Electroproduction of alpha particles from various nuclei showing direct and statistical effects

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α particles from the electrodisintegration of seven nuclei with Z between 29 and 79 have been observed. Energy spectra at 50° in the laboratory for six nuclei and angular distribtions for five nuclei are reported. The cross sections exhibit a broad peak whose magnitude decreases with increasing Z; the energy of the peak increases as Z increases. Angular distributions at the highest energies measured become increasingly forward peaked suggesting a direct-reaction process.

[NUCLEAR REACTIONS ^{63}Cu(e,α), ^{92}Mo(e,α), ^{159}Tb(e,α), ^{166}Er(e,α), ^{181}Ta(e,α), $E=100$ MeV; measured $\sigma(E_\alpha,\theta)$. ^{162}Dy(e,α), ^{197}Au(e,α), $E=100$ MeV; measured $\sigma(E_\alpha)$. Natural and enriched targets.]

I. INTRODUCTION

In an earlier paper[1] we reported on the electroproduction of α particles from ^{63}Cu, ^{107}Ag, ^{159}Tb, ^{165}Ho, ^{169}Tm, and ^{181}Ta. All six nuclei showed broad peaks in the α-production electrodisintegration cross section at 50°. It was found that the energy of the peak increased and its magnitude decreased as the Z of the nucleus increased. Angular distributions for copper were found to be isotropic; for thulium they were isotropic at low energies, but were forward peaked at α energies above 16 MeV. We interpreted our results as indicating that two competing processes were involved. For a low Z nucleus such as copper an evaporation, or boil-off, process is dominant. This was suggested by the isotropic angular distributions of α particles from copper and by the fact that the energy spectrum from copper could be fitted with an evaporation model. For high Z nuclei the larger Coulomb barrier inhibits evaporation α particles which tend to be of low energy; this allows the observation of α particles from a direct-reaction process. The forward peaked angular distributions of α particles from thulium are consistent with a direct process.

The current work was undertaken to establish that the trends seen in the earlier experiments were indeed general characteristics of the electroproduction of α particles. In particular, since α particles originating in a direct-reaction process suggest the existence of α clusters in the nucleus, we wished to learn whether the forward peaked angular distributions seen in thulium were a general feature at higher α-particle energies. Thus, angular distributions for ^{92}Mo, ^{159}Tb, ^{166}Er, and ^{181}Ta as well as higher energy angular distributions for ^{63}Cu were measured. In addition, energy spectra for ^{162}Dy and ^{197}Au are reported. The new work supports the conclusions of the earlier paper.

II. EXPERIMENTAL PROCEDURES

The experimental arrangement used in this experiment was identical to the one used in the earlier work[1] and therefore only the briefest description is included here.

A momentum analyzed electron beam, 100 ± 1 MeV, from the Saskatchewan linear accelerator was incident on a target foil. The targets used are characterized in Table I. The α particles were detected by the positive-ion spectrometer which consisted of five silicon surface barrier detectors positioned in the focal plane of a 127° double-focusing magnet. The energy calibration, energy acceptance, and solid angle of the spectrometer were determined by the use of 5.49 MeV α particles from an ^{241}Am source. The incident

TABLE I. Description of targets used in this experiment.

Element	Z	Isotopic composition		Target thickness (mg/cm^2)
Copper	29	69%	$A=63$	7.92
		31%	$A=65$	
Molybdenum	42	98.3%	$A=92$	12.96
Terbium	65	100%	$A=159$	10.48
Dysprosium	66	90%	$A=162$	1.09
Erbium	68	90%	$A=166$	1.15
Tantalum	73	∼100%	$A=181$	10.54
Gold	79	100%	$A=197$	23.98

beam current was measured by a SLAC-type non-intercepting ferrite monitor whose response was checked against a Faraday cup and was found to be linear and reproducible to better than 2%. The error associated with solid angle, energy acceptance, number of target nuclei, and incident electron flux is $\leq 5.0\%$ for all nuclei except Dy and Er for which it is 12.0%. The larger error for these nuclei is due to a ~10% uncertainty in the foil thickness.

