Alpha-Particle Scattering from Even Tellurium Isotopes

R. F. LEONARD, W. M. STEWART, AND N. BARON
Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio
(Received 8 May 1967)

Angular distributions were measured for elastic and inelastic α scattering by isotopically enriched targets of tellurium-122, -124, -126, -128, and -130 by using the 42-MeV α beam of the Lewis 60-in. cyclotron. In each isotope, cross sections were measured for three excited states. These states were the one-phonon 2^+ quadrupole, the two-phonon 4^+, and the one-phonon 3^- octupole. Optical-model fits were made to the elastic scattering, and ambguities in the optical potentials were investigated for a wide range of optical-model parameters. Such ambiguities are readily explained by assuming that the elastic scattering occurs primarily at the outer edges of the potential, and more penetrating particles are strongly absorbed. Inelastic scattering to one-phonon states was analyzed by using a distorted-wave Born-approximation (DWBA) calculation. Deformation parameters in agreement with previously measured values were obtained for all the one-phonon states. A number of other states having small cross sections were excited in each isotope.

INTRODUCTION AND EXPERIMENTAL RESULTS

THE ambiguities in the optical-model parameters determined from the fitting of elastic angular distributions resulting from the scattering of medium-energy α particles can be interpreted as a nuclear volume and/or surface phenomenon.[1–3] These ambiguities for the elastic scattering of medium-energy α particles from light nuclei[3,4] imply a considerable contribution to the elastic-scattering process of α particles that have penetrated deeply into the nuclear interior. However, there are indications that particles that have penetrated into the interior of heavier nuclei contribute less importantly to the elastic-scattering process.[5] To gain a better insight into α-particle scattering, further empirical studies of elastic scattering of medium-energy α particles from heavier nuclei are important. In addition, it is desirable to obtain angular distributions of two-phonon transitions to provide further tests for existing coupled-channels computer programs.

Angular distributions were measured for elastic and inelastic scattering of α particles by isotopically enriched targets of ^{122}Te, ^{124}Te, ^{126}Te, ^{128}Te, and ^{130}Te. The scattering system, pictured in Fig. 1, included magnetic analysis of the 42-MeV α-particle beam of the Lewis 60-in. Cyclotron and particle detection by lithium-drifted silicon semiconductor counters fabricated at the NASA Lewis Research Center.[6] The overall energy resolution of the experiment was between 80 and 120 keV. Angular resolution was approximately 0.75°. A typical energy spectrum of scattered α particles is shown in Fig. 2.

In each isotope two one-phonon states, in addition to the elastic scattering, were excited with sufficient strength to obtain reliable differential cross sections. These are identified as the 2^+ quadrupole state and the 3^- octupole state. In addition, in four of the isotopes a two-phonon multiplet was excited whose strongest component appeared to be the 4^+ state. In each isotope, several other states were weakly excited with no possi-

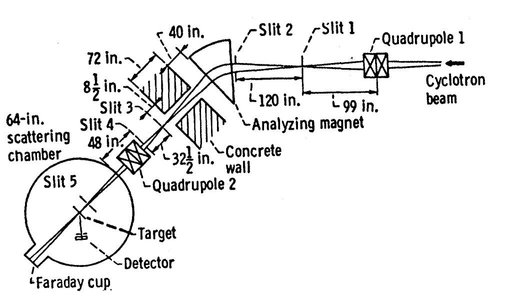

FIG. 1. Experimental scattering system.

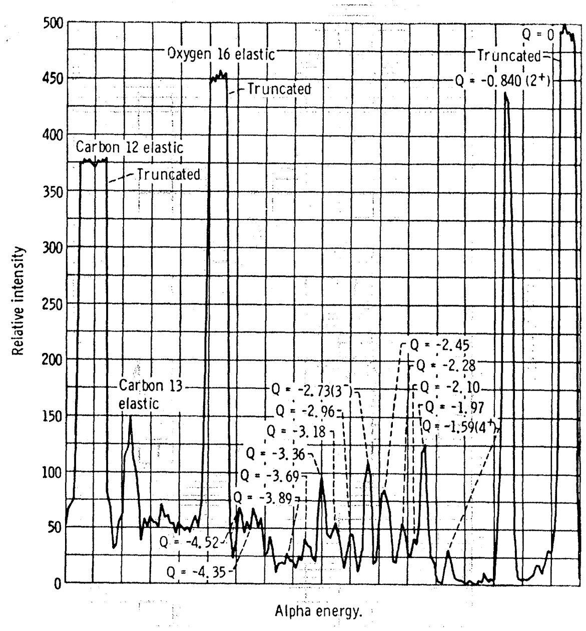

FIG. 2. Typical energy spectrum of scattered α particles. ^{130}Te at $\Theta_{LAB}=44°$.

