Elastic Scattering of Alpha Particles and Deuterons from Heavy Nuclei*†‡

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The angular distributions of 22-Mev alpha particles and 11-Mev deuterons scattered elastically from Ta, Au, Bi, and U have been measured at angles of 20 to 160 degrees in the laboratory system. It is found in all cases that the deuteron cross sections depart from the Rutherford angular dependence at smaller angles than the alpha-particle cross sections for the same nuclei, indicating electric breakup of the deuteron.

I. INTRODUCTION

MANY experimental investigations of the elastic scattering of alpha particles and a few of the elastic scattering of deuterons have been recently performed with cyclotron beams.[1–10]

Some prevalent features of the scattering of alpha particles have emerged: (1) At fixed bombarding energy, the heavier the nucleus and concomitantly the greater its charge, the smoother (less oscillatory) is the angular distribution. (2) Strong, regular diffraction effects appear in the differential cross sections for light and medium weight nuclei. (3) The cross sections approach the Rutherford cross sections at small scattering angles. Insufficient data have been published to make similar generalizations about deuteron scattering.

The present experiments were undertaken with the twofold intention of extending earlier work in this laboratory[4] over a wider range of nuclei and of comparing the elastic scattering of deuterons with that of alpha particles. The target nuclei chosen were ${}_{73}Ta^{181}$, ${}_{79}Au^{197}$, ${}_{83}Bi^{209}$, and ${}_{92}U^{238}$. Each is practically monoisotopic.

The energies of cyclotron beams of particles with the same charge-to-mass ratio but different charges vary in the same way as do the heights of the Coulomb barrier for the different particles at a fixed radius; therefore, the ratio between bombarding beam-energy and nuclear barrier height should be almost the same for cyclotron alpha particles and deuterons incident on the same nucleus, differing only because of the difference in the specific nuclear potentials for the two interactions, the shape-elastic potentials.[11]

II. EXPERIMENTAL TECHNIQUES

(A) Apparatus

The beam of the Indiana University 45-inch cyclotron is extracted by electrostatic deflection, passes along an evacuated tube through a focusing magnet, a shielding wall, and an analyzing magnet, and is admitted to a 15-inch scattering chamber through two sets of adjustable collimating slits. Helium and deuterium nuclei are accelerated to 22 Mev and 11 Mev, respectively. The targets are supported from the top of the chamber, and the particle detector, a CsI(TI) scintillation counter, is mounted on the bottom. The beam, having traversed the chamber, is stopped in a tungsten-backed Faraday cage and the collected charge measured with a current integrator. Secondary electrons are suppressed by a guard ring held at a potential of -275 volts with respect to ground and the Faraday cage. The beam handling techniques employed in this laboratory have been described before.[4,12] Two different settings of the horizontal beam-collimating slits, which consisted of two sets of opposing tantalum vanes spaced $5\frac{1}{8}$ inches apart along the direction of the beam, were used during the experiments. The slit widths were $\frac{1}{32}$ inch and $\frac{1}{16}$ inch. The vertical collimation remained always $\frac{5}{16}$ inch. The area on the target illuminated by the beam was $\frac{5}{16}$ inch high and, at most, $\frac{1}{4}$ inch wide.

In the deuteron experiments contamination of the deuteron beam by protons was eliminated by passing the beam through aluminum leaf.

The scintillation counter was similar to that used in earlier experiments in this laboratory[4] except that the measurement of the scattering angle was improved and CsI(TI) was used as the scintillator. The accuracy with which the detector could be returned to a particular setting, measured by means of the strong angular dependence of small angle Rutherford scattering, was about 0.1 degree. The accuracy of setting was ± 0.2 degree.

