One should point out that even the maverick Mg^{24} and Be^9 exhibit excitation functions very similar in shape to the general trend. This becomes even more obvious when the transfer reaction excitation functions are compared to a typical excitation function for an evaporation reaction such as $O^{16}(N^{14},2p)Al^{28}$. It can be seen that the slopes for $E^*<0$ are different, and for $E^*>0$ the cross section for $O^{16}(N^{14},2p)Al^{28}$ keeps rising to well above 100 mb at $E^*=2.35$ Mev, whereas the transfer cross sections level off around 3 mb.

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Inelastic Scattering of 40.2-Mev Alpha Particles*

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The differential cross section $d^2\sigma/dEd\Omega$ has been measured at 25, 45, 90, 135, and 150 degrees in the laboratory system for the inelastic scattering of 40.2-Mev alpha particles from Al, V, Cu, Nb, Ag, Ta, and Th. Spectra obtained at 135 and 150 degrees have been analyzed in terms of the statistical theory of nuclear reactions. The differential cross section measured at smaller angles is incompatible with the statistical theory of nuclear reactions. A group of alpha particles with energy well below the Coulomb barrier is observed in the spectra of Ta and Th at large angles.

INTRODUCTION

IN the past few years the experimental evidence on the interactions of heavy particles with energies of about 40 Mev has been studied by several experimenters.[1] The relevant conclusions arrived at as far as the present experiment is concerned are that (1) the nucleus is at its maximum opacity, and consequently the mean free path is at a minimum; (2) the level densities of nuclei increase exponentially with excitation energy; (3) the importance of noncompound nucleus processes has been observed (in some reactions the noncompound nucleus cross section is an order of magnitude larger than the cross section for compound nucleus processes), and (4) in the optical-model treatments of elastic scattering of protons[2] and alpha particles[3,4] it is necessary to introduce a nuclear potential with a diffuse surface.

These conclusions can be given an additional test by the investigation of the interactions of energetic alpha particles with nuclei. According to these conclusions, when an energetic alpha particle strikes the dense, central part of a heavy nucleus, it imparts its energy and momentum to the nucleons of the nucleus in a series of collisions since the mean free path is considerably shorter than the radius of the nucleus.[4] According to the statistical theory of nuclear reactions, the compound nucleus which results from the interaction emits particles isotropically.[5]

On the other hand, according to the conclusions stated above, the mean free path is long enough so that collisions in the "skin" of the nucleus can occur in which only one nucleon of the nucleus is involved. Collisions of this type would result in an angular distribution peaked strongly in the forward direction.[6,12] Consequently compound nucleus processes predominate in the backward hemisphere, since surface interactions should have small cross sections in the backward hemisphere. The (α,p) experiment at 40 Mev[7] gives weight to the idea that statistical processes predominate in the backward hemisphere. Consequently a method is available for measuring energy-level densities, namely, by measuring energy spectra in the backward hemisphere.

In the present investigation of inelastic alpha-particle events an independent check is possible on the conclusions reached from the analysis of the 40.2-Mev (α,p) experiment; namely, that the backward scattering is mainly due to statistical processes.

In addition the inelastic scattering of alpha particles into the forward hemisphere and the cross section for

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[1] "Statistical Aspects of the Nucleus," Brookhaven National Laboratory Report BNL-331(C-21), 1955(unpublished).
[2] Melkanoff, Nadrick, Saxon, and Woods, University of California at Los Angeles Report UCLA-7-12-55 (unpublished).
[3] Cheston, Glassgold, Stein, Schuldt, and Erickson, Bull. Am. Phys. Soc. Ser. II, 1, 339 (1956).
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[5] See for instance J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).
[6] R. M. Eisberg and G. Igo, Phys. Rev. **93**, 103 (1954).
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the emission of alpha particles below the Coulomb barrier of heavy elements are measured.

APPARATUS AND PROCEDURE

The scattering apparatus used in these experiments has been described in an earlier paper.[8] The NaI scintillator used in the earlier experiments was replaced by two proportional counters and a NaI scintillator, an arrangement of counters which is sensitive to the mass as well as the energy of the scattered particle. This made it possible to measure alpha-particle spectra in the presence of other particles.