[1] G. Igo, Phys. Rev. **115**, 1665 (1959).
[2] N. Austern, Ann. Phys. (N. Y.) **15**, 299 (1961).
[3] R. M. Drisko, G. R. Satchler, and R. H. Bassel, Phys. Letters **5**, 347 (1963).
[4] H. L. Wilson, Ph.D. thesis, Indiana University 1964 (unpublished).
[5] C. R. Bingham, M. L. Halbert, and R. H. Bassel, Phys. Rev. **148**, 1174 (1966).
[6] N. Baron and G. A. Kaminski, NASA Report No. TN D-3554, 1966 (unpublished).

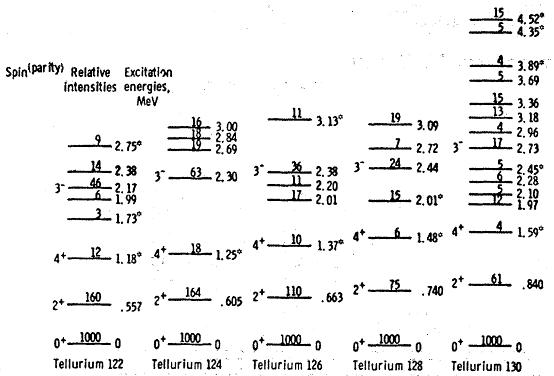

FIG. 3. Experimentally measured excitation energies of states excited by inelastic scattering of 42-MeV α particles by even tellurium isotopes. Spins and parities are noted when known. Relative excitation strengths are also approximated. Asterisks denote probable multiplets. Excitation energies quoted are accurate to ± 20 keV for the more strongly excited states (2^+,4^+,3^-), and to ± 50 keV for the other states.

bility of obtaining differential cross sections. A summary of all states seen, together with excitation energies, spins, and parities, is shown in Fig. 3. Also shown in Fig. 3 is an estimate of the relative strength of excitation for each state. The excitation energies quoted are accurate to ± 20 keV for the more strongly excited states (2^+, 4^+, 3^-), and to ± 50 keV for the more weakly excited states.

The elastic and inelastic angular distributions for each isotope are shown in Figs. 4 to 8. The errors shown there are statistical and do not include errors in the scales of the cross section, which are estimated to be less than 10%. A tabulation of all cross-section data is available elsewhere.[7]

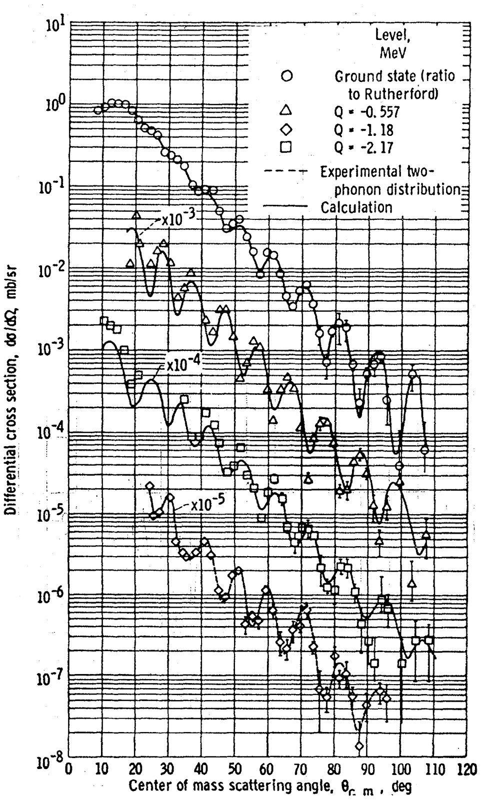

FIG. 4. Angular distributions (experimental and theoretical) for elastic and inelastic scattering of 42-MeV α particles from ^{122}Te.

