' [a]	Scattering	Thick target	Ref. 19	Ref. 4	Ref. 20	work [b]	Ref. 4	Ref. 20	Ref. 3
122	−	−	0.665 ± 0.011					−0.20 ± 0.10			
	−	+	0.665 ± 0.011	0.66 ± 0.03	0.61 ± 0.030			−0.23 ± 0.10			
	+	−	0.667 ± 0.011					−0.43 ± 0.10			−0.50 ± 0.22
	+	+	0.667 ± 0.011					−0.46 ± 0.10			
124	−		0.568 ± 0.011	0.57 ± 0.03	0.71 ± 0.035			−0.11 ± 0.10			
	+		0.571 ± 0.011					−0.46 ± 0.10			
126	−		0.478 ± 0.011	0.50 ± 0.03	0.51 ± 0.020	0.49 ± 0.04		−0.20 ± 0.10	−0.24 ± 0.08		
	+		0.479 ± 0.011					−0.28 ± 0.10	−0.40 ± 0.10		
128	−		0.387 ± 0.011	0.40 ± 0.02	0.39 ± 0.020	0.39 ± 0.03		−0.26 ± 0.11	−0.11 ± 0.10		
	+		0.387 ± 0.011					−0.33 ± 0.11	−0.27 ± 0.13		
130	−		0.290 ± 0.011	0.30 ± 0.02	0.302 ± 0.016		0.30 ± 0.03	−0.09 ± 0.12		−0.12 ± 0.15	
	+		0.290 ± 0.011					−0.14 ± 0.12		−0.19 ± 0.15	

[a] P_3 is the matrix element product $M_{02'}M_{2'2}M_{02}$ and P_3' is the triple product $M_{02''}M_{2''2}M_{02}$.

[b] The errors in the measured values of Q_{2^+} have been calculated considering counting statistics, uncertainty in the exact value of the average beam energy passing through the targets (this is mostly due to the lack of a precise value for the target thickness), atomic screening effect, and vacuum polarization effect. The correction due to the possible effect of the giant dipole resonance (Refs. 21 and 22) has not been applied to the results given in this table. The small quantum-mechanical correction calculated by Alder and Pauli (Ref. 23) has been included in the Q_{2^+} values.

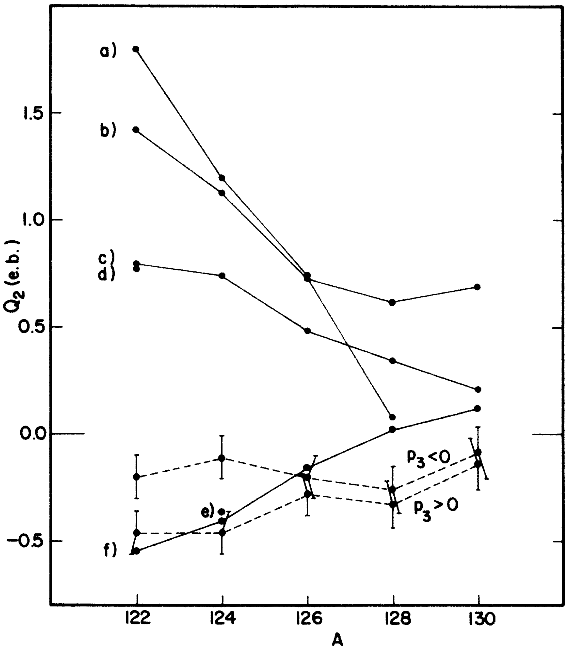

FIG. 4. Comparison between experimentally determined quadrupole moments and various theoretical predictions from: Ref. 10, (a); Ref. 8, (b); Ref. 7, (c); Ref. 9, (d); Ref. 5, (e); and Ref. 6, (f).

the first 2^+ excited states of the even tellurium isotopes, the experimental cross-section ratios R_{exp}, which are given in Table II, were fitted with the computer code of Winther and de Boer.[14]

In addition to the experimental conditions (like type of projectile, bombarding energy, excitation energy, etc.) and the matrix elements M_{12} and M_{22} to be fitted, the program requires as input all the other reduced $E2$ matrix elements to be considered in the calculations.

In order to determine these matrix elements, direct measurements of the $B(E2)$ values for the transitions between the various excited states in these nuclei were carried out by the thick-target yield method.

Coulomb excitation was effected by bombarding thick targets (~45 mg/cm^2) of enriched ^{122,124,126,128,130}Te, evaporated onto a thick aluminum backing, with 42- and 44.8-MeV ^{16}O ions. The experimental setup consisted of a 45-cm^3 Ge(Li) detector having 2.0-keV resolution at 1.33 MeV and placed 10 cm from the target at an angle of 55° with respect to the incoming beam. From the γ-ray yields the reduced $E2$ transition probabilities were extracted by means of the first- and second-order time-dependent perturbation theory of Alder *et al.*[15] Details on the method of analysis can be found elsewhere[16,17] and the results are presented in Fig. 3.