The pulse height spectra for the five detectors were accumulated in five independent 128-channel analog to digital converters gated by the accelerator master trigger for 4 μs at each beam burst. The α-particle peak in each spectrum was integrated to obtain the number of α particles detected. If required, a background obtained by least-squares fitting a smooth curve to points above and below the peak was subtracted before the integration was performed. The electrodisintegration cross section at a spectrometer angle θ_α and for an α-particle energy E_α is given by

$$\frac{d^2\sigma}{d\Omega dE_\alpha} = \frac{C_\alpha(\theta_\alpha, E'_\alpha)}{\Delta\Omega_\alpha \Delta E'_\alpha n_t(\theta_\alpha)} \frac{\Delta E'_\alpha}{\Delta E_\alpha},$$

where $C_\alpha(\theta_\alpha, E'_\alpha)$ is the number of α particles detected per incident electron, $\Delta\Omega_\alpha$ is the spectrometer solid angle, $n_t(\theta_\alpha)$ is the number of target nuclei per unit area, E'_α is the energy of the detected α particle, $\Delta E'_\alpha$ is the energy acceptance of the spectrometer, and ΔE_α is the corresponding energy bite at the center of the target. E_α was calculated from E'_α using the Bethe-Bloch formula and assuming the α particles originated half-way through the foil. The two energy bites, ΔE_α and $\Delta E'_\alpha$, are related by (assuming $dE/dx \approx 1/E$)

$$\frac{\Delta E'_\alpha}{\Delta E_\alpha} = \left(\frac{dE}{dx}\right)_f \Big/ \left(\frac{dE}{dx}\right)_i .$$

The subscripts f and i indicate that the energy loss per unit length is to be evaluated at the kinetic energy of the α particle at the spectrometer (f) and at the center of the target (i).

III. RESULTS AND DISCUSSION

In our earlier paper we found that up to 13 MeV the copper angular distributions were isotropic, consistent with an evaporation production process. Since the higher energy thulium angular distributions were forward peaked, indicating a contribution from a direct-reaction process, it seemed appropriate to investigate the possibility of a direct-reaction process contributing to copper angular distributions above 13 MeV. These distributions are shown in Fig. 1. Forward peaking is evident. It should also be pointed out that at energies above 13 MeV the evaporation model fitted to the 50° energy distribution for copper described in Ref. 1 underestimated the measured cross section. Thus both the angular distributions and the energy distribution at 50° indicate that above 13 MeV a direct process is occurring in the reaction $\mathrm{Cu}(e, \alpha)e'X$.

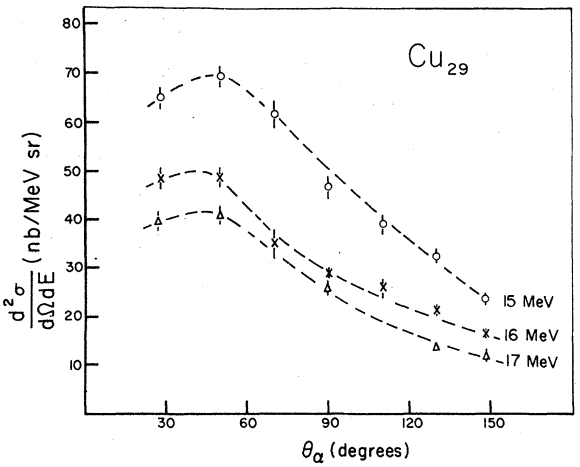

FIG. 1. High energy angular distributions for copper ($Z=29$). The expected forward peaking due to the importance of the direct process is seen.

In Fig. 2 are shown the 50° α-particle energy spectra for the new nuclei studied in this latest experiment as well as for two nuclei studied in the earlier work for which additional data have been obtained. Several features can be noted. First, all the spectra show broad peaks at values near the energy of the classical Coulomb barrier. This is shown in Fig. 3 where the data from this work and the earlier work are all shown. The Coulomb barrier is taken from Marion and Young.[2] Second, the magnitude of this broad peak in the cross section decreases with increasing Z as shown in Fig. 4. These results are in complete agreement with the results reported previously.