ANALYSIS OF ELASTIC-SCATTERING DATA

Elastic-scattering cross sections were analyzed using the optical-model program of Melkanoff *et al.*[8] The nuclear part of the optical potential was assumed to have a Woods-Saxon radial form factor using the same radius and diffuseness for both the real and imaginary parts of the potential;

$$U=-(V+iW)\left[1+\exp\frac{r-R_0A^{1/3}}{a}\right]^{-1}. \quad (1)$$

The parameters V, W, a, and R_0 were varied in order to obtain a best fit. In practice, best results were ob-

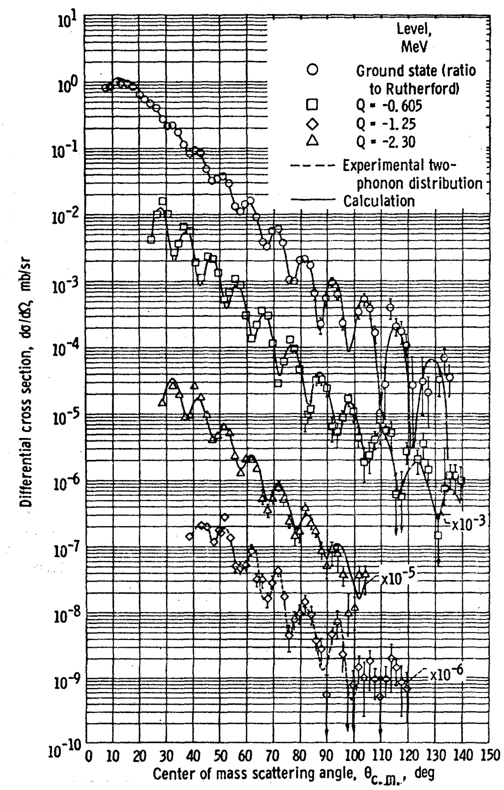

FIG. 5. Angular distributions (experimental and theoretical) for elastic and inelastic scattering of 42-MeV α particles from ^{124}Te.

[7] R. F. Leonard, W. M. Stewart, and N. Baron, NASA Report No. TN D-3991, 1967 (unpublished).

[8] M. A. Melkanoff, J. S. Nodvik, D. S. Saxon, and D. G. Cantor, a FORTRAN *Program for Elastic Scattering Analyses with the Nuclear Optical Model* (University of California Press, Berkeley, 1961).

TABLE I. Summary of optical-model analyses of elastic scattering.

Isotopes	Strength of real part of nuclear optical potential, V (MeV)	Strength of imaginary part of nuclear optical potential, W (MeV)	Diffuseness parameter, a (F)	Nuclear radius constant, R_0 (F)	Total reaction cross section σ_R (mb)	χ^2 per data point χ^2/N
^{122}Te	36.64	19.95	0.671	1.50	1881	1.05
^{124}Te	38.95	21.20	0.672	1.48	1878	1.19
^{126}Te	39.65	21.55	0.682	1.48	1915	1.30
^{128}Te	45.79	22.75	0.655	1.48	1931	0.67
^{130}Te	34.13	20.19	0.671	1.50	1959	1.76

tained by allowing the computer program to optimize automatically V, W, and a, while holding R_0 fixed. By then allowing R_0 to vary in discrete steps, a best set of parameters could be obtained. Typical fits are shown with the data for each isotope in Figs. 4 to 8. The parameters used to calculate these typical fits are shown in Table I.

ANALYSIS OF INELASTIC-SCATTERING DATA

Inelastic-scattering data were analyzed using a distorted-wave Born-approximation computer program.[9] Using the optical-model potential obtained from the fitting of the elastic scattering and a collective model form factor, excellent fits were obtained to the differential cross sections for excitation of the one-phonon states (2^+, 3^-). The fits are shown with the experimental data in Figs. 4 to 8. The use of a collective model form factor permits the determination of β_l, the vibrational amplitude, which may be compared with the β_l's measured by other means, particularly Coulomb excitation and inelastic deuteron scattering. The values of β_l obtained are shown in Table II.