By using the above-determined matrix elements in the analysis of the inelastic scattering data, the results shown in Table III were obtained. In this table the values of the static quadrupole moments and the reduced transition probabilities obtained by other groups by a variety of methods are also presented for comparison.

The various solutions quoted in Table III for Q_{2^+} reflect the ambiguity in the unknown relative signs of the excitation amplitudes to the higher 2^+ states ($2^{+'}$ and $2^{+''}$). It can be noticed that in the case of ^{122}Te, which was the only tellurium isotope where a third 2^+ state ($2^{+''}$) was Coulomb excited (see Fig. 3), the Q_{2^+} value does not appear to be appreciably affected when the presence of the $2^{+''}$ level is taken into account.

III. CONCLUSIONS

In Fig. 4, the results of the quadrupole-moment measurements are summarized and compared with the predictions of the various theoretical calculations.[5-10] It can be observed that only the perturbational calculation of Sips[6] as well as the calculations of Lopac[5] for ^{124}Te give negative moments (up to ^{126}Te for Sips[6]), in fair agreement with the present values. It has been later demonstrated, however, that the calculations of Sips[6] contain errors.[24] It has been reported very recently by Alaga, Paar, and Lopac[25] that the static quadrupole moments of the even tellurium isotopes should be negative and between −0.1 and −0.4 eb. This again would be in fair agreement with our results. (No details on the Q_{2^+} value for each single nucleus are given in their paper.) It is clear, however, that more extensive theoretical work is required in order to have a better physical picture of these weakly collective nuclei near a closed shell. This has been pointed out also in recent reports by Tamura and Kishimoto[26] and Sorensen.[27]

Finally, the Q_{2^+} and $B(E2; 0^+ \to 2^+)$ values of ^{124}Te, ^{126}Te, and ^{128}Te have been measured lately by Kleinfeld, Maggi, and Werdecker[28] with techniques very similar to those employed by us. There is a disagreement between our $B(E2; 0^+ \to 2^+)$ values and theirs, which are approximately 16% lower for ^{124}Te and 5% lower for ^{126}Te and ^{128}Te. Furthermore, there is a reasonable (and probably fortuitous) agreement, only for the Q_{2^+} value of ^{124}Te whereas for ^{126}Te and ^{128}Te there is a divergence since their values tend to be small or about zero.

There is no apparent explanation for these discrepancies. It should be remarked, however, that our $B(E2; 0^+ \to 2^+)$ values, obtained with the completely independent thick target yield and scattering methods are in good agreement (see Table III).

Note added in proof: After this paper was submitted for publication, an article on the determination of the static quadrupole moment of the first 2^+ states of ^{122}Te, ^{124}Te, and ^{130}Te appeared in the literature [R. D. Larsen, W. R. Lutz, T. V. Ragland, and R. P. Scharengerg, Nucl. Phys. A221, 26 (1974)]. The Q_{2^+} values reported in that work are in excellent agreement with the values measured by us.

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[18]The 1497-keV 4^+ level (^{128}Te) was not excited in the present Coulomb-excitation measurements, even though its existence has been reported by several authors [see J. M. Lagrange, Thèse-Orsay, Ser. A, 598 (unpublished)]. The 2-4 matrix element indicated in Fig. 3 has been determined by interpolating the values of the analogous matrix elements of ^{126}Te and ^{130}Te. It should be mentioned, however, that even large variations in the value of the 2-4 matrix element do not alter appreciably the given value of Q_{2^+} of the 743-keV state (see Table III). Only the 840- and 1633-keV states in ^{130}Te were directly excited in the present Coulomb-excitation measurements. Some uncertainty on the spin assignment of the 1598- and 1633-keV levels seems to exist. However, recent decay studies of the ^{130}Sb^{m,g} disintegration [H. N. Erten, thesis Massachusetts Institute of Technology, 1970 (unpublished); J. Blanchot, H. N. Erten, and C. D. Coryell, Bull. Am. Phys. Soc. 15, 1669 (1970); V. G. Kiselev, V. N. Levkovskij, O. I. Artemev, and L. K. Peker, Izv. Akad. Nauk. SSSR Ser. Fiz. 35, 2300 (1971); A. Kerek, P. Carlé, and J. McDonald, Nucl. Phys. A198, 466 (1972)] appear to favor a 2^+ and 4^+ assignment for the 1598- and 1633-keV levels, respectively. The 2-2′ and 0-2′ matrix elements indicated in Fig. 3 have been calculated by extrapolating the 0-2′/2-2′ ratios (matrix elements) and the $B(E2;2^{+\prime}\rightarrow 2^+)/B(E2;2^+\rightarrow 0^+)$ ratios of ^{122}Te, ^{124}Te, ^{126}Te, and ^{128}Te.

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