The exact direction at which the beam entered the

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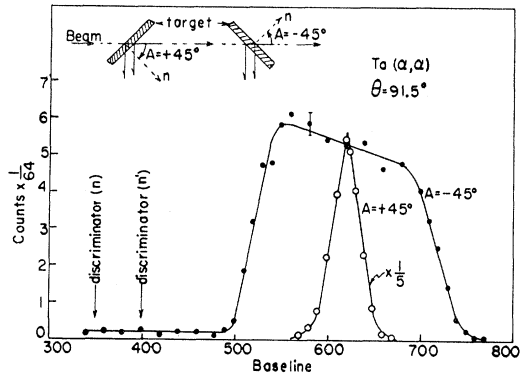

FIG. 1. Typical pulse-height spectra for alpha particles scattered elastically from a 0.00025 in. thick Ta target for the two orientations shown. The slope of the flat top for A equal to $-45°$ is due to the energy dependence of the scattering cross section.

scattering chamber was found to be sensitive to analyzing magnet current, and that current was monitored and held precisely constant.

Zero angle, the angular scale reading when the counter was directly in line with the beam, was measured by taking a portion of the angular distribution on either side of the beam and matching the distributions. This procedure served three purposes: it fixed the zero angle; it verified that the beam intercepted the counter's axis of rotation; and it checked the accuracy of the scale. The zero-angle measurement was believed to be accurate to ± 0.1 degree.

Typical pulse-height spectra taken with an R.C.A. 6199 photomultiplier tube are shown in Fig. 1. "A" is the angle the target normal makes with the beam direction. The Ta, Bi, and U targets were sufficiently thick to contribute to the width of the elastic alpha-particle group. The tilt of the top of the wide distribution ($A=-45°$) is believed due to the energy dependence of the cross section. Deuteron spectra did not exhibit such pronounced target-thickness broadening because of the lower stopping power of the target material for deuterons.

The Ta target was a 0.00025-inch rolled foil obtained from A. D. Mackay, Inc., 198 Broadway, New York, New York. The Au targets were of beaten leaf; several layers were used in large angle (d,d) measurements. The Bi and U targets were prepared by evaporating the metal onto clean sheet steel (shim stock) in a vacuum and peeling off the resulting film by manually flexing the sheet.

(B) Procedure

At the beginning of an alpha-particle run, pulse-height spectra were taken with a single-channel analyzer at crucial counter and target angles. Then two integral discriminators were set to count the entire elastic group, one being set just below the group and the other somewhat lower so that the difference of their counts measured the background level. Typical discriminator settings are shown in Fig. 1 by the arrows marked "discriminator (n)" and "discriminator (n')."

A run comprised taking the data for a complete angular distribution. In the case of alpha particles, data points were taken every 5 degrees between 20 degrees and 160 degrees; in the case of deuterons, this procedure was followed between 20 degrees and 90 degrees; however, at angles larger than 90 degrees, the intense background dictated that a pulse-height spectrum be taken every 10 degrees.

The gain of the pulse circuits was measured before and after each run. After the run, pulse-height spectra were measured again and compared to spectra taken at the start of the run. An oscilloscope provided a running check of pulse height, and a precision pulse generator could be switched on at any time between data points to display either discrimination level simultaneously with the display of the spectrum. The calibration of the beam current integrator was checked before each run.

1. *Alpha Particle Data*

The background decomposed naturally into two components: one small isotropic component and one component varying with angles according to the measured elastic cross section. The latter component was strikingly reduced (by factors of from $\frac{1}{4}$ to $\frac{1}{6}$) by doubling the beam-collimating slit openings, and was therefore attributed to slit edge scattering of the incident beam and since it could be presumed to vary with angle in almost the same way as the principle elastic group, it was not subtracted. The isotropic component of background was subtracted when it was not negligible.

The target had to be turned once during an angular distribution, altering the number of scattering centers encountered by the beam and requiring a normalization of the data taken after turning, to that taken before turning. This normalization was determined by taking a series of counts before and after turning while leaving everything other than the target fixed. This practice introduced a statistical uncertainty in the relative values of points taken before and after the turning which varied from target to target; however, the probable error introduced never exceeded 1.0%.