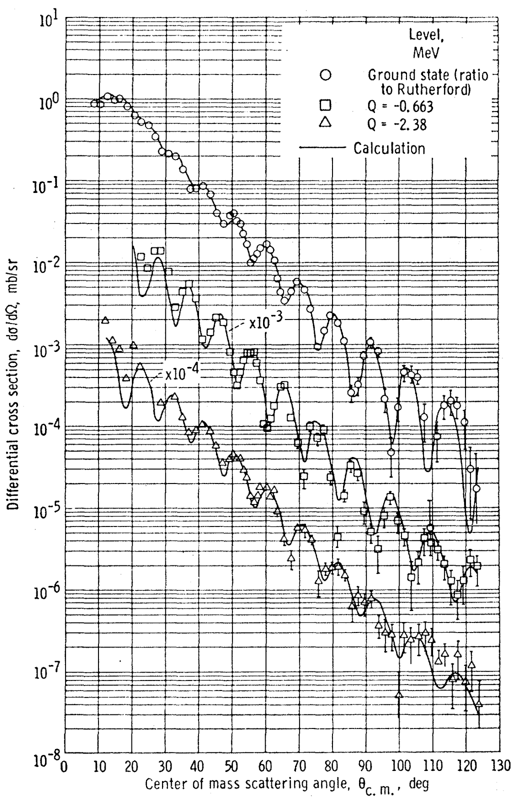

FIG. 6. Angular distributions (experimental and theoretical) for elastic and inelastic scattering of 42-MeV α particles from ^{126}Te.

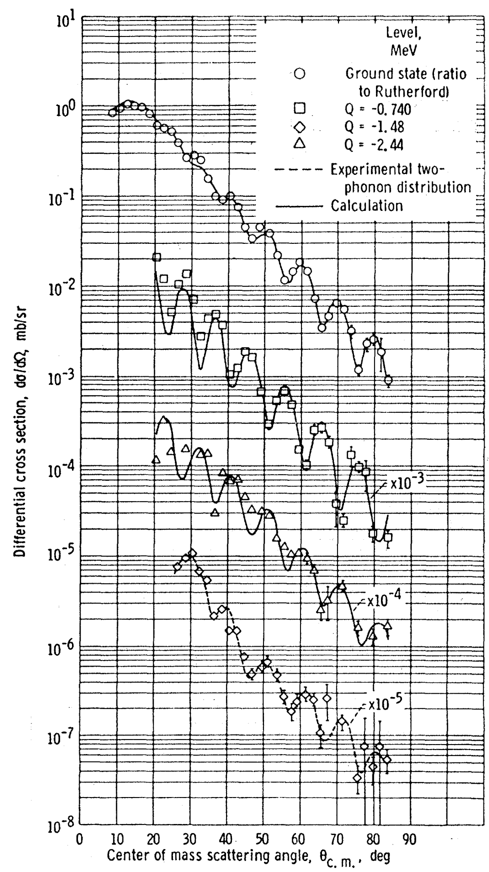

FIG. 7. Angular distributions (experimental and theoretical) for elastic and inelastic scattering of 42-MeV α particles from ^{128}Te.

[9] W. R. Gibbs, V. A. Madsen, J. A. Miller, W. Tobocman, E. C. Cox, and L. Mowery, NASA Report No. TN D-2170, 1964 (unpublished).

TABLE II. Summary of DWBA analyses of inelastic scattering.

Isotope	Present work: Deformation parameter β_2	Present work: Deformation parameter β_3	Previous works: Deformation parameter β_2	References	Deformation parameter β_3	References
^{122}Te	0.20	0.11	0.19	a	...	...
^{124}Te	0.18	0.13	0.174	b	0.07	d
^{126}Te	0.17	0.11	0.16	c	0.12	e
^{128}Te	0.15	0.08	0.141	c	0.10	d
^{130}Te	0.12	0.06	0.127	c	0.11	d

[a] L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. **35**, 853 (1963).
[b] G. M. Temmer and N. P. Heydenberg, Phys. Rev. **104**, 967 (1956).
[c] P. H. Stelson and F. K. McGowan, Phys. Rev. **110**, 489 (1958).
[d] Y. S. Kim and B. L. Cohen, Phys. Rev. **142**, 788 (1966).
[e] G. C. Pramila, R. Middleton, T. Tamura, and G. R. Satchler, Nucl. Phys. **61**, 448 (1965).

AMBIGUITIES IN OPTICAL-MODEL PARAMETERS

As is typical in α-particle scattering, there is considerable ambiguity in the optical-model parameters determined from the fitting of the elastic scattering. Drisko *et al.*,[3] and Austern[2] have suggested that these ambiguities arise from two sources, depending on whether the α particle is reflected from the nuclear surface or the nuclear interior. Two optical potentials are expected to give the same reflections from their interiors if the difference in their depths is just sufficient to allow the addition of one-half wavelength of the incident particle within the potential well. Drisko *et al.*[3] have investigated these discrete ambiguities for the elastic scattering of 43-MeV α particles from ^{58}Ni. In addition, Wilson[4] has seen a similar effect in the scattering of 22-MeV α particles from the even zinc isotopes. More recently, Bingham *et al.*[5] have observed similar but less pronounced effects in the elastic scattering of 65-MeV α's from ^{92}Zr.

