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Reorientation effect measurements in ^{122}Te and ^{128}Te[†]

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Measurements of the Coulomb excitation probabilities of the first 2^+ state of ^{122}Te and ^{128}Te were carried out using back-scattered ions of ^{4}He, ^{14}N, ^{16}O, and ^{18}O. Quadrupole moments Q_{2^+} and reduced transition probabilities $B(E2;\, 0^+ \rightarrow 2^+)$ were determined. The Q_{2^+} deduced for the positive sign of the 2_2^+ interference term are -0.57 ± 0.05 e b and -0.06 ± 0.05 e b for ^{122}Te and ^{128}Te, respectively.

NUCLEAR REACTIONS ^{122,128}Te(α,α'), E_α = 8–10 MeV; ^{122,128}Te(^{14}N, ^{14}N′), $E_{^{14}\mathrm{N}}$ = 32–37 MeV; ^{122,128}Te(^{16}O, ^{16}O′), $E_{^{16}\mathrm{O}}$ = 30.5–42 MeV; ^{122}Te(^{18}O, ^{18}O′), $E_{^{18}\mathrm{O}}$ = 34–35 MeV; measured $\sigma(E_\alpha, E_{\alpha'})$, $\sigma(E_{^{14}\mathrm{N}}, E_{^{14}\mathrm{N}'})$, $\sigma(E_{^{16}\mathrm{O}}, E_{^{16}\mathrm{O}'})$, $\sigma(E_{^{18}\mathrm{O}}, E_{^{18}\mathrm{O}'})$. ^{122,128}Te deduced Q_{2^+}, $B(E2, 0^+ \rightarrow 2^+)$. Enriched targets.

I. INTRODUCTION

The reorientation effect in Coulomb excitation[1] is by now an accepted technique with which a large number of quadrupole moments of excited 2^+ states were measured. The experimental observation of relatively large quadrupole moments[2] in the first 2^+ excited states in even-even nuclei near $Z = 50$ has attracted considerable interest in the past few years. The even tellurium isotopes present a typical example where the A dependence of the quadrupole moment was assessed.[3]

At the time the present work was started, there were conflicting results for the experimentally determined values of Q_{2^+}.[4-7,3] Since then, a number of investigations have been reported[8-12] which have helped to clarify the experimental situation to a considerable degree. Some disagreement, however, still exists among some of the experimental results. In the present work we attempted to achieve a high degree of reliability by collecting a large body of data using various beams and bombarding energies. The data are more than sufficient to determine the quadrupole moments and the $B(E2)$ values, and allow a careful check of the internal consistency of the analysis. These checks are mandatory for such difficult experiments as the reorientation measurements.

Among the various attempts[13-17] to explain the observed quadrupole moments in the Te isotopes, the most successful is the semimicroscopic model of Ref. 17. It predicts an increase of the quadrupole moment from about -0.35 e b for the lighter isotopes to approximately 0 e b for the heavier Te isotope. In the present study we measured the quadrupole moment of ^{122}Te(2_1^+) and ^{128}Te(2_1^+) and confirmed the theoretically predicted trend.

II. EXPERIMENTAL PROCEDURE

The experimental method and procedures for data reduction are similar to those used in Ref. 18 and will not be described in detail here. Charged particle beams were obtained from the tandem electrostatic accelerators at the Weizmann Institute and at the University of Sao Paulo. The experimental setup and scattering chamber geometries were quite similar at both laboratories.

The targets consisted of thin layers (~8 μg/cm^2 for heavy ions and ~25 μg/cm^2 for α particles) of tellurium metal enriched in isotopes of mass 122 (96.2%) or 128 (99.5%) evaporated onto ~10 μg/cm^2 C foils. The scattered ions were detected in silicon surface barrier detectors of 100 μm depletion depth placed at various angles. At the most backward scattering angle (~175°) an annular detector was used. Standard techniques were applied to achieve very good energy resolution and to minimize the background in the spectra.