In order for the counter arrangement to record the passage of a particle as a real event, the particle must pass through both proportional counters and into the NaI scintillator. A 40-Mev alpha particle loses an amount of energy ΔE which is proportional to its specific ionization in each proportional counter, and stops in the NaI crystal. The output pulse height of the NaI scintillator is proportional to the energy since the 40-Mev alpha particle loses less than one percent of its energy in the proportional counters. The output pulse from the proportional counter circuit and the output pulse from the photomultiplier are fed into a multiplying circuit. The product pulse height is approximately proportional to the product of the mass and the square of the charge of the scattered particle. The product pulse from the multiplying circuit was fed to a single-channel analyzer. The product pulse height for alpha particles fell between the upper and lower limits of the voltage window of the pulse height analyzer. (The method of alignment is described in the next paragraph.) The output pulse from the single-channel analyzer was used to "gate-on" a twenty-channel pulse height analyzer into which the pulses from the NaI scintillation counter were fed after suitable amplification.

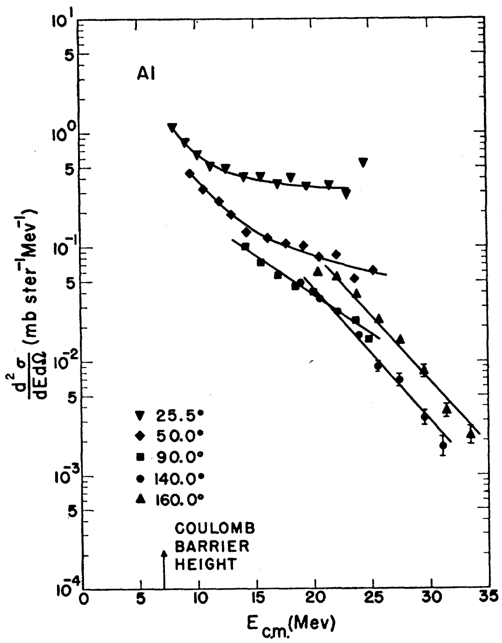

FIG. 1. The differential cross section, $d^2\sigma/dEd\Omega$, for the inelastic scattering of 40.2-Mev alpha particles from Al.

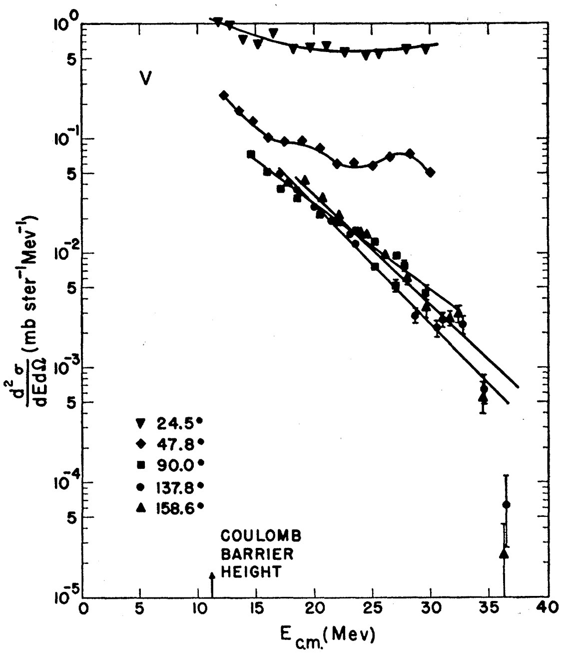

FIG. 2. The differential cross section, $d^2\sigma/dEd\Omega$, for the inelastic scattering of 40.2-Mev alpha particles from V.