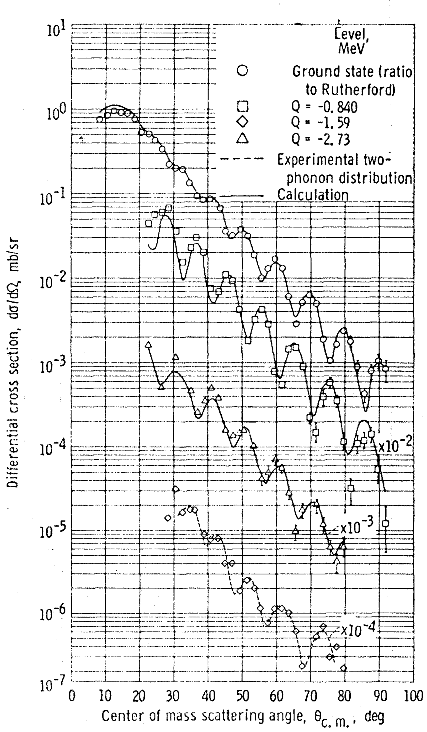

FIG. 8. Angular distributions (experimental and theoretical) for elastic and inelastic scattering of 42-MeV α particles from ^{130}Te.

Elastic scattering from the nuclear surface, on the other hand, is expected to yield a continuous set of optical-model parameters, all of which predict the same scattering, provided the outer edges of the potential remain constant. For the potential shape most commonly employed (Woods-Saxon) this means that the potentials must satisfy the relations

$$V\exp(R_0A^{1/3}/a)=\text{constant}, \quad (2)$$

$$W\exp(R_0A^{1/3}/a)=\text{constant}, \quad (3)$$

$$a=\text{constant}. \quad (4)$$

For the data presented herein, a wide range of optical-model potentials yield nearly equivalent predictions to the elastic scattering. The automatic search routine minimized χ^2, defined by

$$\chi^2=|(\sigma_{\text{ex}}-\sigma_{\text{th}}/\Delta\sigma_{\text{ex}})|^2. \quad (5)$$

In the expression for χ^2, either the statistical error or a simple 10% of the cross section, whichever was larger, was used for the quantity $\Delta\sigma_{\text{ex}}$. This procedure yielded the set of potentials shown in Fig. 9, where the real and imaginary strengths are plotted against the radius

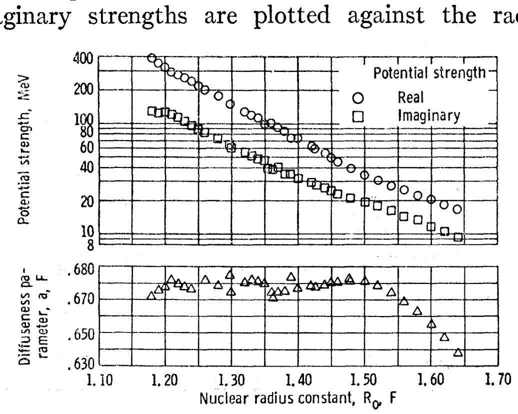

FIG. 9. Real and imaginary optical-model potential strengths V and W, diffuseness parameter a plotted as function of radius parameter R_0. These plots are well described by Eqs. (2)–(4).

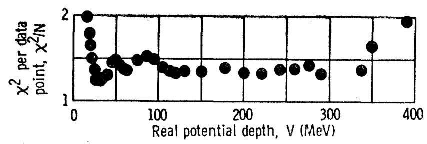

FIG. 10. χ^2/N plotted as function of real optical-model potential strength.

parameter. It is clear that both satisfy Eqs. (2) and (3) very well. Also shown in Fig. 9 are the values of the diffuseness parameter obtained in these searches. It is also clear that, to within $\pm 2\%$, the diffuseness parameter is a constant as is predicted by Eq. (4). Finally, if discrete ambiguities exist some sets of parameters should yield much better fits to the experimental data than others. Figure 10 shows the values of χ^2 obtained for each set of parameters, plotted as a function of the real potential depth V. There are small variations in χ^2 which are somewhat similar to the discrete ambiguities previously observed. It is clear, however, that the amplitude of the variations in χ^2 is considerably smaller than those reported in Refs. 3, 4, or 5. In fact, no set of parameters (with the exception of the very deep and very shallow wells) yields a value of χ^2 which differs from the average χ^2 by more than 10%. It would appear, then, that the importance of the discrete ambiguities is considerably less for the scattering of 42-MeV α particles from tellurium than for any of the other cases investigated. Bingham *et al.*[5] have pointed out, however, that the detection of small variations in χ^2 seems to depend on the accuracy and the weight given data at minima of the differential cross section. It is possible, in the present case, that changes in the weighting of such points could make the minima in χ^2 more pronounced.