Resolutions full width at half maximum (fwhm) of ~30 keV for ^{4}He and ~100–120 keV for heavy ions were obtained. A typical heavy-ion sectrum (^{14}N) is shown in Fig. 1 together with the fits used in the analysis of the data. A typical example of an α spectrum can be found in Fig. 1 of Ref. 19. The elastic and inelastic peaks were well resolved in all heavy-ion spectra, usually with a high value (~20 : 1) for the ratio between the inelastic peak height to the valley between peaks. The ratios of inelastic peak heights to the background were also

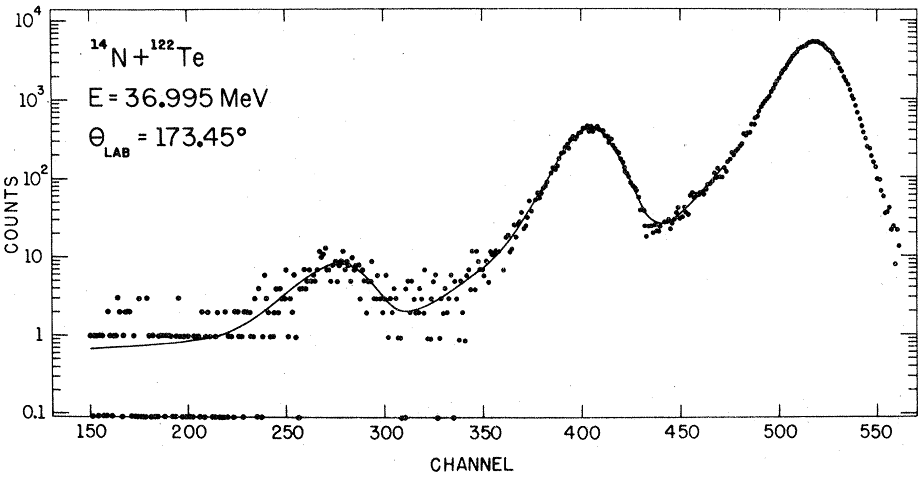

FIG. 1. Spectrum of ^{14}N ions back scattered from ^{122}Te. The line passing through the experimental points represents the fit to the spectrum from which the contributions of scattering from contaminants were subtracted.

very good ranging from 200 : 1 to 100 : 1.

The excitation probabilities defined as the ratio of the inelastic to the elastic cross sections

$$R_{\text{exp}} = \frac{(d\sigma/d\Omega)_{2^+}^{\text{lab}}}{(d\sigma/d\Omega)_{0^+}^{\text{lab}}}$$

were extracted from the spectra using the methods and the line shape fitting programs described in Ref. 18. The elastic and inelastic contribution of the other Te isotopes were subtracted from the spectra using the shape of the elastic peak of the main isotope and the supplier assay of the target material. In the case of the ^{122}Te targets, an independent determination of the concentration of the heavier isotopes could be made using the heavy-ion spectra and was found to be in agreement with the suppliers' assay. A careful search for other contaminant peaks was also made through a comparison of ^{4}He and heavy-ion spectra taken with the same target. Statistical plus fitting uncertainties in the evaluation of R_{exp} are, for most of the data, of the order of 1 to 2%. The results of this analysis for the experimental excitation probabilities are shown in Table I, together with the corresponding uncertainties, for the various projectiles, bombarding energies, and laboratory scattering angles employed.

The determination of the Q_{2^+} and $B(E2; 0^+ \rightarrow 2^+)$ values was accomplished by comparing the measured R values (R_{exp}) with those calculated (R_{comp}) using the multiple Coulomb excitation (MCE) program of Winther and de Boer.[20] The first six and four levels of ^{122}Te and ^{128}Te, respectively, and their associated electric quadrupole matrix elements

$$M_{ij} = (I_j \| M(E2) \| I_i)$$

were used in the calculation. These matrix elements, obtained from the measured $B(E2)$ values and branching and mixing ratios for ^{122}Te and ^{128}Te (Refs. 8 and 10) are given in Tables II and III.

A least-squares analysis was applied to the data, treating $M_{12} = [B(E2, 0^+ \rightarrow 2^+)]^{1/2}$ and $M_{22} = -1.32 Q_{2^+}$ as free parameters, after expressing R_{comp} in a functional form given by

$$R_{\text{comp}}^{i}(M_{12}, M_{22}) = \alpha_i M_{12}^{2} + \beta_i M_{12}^{2} M_{22} + \gamma_i M_{12}^{3},$$

where the index i refers to the different experimental parameters of R_{exp}^{i} to which the computed ratio shall be compared. This expression reproduces the calculations obtained from the MCE program quite accurately (within less than 0.06%) over our range of M_{12} and M_{22} values. The coefficients α_i, β_i, and γ_i were determined from sets of ratios R_{comp} calculated with different values of M_{12} and M_{22}.