We have attempted to fit the energy spectra of Fig. 2 with evaporation cross sections calculated from

$$\frac{d^2\sigma}{d\Omega dE} \propto E\beta(E)e^{-E/\theta}, \tag{1}$$

where E is the α-particle energy and θ is the nuclear temperature. The quantity $\beta(E)$ which we called the penetrability in Ref. 1 is more generally called the capture cross section and is proportional to the barrier penetrability and a factor called the sticking probability. To calculate $\beta(E)$ in a consistent way for all the nuclei studied we follow Morrison[3] and write

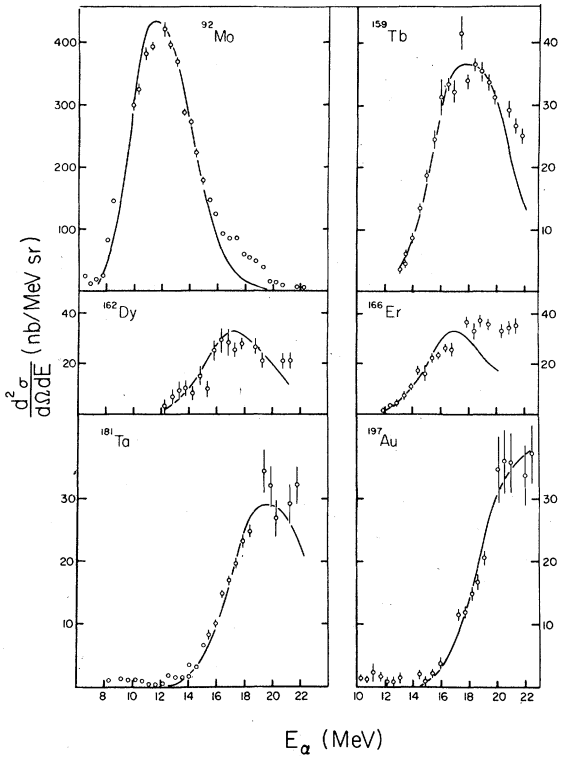

FIG. 2. The α-particle energy spectra at 50° in the laboratory for the four new nuclei studied as well as for two nuclei in which additional data have been obtained. The solid curves are the evaporation model fits described in text.

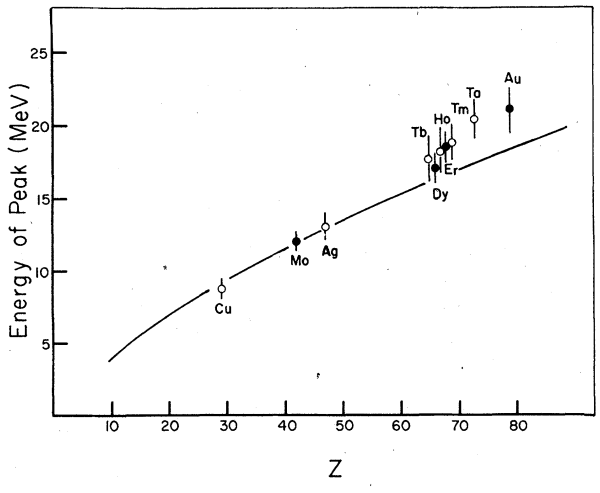

FIG. 3. Energy of the cross section peak as a function of Z. The solid line is the energy of the classical Coulomb barrier. The closed circles are the current work; the open circles are from Ref. 1.

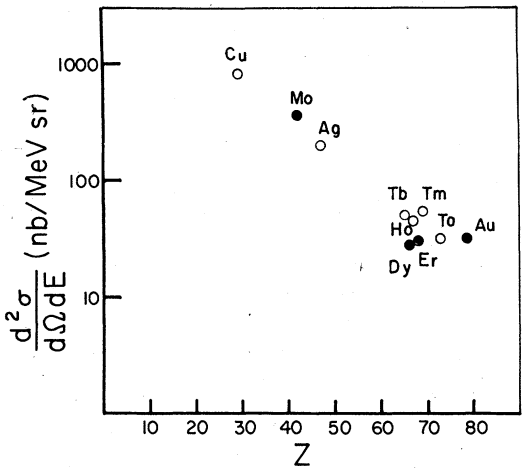

FIG. 4. Magnitude of cross section peak as a function of Z. The closed circles are the current work; the open circles are from Ref. 1.

