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Elastic Scattering of Protons, Deuterons, and Alpha Particles from Heavy Elements*

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The elastic scattering of 7.8-Mev protons from Au^{197}, 27.5-Mev alpha particles from Au^{197}, and 15.2-Mev deuterons from Pb^{208} and Bi^{209} has been measured as a function of angle. Except for the proton scattering which bears a constant ratio to Coulomb scattering, the cross sections when plotted as a ratio to the Coulomb cross sections fall sharply below unity at an angle of about 50° for the alpha particles on gold and about 30° for the deuterons on lead and bismuth. The absolute cross section for elastic scattering of 15.2-Mev deuterons from gold at 30° is equal to the Coulomb value within 20%, the energy variation is proportional to E^{-2} from 15.2 to 8.5 Mev to within 6%, also at 30°.

INTRODUCTION

THE recent work of Farwell and Wegner on the elastic scattering of intermediate-energy alpha particles by heavy nuclei,[1] Wall, Rees, and Ford on the elastic scattering of 22-Mev alpha particles,[2] Wegner, Eisberg, and Igo on the elastic scattering of 40-Mev alpha particles from heavy elements,[3] and the theoretical work of Blair,[4] Izumo,[5] and Porter[6] have prompted the present publication of some experiments along similar lines completed a few years ago,[7] which employed 7.8-Mev protons, 15.2-Mev deuterons, and 27.5-Mev alpha particles from the M.I.T. cyclotron. The experiments were begun originally to check absolute cross-section measurements for (d,p) reactions.[8]

EXPERIMENTAL TECHNIQUES

The apparatus used in these experiments has been described previously.[9] A method of monitoring the beam was provided in addition to the shallow ionization chamber at the entrance to the scattering chamber described in this reference. A proportional counter was located on the scattering chamber lid so that it could view the target at an angle of 30°. This procedure enabled the angular distributions to be measured with somewhat more consistent results, since any changes in target thickness reflect themselves equally in the counts recorded by both proportional counters. In addition, a set of various apertures was provided which could be inserted automatically between the target and the rotating counter to accommodate the large variation in counting rate with angle encountered in elastic scattering. Aperture ratios were measured experimentally at fixed angles. The zero-degree angle was established by scattering 7.8-Mev protons from a 0.2-mg/cm² gold target at three angles between about 30° and 40° on each side of the proton beam. The counter could be set to any angle in a relative sense to an accuracy of better than ±0.5 degree. With the zero-degree angle established as described, the counter absolute angle was accurate to within ±0.5 degree. Since the rate of change of intensity of scattered particles varies rather rapidly with angle, a counter of finite resolution measures the cross section at a somewhat smaller angle than that measured to the center of the aperture. This correction amounted, at most, to 0.3 degree, and was neglected. To test the apparatus the angular distributions of 7.8-Mev protons elastically scattered from gold was measured between 20° and 90°. The resulting distribution plotted as a ratio to Coulomb scattering is shown in Fig. 1. This ratio is seen to be constant within the accuracy to which the angles can

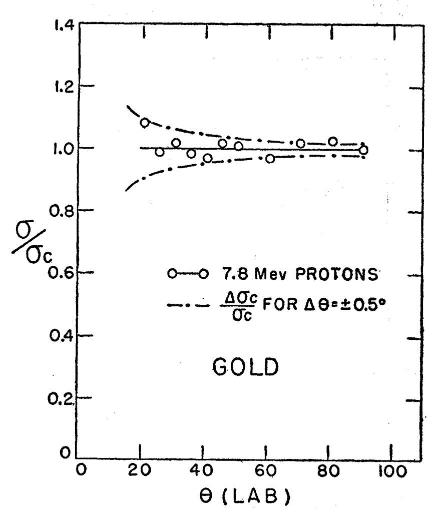

FIG. 1. The cross section for elastic scattering of 7.8-Mev protons from a 0.2-mg/cm² gold target plotted as a ratio to the Coulomb cross section against angle in the laboratory system. The two dotted curves show the fractional variation in the Coulomb cross section for a ±0.5-degree variation in counter angle which is the accuracy of the counter setting.