It is well known that the computed excitation probability is sensitive to the sign of the second order interference term $M_{12} M_{2s} M_{1s}$ arising from the excitation of the 2_1^+ level through a higher lying intermediate 2^+ state S. There are two such higher 2^+ levels known in ^{122}Te (levels Nos. 4 and 6 in Table II) and one in ^{128}Te (level No. 4 in Table III). The values obtained for $B(E2)$ and Q_{2^+} are listed in Table IV for both positive and negative signs of the matrix elements products $M_{12} M_{14} M_{24}$ and $M_{12} M_{16} M_{26}$ for ^{122}Te and $M_{12} M_{14} M_{24}$ for ^{128}Te. The values of Q_{2^+} are strongly affected by the sign chosen while the $B(E2)$ values are largely independent of it.

The quoted errors in the measured values given in Table IV have been evaluated from a quadratic

TABLE I. Summary of the experimental excitation probabilities ($R_{\rm exp}$) and errors (in percent). The laboratory where the experiment was carried out is indicated.

Isotope	Projectile	$E_{\rm lab}$ (MeV)	$\theta_{\rm lab}$ (deg)	Lab	$R_{\rm exp}$ ($\times 10^3$)	Error (%)
122	^{4}He	7.99	177.3	WIS	2.21	2.0
		9.49	177.3	WIS	5.56	1.5
			150.0	WIS	5.09	1.9
			119.7	WIS	3.97	2.5
			90.3	WIS	2.44	2.0
			90.1	WIS	2.33	2.0
			70.0	WIS	1.27	2.8
		9.99	177.3	WIS	7.15	1.1
			150.0	WIS	6.68	1.4
			119.7	WIS	4.99	2.0
			90.3	WIS	2.86	1.9
			90.1	WIS	2.92	2.0
			70.0	WIS	1.53	2.2
	^{14}N	36.99	173.5	USP	78.90	0.97
	^{16}O	30.48	176.1	WIS	16.94	1.1
		31.64	176.1	WIS	20.49	1.8
		32.74	176.1	WIS	26.22	1.0
		37.96	173.5	USP	57.0	1.1
		41.81	173.5	USP	91.4	1.1
		41.94	173.5	USP	93.8	1.4
	^{18}O	33.99	176.1	WIS	29.96	1.8
		34.99	176.1	WIS	34.37	1.4
		35.04	176.1	WIS	35.87	1.5
128	^{4}He	8.00	173.5	USP	0.652	1.1
		9.00	173.5	USP	1.484	0.88
		9.49	170.0	WIS	2.038	1.0
			125.3	WIS	1.58	1.8
			109.9	WIS	1.29	2.2
			90.0	WIS	0.938	1.4
		9.99	170.0	WIS	2.70	1.0
			125.3	WIS	2.12	1.9
			109.9	WIS	1.70	2.0
			90.0	WIS	1.22	1.4
		10.00	173.5	USP	2.718	0.81
			90.0	USP	1.25	2.1
	^{14}N	32.00	173.5	USP	14.75	1.5
		33.00	173.5	USP	18.27	1.4
	^{16}O	37.94	173.5	USP	22.73	1.8
		37.99	173.5	USP	22.86	1.4
		39.50	173.5	USP	29.16	1.2
		41.00	173.5	USP	35.12	1.2
		41.81	173.5	USP	38.84	1.5
		42.00	173.5	USP	40.16	1.1

TABLE II. Energy levels and matrix elements (M_{ij}) of the $E2$ operator (in eb) used in the multiple Coulomb excitation calculations for ^{122}Te.

Level	I^π	Energy (MeV)	1	2	3	4	5	6
1	0^+	0	0	M_{12}	0	0.097	0	0.069
2	2^+	0.564	M_{12}	M_{22}	1.327	0.925	0.339	0.265
3	4^+	1.182	0	1.327	0	0	0	0
4	$2^{+\prime}$	1.257	0.097	0.925	0	0	0	0
5	$0^{+\prime}$	1.357	0	0.339	0	0	0	0
6	$2^{+\prime\prime}$	1.752	0.069	0.265	0	0	0	0

TABLE III. Energy levels and matrix elements (M_{ij}) of the $E2$ operator (in eb) used in the multiple Coulomb excitation calculations for ^{128}Te.