After the background subtraction and the adjustment of large-angle data for the turning of the target, the data were all transformed into the center-of-mass system.

After the center-of-mass transformation was completed, the data were multiplied by $\sin^{+4}(\Theta_{c.m.}/2)$ to display the ratio of the observed angular distribution to the Rutherford angular distribution. These ratios were multiplied by an arbitrarily chosen constant, a scale factor, to adjust the forward angle ratios to 1.0 and then plotted. The quantity plotted is called the relative cross section.

2. *Deuteron Data*

The procedure here differed from that already described, only in the treatment of the background and of the large angle data. The raw data for angles less than 90 degrees consisted of counts, exactly like the alpha-particle data; however, for larger angles, it consisted of pulse-height spectra measured with the single-channel analyzer.

Again the background consisted of an isotropic component and a component standing in constant ratio to the elastic group and believed to be due to the presence of a low-energy tail on the incident beam. The isotropic component was, in this case, estimated by studying the pulse-height distributions, and it was subtracted from the small angle counts.

The method of converting to counts the spectra taken at large angles varied from element to element depending on the quality of the spectra. In the cases of bismuth and tantalum, curves were drawn by eye through the points; the background was estimated by drawing a straight line under the peak; and the area under the peak but above the background line was measured by means of a planimeter. Figure 2 shows such a spectrum. The areas so obtained were converted to counts by multiplication with a constant number (a count density) which was determined by comparing areas on spectra with integral counts taken at the same angles.

The spectra obtained from the gold target were poor owing to instability of the photomultiplier tube in use at the time the gold data were taken. Since the target was thin, it was assumed that the width of the elastic group did not vary with angle and the peak height was taken as the measure of the number of counts.

In the case of uranium, the spectra taken at large angles were used only to determine the isotropic component of the background, integral counts being used as the raw data.

III. RESULTS

(A) Errors and Uncertainties

The great majority of points in the (α,α) angular distribution represent 10 000 counts or more. No count smaller than 6400 was used. These same remarks apply to (d,d) data at angles smaller than 90 degrees. To the (d,d) data beyond 90 degrees, an average probable error of 3% and a maximum probable error of 5% are assigned. The scattering angle is believed accurate to 0.2 degree. This uncertainty introduces a fractional error into the Rutherford cross section which diminishes with increasing angle, being 2% at 20 degrees and diminishing to 1% at 40 degrees and 0.5% at 90 degrees. The data are presented in the form σ/σ_C where σ_C is the Rutherford cross section, so the angular accuracy affects the magnitude of the plotted data.

The rise of the Ta and Bi data at small angles is believed due to leakage currents from the guard ring to the Faraday cage across their common insulator. The magnitude of this effect may be as large as 10% at 20 degrees where the intensity of Rutherford scattering dictated extremely small beam currents; however, the effect is negligible at angles larger than 50 degrees. Exclusive of this effect beam current integration introduces an error no larger than $\pm 0.5\%$. A calculation eliminated the possibility that multiple scattering in the target foils might be responsible for the rise of the data at small angles.

The treatment of the data is believed to reduce the error due to the presence of background to no more than 1% in the (α,α) data and no more than 1.5% in the (d,d) data at angles less than 90 degrees. At angles greater than 90 degrees, the effect of background on the graphically determined (d,d) data is considered in assigning the errors mentioned above in connection with counting statistics.