The method described below was used to insure that all alpha particles would be counted. Forty-Mev alpha particles which had been elastically scattered from Au at an angle of 20 degrees were allowed to enter the detector. The differential cross section for elastic scattering at 20 degrees represents 99% of the differential cross section for all processes at this angle. The single-channel analyzer was set so that the ratio of the number of counts per unit incident flux was unity to within one percent when the requirement of the gate pulse from the single-channel analyzer was and was not required. The energy of the elastically-scattered particles was reduced in steps by introducing absorbers between target and counter to that of the lowest energy alpha particle detected in the experiment, and the voltage channel was adjusted so that the ratio was within one percent of being unity at all energies. With the single-channel analyzer adjusted for alpha particles, the cyclotron was readjusted to produce 20-Mev deuterons. The same measurements were repeated, and it was found for all deuteron energies that the ratio of counting rate for gate pulse required (gate-on) and counting rate for gate pulse not required (gate off) was equal to zero within 0.1%. The same experiment was repeated using the 10-Mev proton beam from the 60-in. cyclotron. The gate-on/gate-off counting ratio was again determined to be zero.

[8] Wegner, Eisberg, and Igo, Phys. Rev. 99, 825 (1955).

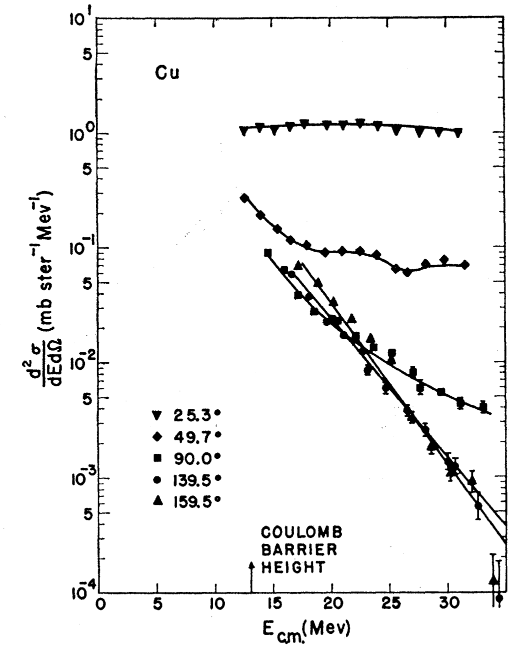

FIG. 3. The differential cross section, $d^2\sigma/dEd\Omega$, for the inelastic scattering of 40.2-Mev alpha particles from Cu.

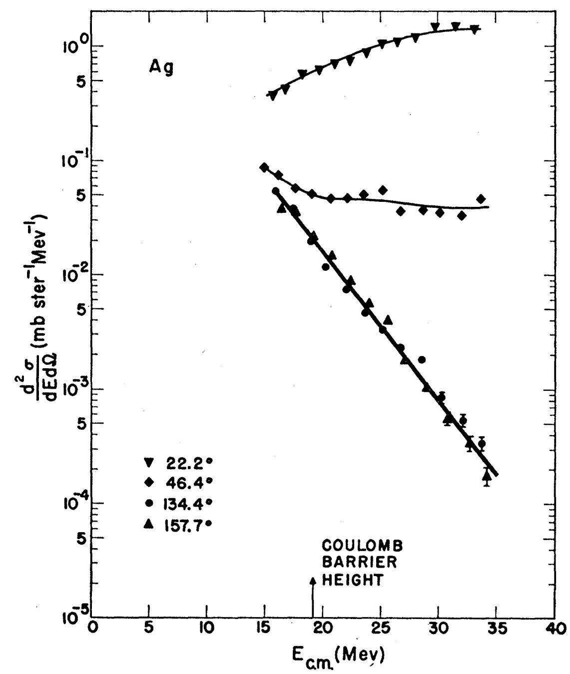

FIG. 5. The differential cross section, $d^2\sigma/dEd\Omega$, for the inelastic scattering of 40.2-Mev alpha particles from Ag.