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[8] H. E. Gove, Phys. Rev. **81**, 364 (1951).
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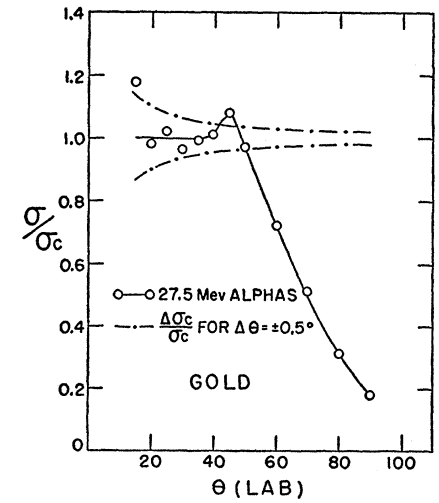

FIG. 2. The cross section for elastic scattering of 27.5-Mev alpha particles from a 26.4 mg/cm² gold target plotted as a ratio to the Coulomb cross section against angle in the laboratory system. The two dotted curves show the fractional variation in the Coulomb cross section for a ±0.5-degree variation in counter angle which is the accuracy of the counter setting.

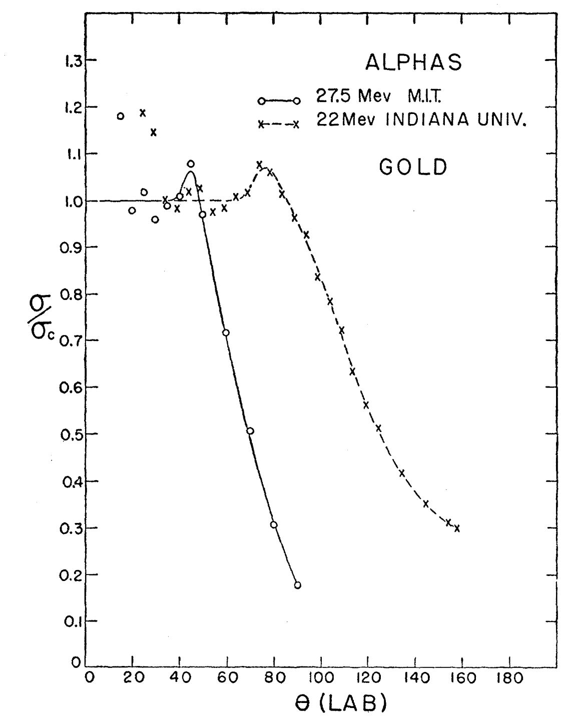

FIG. 4. σ/σ_c for 27.5-Mev alphas on gold (open circles) compared to that for 22-Mev alphas on gold (crosses) measured at Indiana University, plotted against angle in the laboratory system.

be set and is assumed to be unity on the average for purposes of plotting.

The absolute cross sections for the elastic scattering of 15.2-Mev deuterons from gold were measured at small angles in the following fashion. The integral range spectrum of deuterons elastically scattered from a 0.2-mg/cm² gold foil was measured at 30°, the exact angle having been determined as described above, for a fixed number of microcoulombs of deuterons passing through the shallow ionization chamber at the entrance to the scattering chamber. This gives the absolute number of deuterons scattered within the solid angle defined by the counter for a fixed number of deuterons incident on the target. The ionization chamber was calibrated in the following three independent ways:

(1) By measuring the current produced when the deuterons are stopped by a thick copper plate of the size of the target, placed in the target position.

(2) By measuring the temperature rise in such a copper plate after a given bombardment time.

(3) By measuring the activity of Na^{24} produced by bombarding a thin aluminum foil placed in the target position for a measured time. The cross section for the

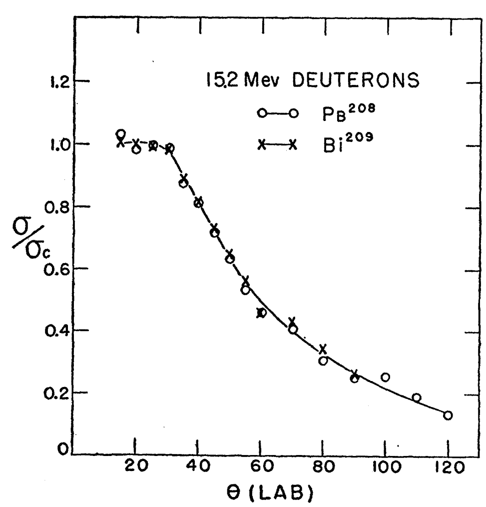

FIG. 3. The cross section for elastic scattering of 15.2-Mev deuterons from a 21.1-mg/cm² Pb^{208} target (open circles) and from a 10-mg/cm² Bi^{209} target (crosses) plotted as a ratio to the Coulomb cross section against angle in the laboratory system.