In order to provide a comparison of deuteron and alpha-particle cross sections independent of any arbitrary normalization procedure, the normalization constant which was applied to the alpha-particle distribution for each element to set the forward-angle relative cross section equal to 1.0 was also applied to the deuteron relative cross section for that same element. Since the same targets were used for both measurements (except in the case of gold) it is to be expected that at a given angle the ratio of the deuteron count to the alpha-particle count should be equal to the ratio of the 11-Mev deuteron cross section to the 22-Mev alpha-particle cross section for that angle, except for a factor of 2 owing to the different charges of the particles. This expectation will not be born out unless the target angle is the same in both cases. That this was the case cannot be asserted with any confidence in the cases of bismuth, gold, and uranium where the forward-angle data were taken with the target at 45 degrees to the beam direction. The yield of scattered particles from the target varies as $\cos A$, where A is the angle between the target normal and the beam direction (see Fig. 1). The cosine varies rapidly at 45°, so failing to return the target to exactly the same angle, causes the yield to vary markedly. For example, a 3-degree discrepancy in target angle near 45 degrees causes a 5.0 discrepancy in

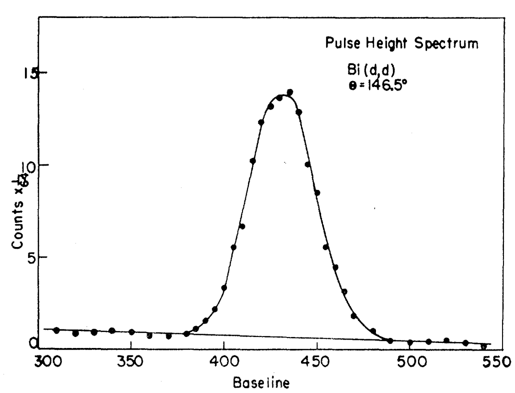

FIG. 2. A typical pulse-height spectrum for deuterons scattered inelastically from a Bi target. The area under the curve with the background subtracted was taken as proportional to the total counts.

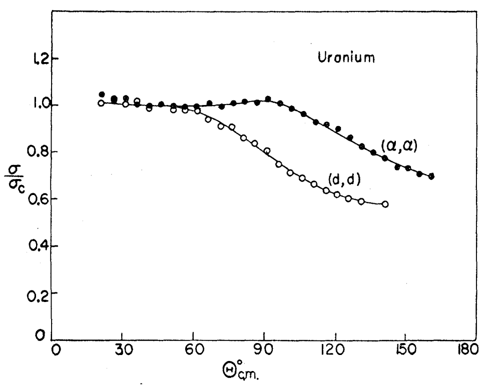

FIG. 3. The relative cross sections for the elastic scattering of 22-Mev alpha particles, and 11-Mev deuterons, from uranium.

yield. The target angle could be reset within ± 1.5 degrees so that the relative values of the cross sections for deuterons and alpha particles on bismuth and uranium are subject to $\pm 2.5\%$ uncertainty from this source.

This uncertainty does not affect the tantalum measurements since the forward-angle data were taken with $A = 0°$. The gold measurements were not made with the same target, and are therefore subject to an additional discrepancy due to the nonuniformity of commercial gold leaf.

In comparing deuteron and alpha-particle cross sections, account must be taken of the thickness of the target, since, for thick targets, the average energy of the scattering will differ for deuterons and alpha particles. Unless the energy dependence of the differential cross section is known, exact account cannot be taken of this effect, however at small angles it is reasonable to assume the E^{-2} dependence of Rutherford scattering. With this assumption, and taking the stopping power for 11-Mev deuterons to be one-fourth that for 22-Mev alpha particles, we find

$$\frac{\sigma(d)}{\sigma(\alpha)} = \left(1 - \frac{\Delta E}{E_0}\right)_\alpha \Big/ \left(1 - \frac{1}{2}\frac{\Delta E}{E_0}\right)_\alpha ,$$

where $\sigma(d)/\sigma(\alpha)$ is the ratio of cross sections for deuterons and alpha particles at the same angle and $(\Delta E/E_0)_\alpha$ is the fractional energy loss of an alpha particle passing through the target.