Level	I^π	Energy (MeV)	1	2	3	4
1	0^+	0	0	M_{12}	0	0.071
2	2^+	0.743	M_{12}	M_{22}	0.960	1.01
3	4^+	1.497	0	0.960	0	0
4	$2^{+\prime}$	1.520	0.071	1.01	0	0

combination of errors due to statistical and systematic errors in the experimental intensities, and errors due to beam-energy and target-thickness uncertainties. Small corrections[18] to the $B(E2)$ and Q_{2^+} values have been made for effects due to electronic screening and vacuum polarization. Corrections arising from the semiclassical approximation have also been taken into account but no corrections have been made for the effects of excitation modes other than $\lambda = 2$.

The results of the analysis are presented in a graphical form in Fig. 2 where the ratio $R_{\text{exp}}/R_{\text{comp}}(Q=0)$ (computed in this case for positive interference terms) has been plotted against the sensitivity parameter ρ defined[1] by

$$R_{\text{comp}}(Q) = R_{\text{comp}}(Q=0)(1+\rho Q) ,$$

where $R_{\text{comp}}(Q=0)$ is the computed excitation probability for $Q_{2^+}=0$. The experimental values of $B(E2)$ given in Table IV were used in computing $R_{\text{comp}}(Q)$ and $R_{\text{comp}}(Q=0)$.

III. RESULTS AND DISCUSSION

Figure 3 displays the available experimental information for the $B(E2; 0^+ \to 2^+)$ and the Q_{2^+} of ^{122}Te and ^{128}Te. In comparing the results of different authors we will refer mostly to those obtained with the positive sign of the interference terms since there exists now experimental evidence[21-23] supported by theoretical predictions for nuclei in this mass region which indicate that the interference should in fact be constructive.

TABLE IV. The $B(E2; 0^+ \to 2^+)$ and Q_{2^+} experimental values obtained in the present work for ^{122}Te and ^{128}Te.

Isotope	$B(E2; 0^+ \to 2^+)$ (e^2b^2)	Q_{2^+} (eb)	Sign of interf. terms a	b
122	0.665 ± 0.004	−0.57 ± 0.05	+	+
	0.666 ± 0.004	−0.56 ± 0.05	+	−
	0.665 ± 0.004	−0.41 ± 0.05	−	+
	0.664 ± 0.004	−0.35 ± 0.05	−	−
128	0.376 ± 0.003	−0.06 ± 0.05	+	
	0.375 ± 0.003	+0.12 ± 0.05	−	

[a] Sign of the matrix element product $M_{12}M_{14}M_{24}$.
[b] Sign of the matrix element product $M_{12}M_{16}M_{26}$.

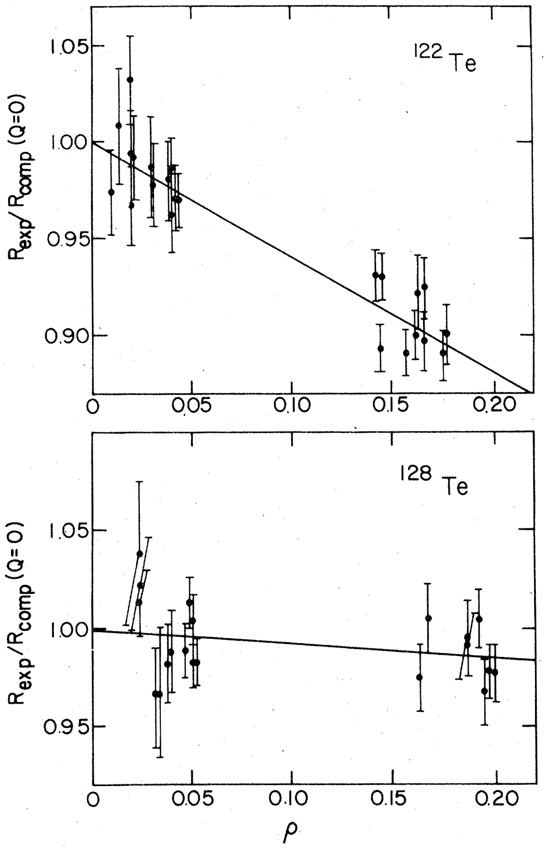

FIG. 2. The ratio $R_{\text{exp}}/R_{\text{comp}}(Q=0)$ as a function of the sensitivity parameter ρ, calculated for the positive sign of the interference terms. The lines are fits to the data using the values of $B(E2; 0^+ \to 2^+)$ listed in Table IV. Points for $\rho < 0.05$ correspond to ^{4}He ions.