$$\beta(E) = \pi\lambda^2 \sum (2l+1) P_l \xi_l \quad = \pi\lambda^2 \sum (2l+1) e^{-2C_l},$$

where P_l is the barrier penetrability, and ξ_l is the sticking probability for angular momentum l. The expression for C_l is complicated but given in analytic form in Ref. 3; it depends on the ratio E/B_l where B_l is the barrier height for a particle of angular momentum l. This expression is valid only for $E < B_l$. For $E > B_l$ we take

$$\beta(E) = \pi(R+\lambda)^2 \left[1 - \frac{B_0(R+\lambda)}{E}\right]$$

as suggested by Blatt and Weisskopf.[4] Since the values of $\beta(E)$ are fixed by the equations cited, only the nuclear temperature θ in Eq. (1) may be freely varied in an effort to fit the energy spectra of Fig. 2. The fits obtained are shown as the solid curves in the figure. For the lightest nucleus, molybdenum, the fit is satisfactory from the lowest energies to energies above the peak. Only at the highest energies measured is the experimental cross section significantly larger than the evaporation cross section. For the heavier nuclei the disagreement begins near the peak energies. One concludes that for all the nuclei studied at higher energies a direct-reaction process makes a significant contribution to the cross sections. The energy spectra reported in Ref. 1 were fitted in the same way. Again for the lightest nuclei, copper and silver, the fits were good past the peak; for the heavier nuclei the fits begin to fail near the peak. The nuclear temperatures obtained in the fitting process varied from near 1 MeV for the lighter nuclei to 1.8 MeV for the heavier. These

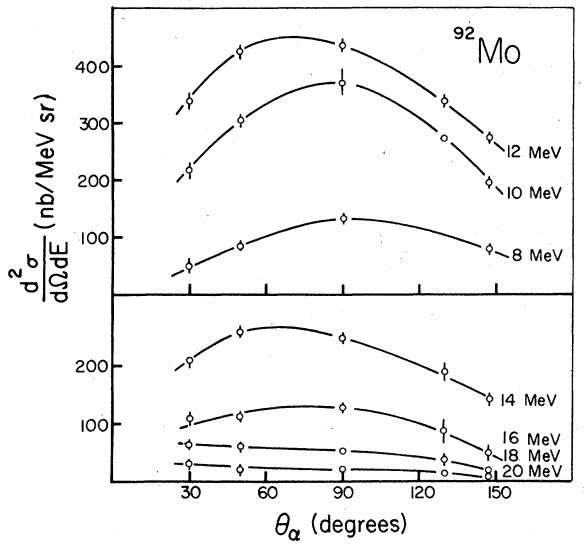

FIG. 5. Angular distributions for molybdenum. Errors are statistical; curves are to guide the eye. Increased forward peaking with increasing energy is taken as evidence for the importance of the direct process at higher energies.

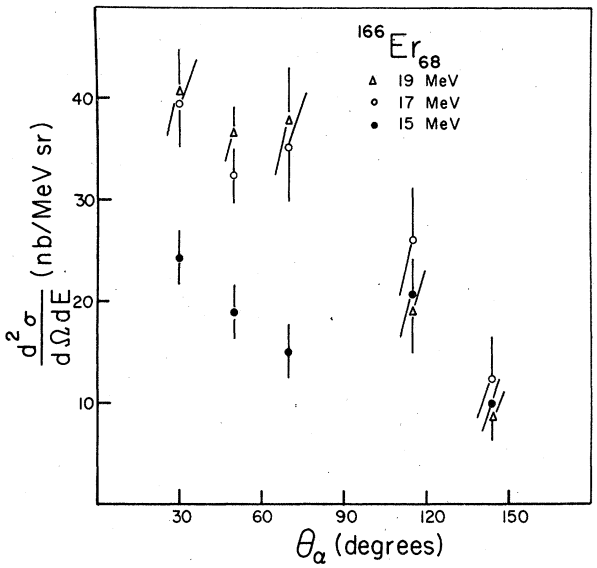

FIG. 7. Angular distributions for erbium. The comments made for Fig. 5 apply here.

values for the nuclear temperature are consistent with the values obtained from level density calculations.[3]

We have previously reported[5] α particles at energies below the Coulomb barrier for ^{159}Tb, ^{162}Dy, and ^{166}Er. Since electron scattering measurements performed at this laboratory did indicate an oxygen contamination in the target foil, we have used the elastic form factor results of Cooper *et al.*[6] for ^{166}Er and of Sick and McCarthy[7] for ^{16}O to extract from our electron scattering data the percentage contamination of oxygen. These results along with a measurement of the ^{16}O(e, α) cross section at $E_0 = 100$ MeV indicate that the low energy α