EXPERIMENTAL RESULTS

The energy distributions measured at various angles in the laboratory system are first corrected for energy losses in the scattering chamber window, in the counter window and gas, and in the air path. They are then converted to the center-of-mass system. The data for Al is shown in Fig. 1. The differential cross section $d^2\sigma/dEd\Omega$ is plotted as a function of the energy of the inelastically-scattered alpha particle in the center-of-mass system. The height of the Coulomb barrier is indicated on the abscissa. The errors due to statistical fluctuations in the counting rate are equal to or less than the size of the dots or else flags indicate the error. There is an uncertainty in the absolute cross-section scale of the 25.5° spectrum due to instability in the beam-current integrator for small beam currents. However, this does not affect the relative values of the experimental points in this spectrum. There is an uncertainty not larger than one percent in the position of the absolute cross-section scale for spectra taken at other angles. These remarks apply to the data for other elements. The dependence of the differential cross section of Al at 25.5° on the energy of the emitted particle is slight. At large angles the energy spectra decreases rapidly with increasing energy of the emitted alpha particle. The differential cross section $d^2\sigma/dEd\Omega$ has an average value of 0.5 mb at 25.5° and 0.01 mb at 160°. In V (Fig. 2) the corresponding differential cross sections are quite similar in magnitude to the Al data. In Cu (Fig. 3) the average differential cross section at 25° is twice the value measured in Al. The energy spectrum at 159° drops more steeply than the energy spectra of Al and V at approximately the same angle. In Nb (Fig. 4) the average value of the differential cross section at 23° is more than twice the average value for Cu.

In Ag (Fig. 5) the differential cross section at small

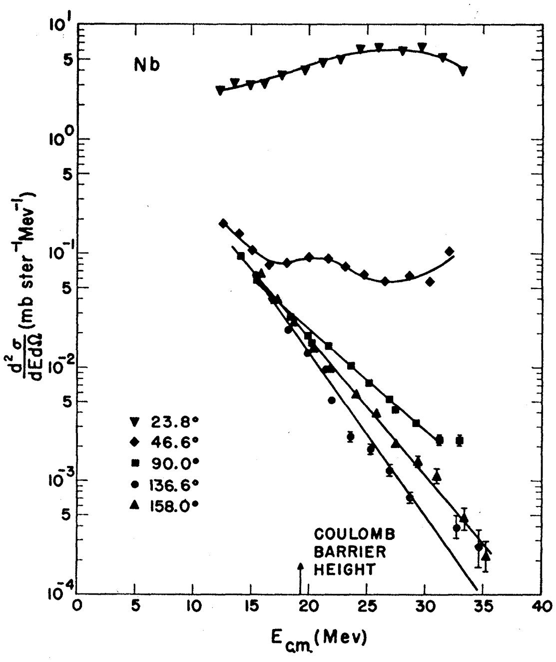

FIG. 4. The differential cross section, $d^2\sigma/dEd\Omega$, for the inelastic scattering of 40.2-Mev alpha particles from Nb.

angles is smaller than the cross section in Nb. In Ta (Fig. 6) the average value of the differential cross section at small angles is about twice the value obtained from the Nb data. At larger scattering angles, the differential cross section peaks below the Coulomb barrier, and at larger energies, drops monotonically. In Th (Fig. 7) a peak is also found below the Coulomb barrier. The average value of the differential cross section at 45° is larger by a factor of two compared with the same measured quantity in Ta.

In summary, it is observed that (1) at small angles, the differential cross section increases with increasing atomic number and the shape of the energy spectrum does not change; (2a) in the backward hemisphere, the differential cross section of Ta and Th show a prominent peak below the coulomb barrier superimposed on an exponentially decreasing component; (2b) the energy spectra of the other elements also drop exponentially with increasing energy; and (3) the differential cross sections of all elements investigated are approximately independent of angle in the backward hemisphere.

The latter two results are expected on the basis of the statistical theory of nuclear reactions, and consequently the data at large angles are analyzed in terms of the theory. As was mentioned in the introduction, the 40-Mev (α,p) experiment gave weight to the idea that statistical processes predominate in the backward hemisphere, and the (α,α') results support this conclusion.