There is an excellent agreement between the several existing values of $B(E2; 0^+ \to 2^+)$. For ^{122}Te our value is 1% higher than the value reported in Ref. 12, which was determined with the same degree of precision as ours. The other two existing results,[8,19] while in very good agreement with our value, have much larger uncertainties. For ^{128}Te the best previous measurement[11] of $B(E2; 0^+ \to 2^+)$ is 0.6% higher than the present one. Again the values obtained by other authors[5,8,10,19] while in agreement with ours, have larger uncertainties.

The Q_{2^+} value reported here for ^{122}Te, while also in agreement with the four existing measurements,[4,8,9,12] is 20% more negative than the weighted average ($\langle Q_{2^+} \rangle = -0.47 \pm 0.05$ e^2b^2) of these earlier results. The measurements of Barrette *et al.*[8] and of Bockish *et al.*[12] have been performed with techniques very similar to those employed in

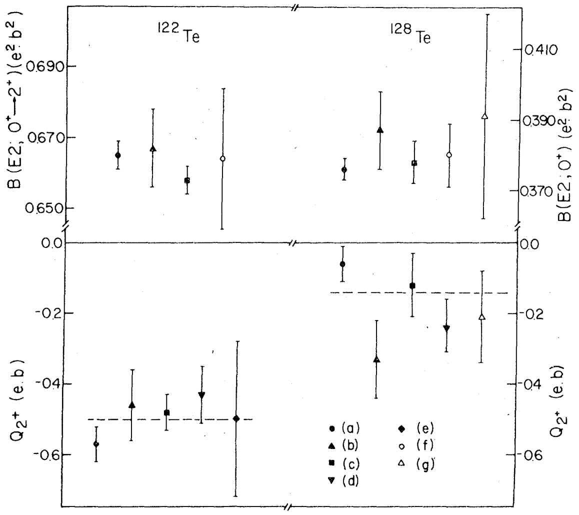

FIG. 3. The available experimental information for $B(E2; 0^+ \rightarrow 2^+)$ and Q_{2^+} for ^{122}Te and ^{128}Te corresponding to the positive sign of the interference terms. (a) WIS-USP, present work. (b) Montreal, Ref. 8. (c) Koln, Ref. 12 for ^{122}Te and Ref. 11 for ^{128}Te. (d) Purdue, Ref. 9 for ^{122}Te and Ref. 10 for ^{128}Te. (e) Oak Ridge, Ref. 4. (f) Rehovot, Ref. 19. (g) Caltech, Ref. 5. The dashed line is the weighted average of the measurements.

the present work and the matrix elements used in the data analysis are essentially the same for the three experiments. The small discrepancy in the Q_{2^+} results probably reflects the uncertainty with which the excitation probabilities can reliably be extracted from the experimental data. The new average value of Q_{2^+} for ^{122}Te, including the result of the present work is $\langle Q_{2^+} \rangle = -0.50 \pm 0.05$ *e* b.

For ^{128}Te the Q_{2^+} values reported here, for both the positive and negative interference terms, while in good agreement with those of Kleinfeld *et al.*,[11] are less negative than the results reported by other authors.[5,8,10] In fact for the positive sign of the interference term the average of our value and that of Ref. 11 is approximately 0.2 *e* b smaller in magnitude than the average value of the results of Barrette *et al.*[8] and Ragland *et al.*[10] The result of Stokstad and Hall,[5] after correcting for deorientation effects,[11] is in agreement with both sets of data. It should be pointed out, however, that the matrix elements that we have adopted in our analysis are slightly different from those adopted by Kleinfeld *et al.*[11] or by Barrette *et al.*[8] Such differences, however, would only account for changes in the $B(E2, 0^+ \rightarrow 2^+)$ and the Q_{2^+} values which are well within the range of the stated uncertainties. The weighted average of the existing measurements, including our own, will give for the quadruple moment of ^{128}Te a value of $\langle Q_{2^+} \rangle = -0.14 \pm 0.12$ *e* b for the positive sign of the interference term.

The results of this experiment support the observation[3] that the quadrupole moments of the Te isotopes are negative and decrease in magnitude with the mass number. This trend is also predicted by the theoretical calculations based on the semimicroscopic model.[13,17] However, such calculations (see, e. g., Ref. 17) in general fail to reproduce other matrix elements of the *E*2 operator and depend critically on the position of the proton single particle states.

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