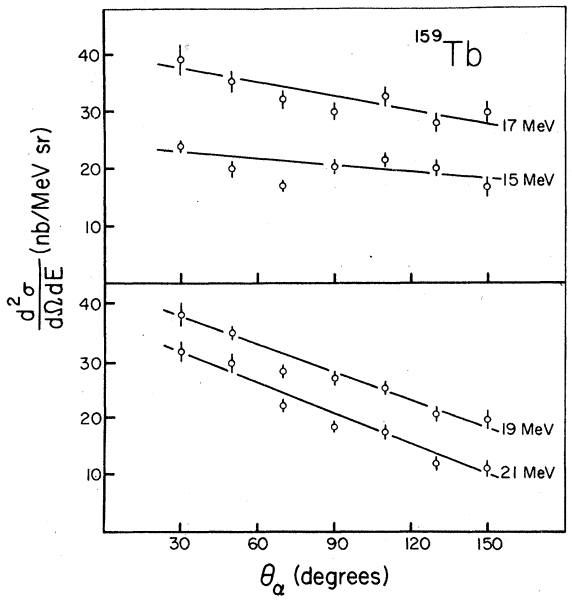

FIG. 6. Angular distributions for terbium. The comments made for Fig. 5 apply here.

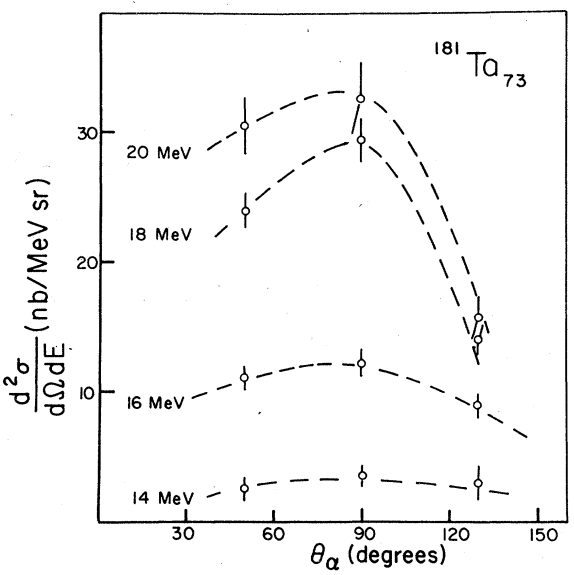

FIG. 8. Angular distributions for tantalum. The comments made for Fig. 5 apply here.

particles arise from ^{16}O contamination in the targets. The spectra shown in Fig. 2 have had the oxygen contribution to the cross section removed. This subtraction is negligible at $E > 15$ MeV.

Angular distributions for $^{92}Mo_{42}$, $^{159}Tb_{65}$, $^{166}Er_{68}$, and $^{181}Ta_{73}$ are shown in Figs. 5, 6, 7, and 8, respectively. All show more forward peaking with increased α-particle energy, indicating an increasing contribution from a direct process.

Recently Flowers *et al.*[8] have reported similar results for ^{60}Ni. Their energy spectra exceed their statistical-model calculation and their angular distributions become forward peaked at higher α-particle energies. They conclude that there is a direct process contributing to the $^{60}Ni(e, \alpha)$ cross section at higher α-particle energies.

IV. SUMMARY

The systematics of the electroproduction of α particles from nuclei with Z between 29 and 79 are established by the data presented in this paper combined with the data from Ref. 1. The peak cross sections occur at energies within a few MeV of the classical Coulomb barrier; the magnitude of the peak cross section decreases logarithmically with increasing Z. These facts are consistent with an evaporation process for the production of the observed α particles. Furthermore, a large portion of the energy spectra data can be reproduced quite well by an evaporation model. However, for the highest energy α particles measured, the evaporation model significantly underestimates the experimental cross section, indicating the importance of a direct-reaction process at these higher energies. For low Z nuclei, typified by copper, the Coulomb barrier is low enough that the peak of the cross section occurs in the evaporation dominated region. For nuclei of higher Z the Coulomb barrier is higher and the peak of the cross section is at higher energies which are in the region in which the direct-reaction process becomes important. Evidence for this transition from low energy evaporation to high energy direct α particles is seen also in the fact that for all the nuclei for which we have data the angular distributions become more forward peaked as the α-particle energy increases. One concludes that while the evaporation process dominates at lower energies, a direct-reaction process becomes increasingly important as the α-particle energy increases. The importance of this direct process may indicate the existence of α clusters in the nucleus.

While it is possible to fit the data in the evaporation dominated energy region with the model described in the text, we know of no α-cluster model for nuclei in this part of the Periodic Table which would permit a calculation of either energy spectra or angular distributions in the region in which the direct process is important.

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