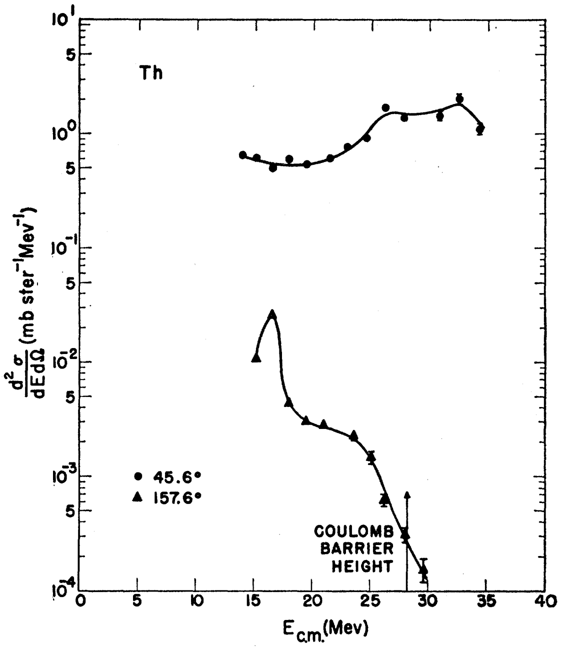

FIG. 7. The differential cross section, $d^2\sigma/dEd\Omega$, for the inelastic scattering of 40.2-Mev alpha particles from Th.

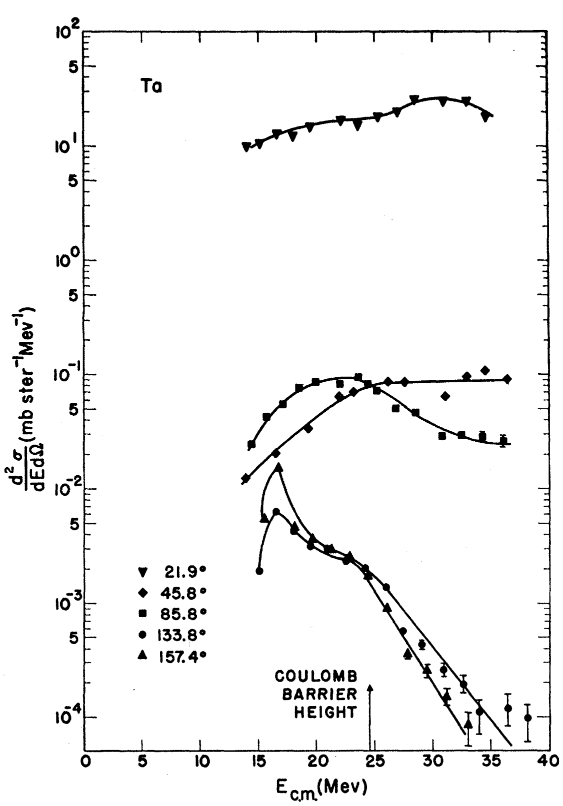

FIG. 6. The differential cross section, $d^2\sigma/dEd\Omega$, for the inelastic scattering of 40.2-Mev alpha particles from Ta.

In the analysis of the large-angle data it was assumed that the relation between the measured alpha-particle energy distributions and the energy level densities was provided by the following formula:

$$N(E)dE=\text{const}E\sigma_c(E)\rho(E_r)dE, \qquad (1)$$

where $N(E)dE$=number of alpha particles emitted with energy between E and $E+dE$, $\sigma_c(E)$=cross section for capture of an alpha particle of energy E by the residual nucleus, and $\rho(E_r)$=density of energy levels of the residual nucleus at excitation E_r where $E_r=40.2-E_0$.

This formula follows from the assumption that the reaction proceeds through the compound-nucleus mechanism and depends upon detailed balancing between the compound system and the system consisting of the residual nucleus plus the emitted alpha particle.

Rewriting Eq. (1), one obtains

$$\frac{N(E)}{E\sigma_c(E)}=\text{const}\rho(E_R). \qquad (2)$$

The assumption that Eq. (2) is valid provides a relation between $N(E)$, the measured quantity, and $\rho(E_R)$, the desired quantity.