The effect of the wide variation of optical-model parameters on the inelastic-scattering calculation was investigated briefly. Two extreme potentials, $V=322.5$ MeV and $V=31.11$ MeV, were used to calculate the cross section for scattering to the first excited (2^+) state of ^{126}Te. The results were virtually identical in shape, as shown in Fig. 11, with a change of about 40% in the magnitude of the calculated cross section. Hence, the value of β_2, obtained when the deeper potential was used, would be about 20% larger than that obtained when the shallow well was used. ($\beta_2=0.20$ for $V=322$ MeV, 0.16 for $V=31.1$ MeV.) The deformation length $\beta_2 R_0$, however, changes by only about 2%. ($\beta_2 R_0=1.20$ for the shallow potential, 1.22 for the deeper potential.)

DISCUSSION AND CONCLUSIONS

The Blair phase rule is obeyed for the quadrupole and octupole one-phonon transitions induced by the inelastic scattering of 42-MeV α particles by the even tellurium isotopes. A reversal of the usual phase rule is observed for the two-phonon states. The present identification of the 4^+ member of the two-phonon triplet in each isotope

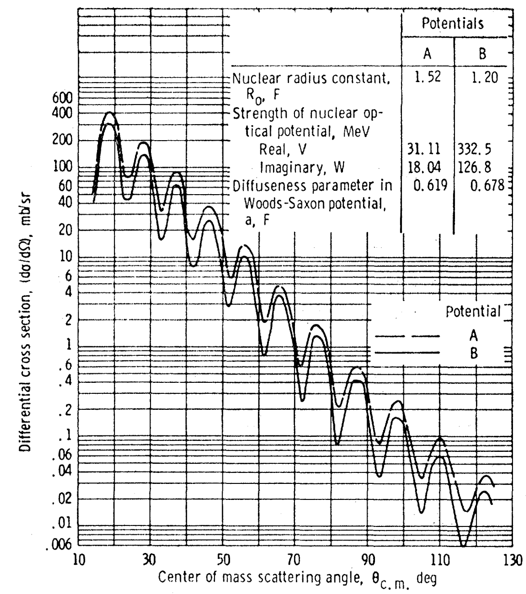

FIG. 11. Inelastic angular distributions calculated for excitation of one-phonon 2^+ level of ^{126}Te using very different but equivalent optical-model potential parameters.

is based on the assignment given a state at this energy by Cookson and Darcey.[10]

The ratio of the excitation strength of the first 2^+ state to that of the 3^- state is about a constant 3:1 in each isotope; whereas, the ratio of the first 2^+ to the 4^+ is about 13:1. The fact that the 2^+ and 0^+ members of the two-phonon triplet are not observed might indicate a $2J+1$ dependence of the cross section for two-phonon excitation.

It is seen from the optical-model analysis on ^{126}Te that a continuous set of good optical-model potential parameters may be found which fit the elastic angular distribution equally well. From Eqs. (2)–(4) and Figs. 9 and 10, it is concluded that the elastic scattering of 42-MeV α particles from tellurium nuclei occurs predominantly at the nuclear surface and more deeply penetrating α particles are strongly absorbed.

The distorted-wave Born-approximation (DWBA) calculations using the vibrational model fit the experimental inelastic angular distributions very well. Deformation lengths $\beta_2 R_0$ are quite insensitive to the choice of good optical-model parameters used in the inelastic-scattering calculation. Values of the nuclear deformation parameter β_l obtained using the vibrational model are shown in Table II. The β_2 and β_3 values measured in the present work agree satisfactorily with previous measurements also listed in Table II. Generally, the deformation parameters for the quadrupole state show a marked decrease with increasing neutron number; the octupole deformation parameters for tellurium also tend to decrease with increasing neutron number, but somewhat erratically.

[10] J. A. Cookson and W. Darcey, Nucl. Phys. **62**, 326 (1965).