The energy-thickness of the gold and uranium targets was negligible. The pulse-height spectra of particles from bismuth and tantalum, taken at 90 degrees (of which Fig. 1 is an example), indicated that $(\Delta E/E_0)_\alpha$ was about 9.5% for the tantalum target and about 16.3% for the bismuth target. Thus, for the tantalum measurements, $\sigma(d)/\sigma(\alpha)$ is about 0.94, and for bismuth it is about 0.91. The reason for the greater energy thickness of the bismuth target is that it was used at an angle of 45 degrees to the beam, while the tantalum was normal to the beam for small-angle measurements. By multiplying the plotted alpha particle data by these numbers the (α,α) and (d,d) curves could be brought more closely into coincidence at small angles, but, since the energy dependence of the cross section at large angles may not be identical with that of the Rutherford cross section this was not done.

B. Angular Distributions

The angular distributions of elastically scattered particles from uranium are shown in Fig. 3 in the form of relative cross sections. The curve drawn for the (α,α) distribution does not follow the rising trend of the plotted points at small angles because a more careful measurement showed that it varies no more than 1.4% from the Rutherford angular dependence between 19.3 degrees and 44.3 degrees. The rising trend in this region is attributed to leakage of current from the guard ring to the Faraday cage.

For most of the angular distributions, it was decided to draw smooth curves even though a hint of fine angular structure (e.g., diffraction) might appear, because the experimental methods were not deemed sufficiently refined to verify such structure.

The relative cross sections for bismuth are shown in Fig. 4. The dotted lines indicate the probable small-angle dependence. It is again felt that the rising data at

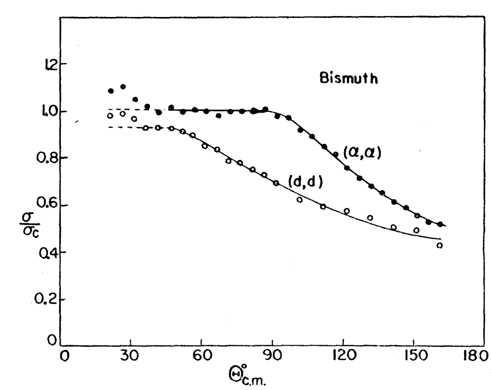

FIG. 4. The relative cross sections for the scattering of 22-Mev alpha particles, and 11-Mev deuterons, from bismuth. The rise at small angles is due to current leakage to the integrator.

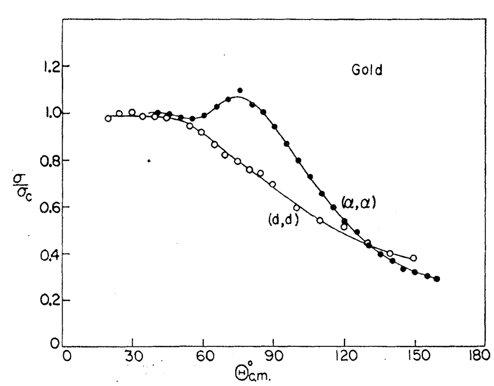

FIG. 5. The relative scattering cross sections for gold. The rise above the Coulomb cross section for alpha particles is real.

small angles are due to leakage from the guard ring. The difference at small angles between the (α,α) and the (d,d) relative cross sections is attributable to the target thickness effect mentioned above. This same effect will, of course, affect the data at all angles in a manner depending upon the energy dependence of the angular distributions.

The relatively fine angular structure drawn for the $\mathrm{Au}(\alpha,\alpha)$ reaction (Fig. 5) may not be justified; however, the same sort of behavior has been observed previously,[3,4] and in later experiments in this laboratory.

A supplementary measurement verified the smooth angular dependence of the $\mathrm{Au}(d,d)$ relative cross section between 20 degrees and 50 degrees.

In the case of tantalum, again (Fig. 6) the rising trend of the (α,α) data at small angles is felt to be due to integration difficulties, and it follows that the same losses warp the $\mathrm{Ta}(d,d)$ curve.