The energy of the alpha particles measured in this experiment varies between 0.6 and 5 times the Coulomb barrier energy. Since a sizable proportion of them lie below the Coulomb barrier, especially for heavy elements, the model used for the charge distribution

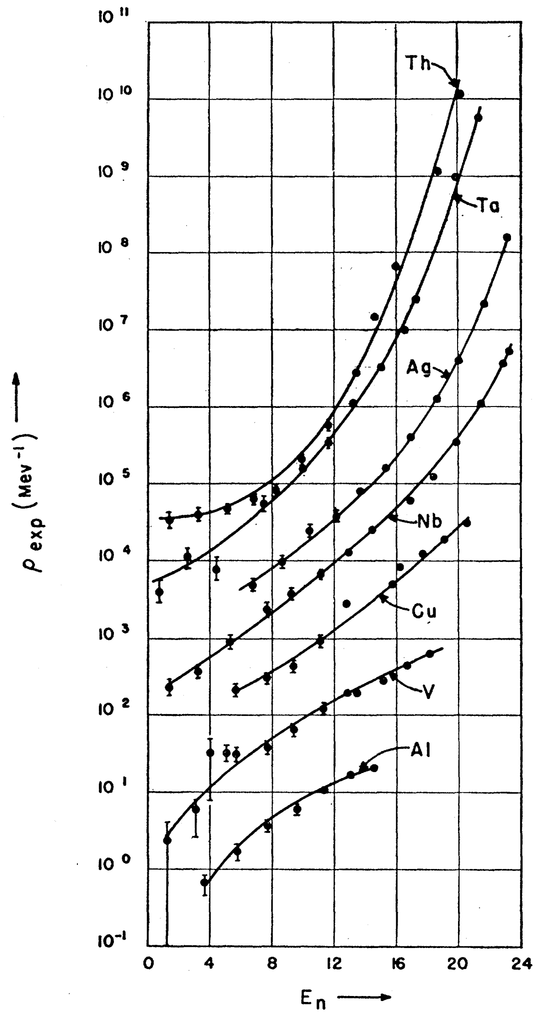

FIG. 8. The quantity, $\rho_{exp}(E_R)$, is plotted against the excitation energy, E_R, for Al, V, Cu, Nb, Ta, and Th.

and consequently the shape and penetrability of the Coulomb barrier will have an effect on the value of the level densities derived from experiment. The values of σ_c obtained from the paper of Shapiro[9] were used.

In Fig. 8, $N(E)E^{-1}\sigma_c(E)^{-1}\equiv\rho_{exp}(E_R)$ is plotted against E_R. The curves have been normalized to the level densities measured in slow-neutron cross-section experiments.[10]

CONCLUSIONS

Compound nucleus processes appear to predominate in the backward hemisphere, since the differential cross section is approximately independent of angle there, and because cross sections for direct processes are small in the backward hemisphere.

The same conclusion was reached when the proton spectra from the bombardment of Au, Ag, and Cu with 40-Mev alpha particles were measured in the (α,p) experiment[7] at a scattering angle of 150°. The shape of the energy-level distribution determined from the 40-Mev (α,p) experiment was compatible with the Fermi gas model level density formula $\rho(E_R) = \text{const}\exp[(aE_R)^{\frac{1}{2}}]$. On the other hand, the parameter a was found to have the same value for Cu, Ag, and Au. According to the Fermi gas model, a should increase linearly with the atomic number. The results of other energy level density measurements have been summarized previously.[11]

The results of the present experiment, when they are analyzed in terms of the statistical theory, are not compatible with the Fermi gas model for the nucleus. The experimentally measured level density increases much less rapidly at low excitation energies than the Fermi gas level density. On the other hand, in contrast to the (α,p) result, the rate of increase of level density with the nuclear excitation energy measured in the present experiment increases with atomic number as can be seen in Fig. 8. This is a general prediction of most nuclear models.

The divergencies in the results of the (α,p) and (α,α') experiments when analyzed in terms of the statistical theory of nuclear reactions[5] may be due to differences in the interactions of alpha particles and protons in nuclear material. From analyses[1,4] of elastic scattering data, the mean free path of a 20-Mev alpha particle is found to be approximately one-half the mean free path of a 20-Mev proton. In view of the divergences between the experimental data from a number of experiments[11] and existing theoretical calculations,[1,5] a calculation taking in account the difference in mean free paths would be of very great interest.

The group of particles observed below the Coulomb barrier in Ta and Th may be due to interactions in the classically forbidden region outside the nuclear surface.[12]

ACKNOWLEDGMENT

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