Figure 7 shows all of the (d,d) relative cross sections plotted together to display the variation from element to element. The gold data show a different character than the rest. The relative cross sections, σ/σ_C rise in the order of increasing atomic weight and charge. It should also be noted that the negative slope of the large-angle gold data is somewhat steeper than that of the tantalum data; except for gold, the average negative slope decreases with increasing Z and A.

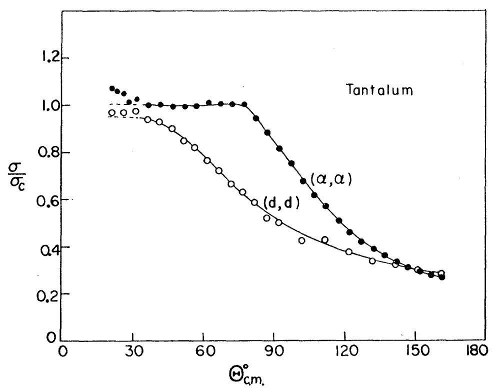

FIG. 6. The relative cross sections for tantalum. The rise at 30° is again due to current leakage to the integrator.

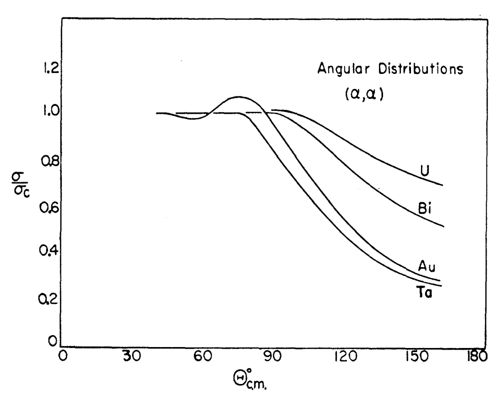

FIG. 7. A comparison of the angular distributions for elastic scattering of 22-Mev alpha particles from the four elements measured.

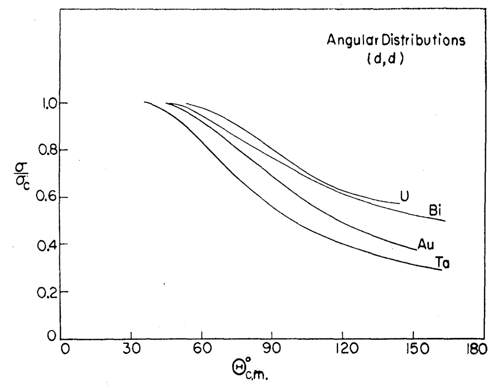

FIG. 8. Comparison of the angular distributions for elastic scattering of 11-Mev deuterons from the four elements measured.

Figure 8 shows the variation of the (d,d) relative cross section from element to element. For this figure the curves have been normalized to unity at small angles. It is noteworthy that again, as in the case of the (α,α) distributions the relative magnitudes of the relative cross sections at large angles go in the order of increasing atomic number and atomic weight.

The most salient feature of the angular distributions is the fact, confirmed in all cases, that the deuteron cross section departs from the Rutherford dependence at a smaller angle than does the alpha-particle cross section for the same nucleus. We summarize this difference in angle of departure by defining an "interaction distance" in terms of classical mechanics. The interaction distance of a particle is the apsidal distance of its classical trajectory when it is scattered through the angle of departure, i.e., the angle at which the cross section falls below the Rutherford cross section. The average of the differences between the interaction distances for deuterons and alpha particles scattered by the same nucleus was 5.2×10^{-13} cm. This value suggests that the electric breakup of the deuteron plays an important role in the scattering.[13]

Attempts were made to fit the data with the theory of Ford and Wheeler,[14] but the approximations of the theory were found not to be warranted in the cases studied.

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[13] See also Y. Nishida, Progr. Theoret. Phys. Japan **17**, 506 (1957).

[14] A partial account of the theory of Ford and Wheeler appears in reference 5. A more complete exposition appears in the dissertation of J. R. Rees, Indiana University, 1956 (unpublished).