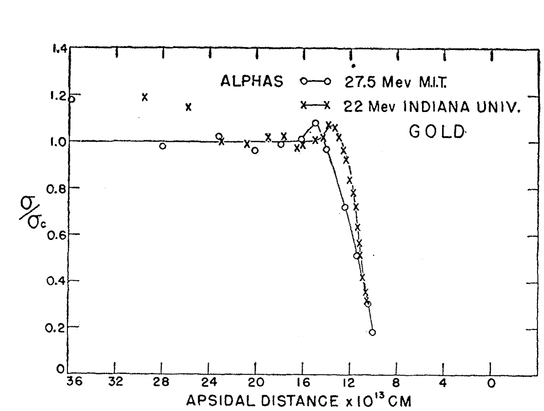

FIG. 5. σ/σ_c for 27.5-Mev alphas on gold (open circles) compared to that for 22-Mev alphas on gold (crosses) measured at Indiana University, plotted against apsidal distance.

$Al^{27}(d,p\alpha)Na^{24}$ reaction is known as a function of deuteron energy.[10]

The three methods agree to within $\pm 10\%$. The counter solid angle, defined by a 0.5-inch diameter hole at a distance of $4\frac{7}{8}$ inches from the target, was 0.066% of a sphere. After the experiment the target thickness was determined by weighing a known area of the foil on a microbalance. The cross section measured in this way agreed with the calculated Coulomb cross section to within 20%.

EXPERIMENTAL RESULTS

The cross section for elastic scattering as a ratio to the Coulomb cross section *versus* angle is shown in Fig. 1 for 7.8-Mev protons from a 0.2-mg/cm² gold target, in Fig. 2 for 27.5-Mev alpha particles from a 26.4-mg/cm² gold target, and in Fig. 3 for 15.2-Mev deuterons from a 21.1-mg/cm² Pb^{208} target[11] and from a 10-mg/cm² bismuth target. The elastic scattering of deuterons from gold was measured accurately only at forward angles where the cross section was still Coulomb. Earlier measurements[12] indicate that the results of scattering 14-Mev deuterons from gold are similar, but a detailed comparison cannot be made.

The energy variation for the elastic scattering of deuterons from gold at 30° was also measured over the range of deuteron energies from 15.2 to 8.5 Mev, and found to vary as $1/E^2$ to within 6%.

DISCUSSION

The experimental results of the elastic scattering of 27.5-Mev alpha particles from gold plotted as a ratio to the Rutherford cross section *versus* angle (Fig. 4) and *versus* apsidal distance (Fig. 5) are compared with the results of Wall *et al.*[2] at 22 Mev. The apsidal distance q is defined as

$$q=\frac{1}{2}\frac{Zze^2}{E}\left(1+\csc\frac{\theta}{2}\right),$$

where Z and z are the atomic numbers of helium and gold and E is the alpha energy. In this expression the scattering angle θ is variable.

The initial 10% rise in the cross-section ratio before fall-off, which occurs in the results at 22 Mev, also appears to occur in these data taken at 27.5 Mev.

According to the theory of Blair,[4] a simple recipe obtains for the sum of the alpha-particle radius and the radius of the bombarded nucleus, and that is the apsidal distance at which $\sigma/\sigma_c=\frac{1}{4}$. This quantity (referred to as $q_{1/4}$) is listed in Table I for the present work at fixed energy, and for the work of Farwell and Wegner[1] at two fixed angles. These three values agree within their uncertainties, and give an average of $(10.23\pm 0.12)\times 10^{-13}$ cm. From this, assuming that $R=R_0A_{Au}^{\frac{1}{3}}+R_\alpha$, one obtains $R_0=1.55\times 10^{-13}$ cm for $R_\alpha=1.2\times 10^{-13}$ cm,[6] or $R_0=1.52\times 10^{-13}$ cm for $R_\alpha=1.38\times 10^{-13}$ cm.[1] In any case there appears to be some justification for Blair's result that $q_{1/4}$ is substantially constant. The results of Wall *et al.*,[2] although not quite reaching $\sigma/\sigma_c=\frac{1}{4}$, will clearly be very close to $q_{1/4}=10.2$ as can be seen from Fig. 5. The results of Wegner *et al.*[3] for 40-Mev alpha particles also give closely the same value of $q_{1/4}$.

Although it is probably true that the theory of Blair[4] should not be applied to elastic deuteron scattering, it is interesting to note that for the elastic scattering of 15.2-Mev deuterons from Pb^{208} and Bi^{209} the value of $q_{1/4}$ is 9.34×10^{-13} cm for both. This is appreciably smaller than the above value for alpha particles on gold.

TABLE I. The value of the apsidal distance $q_{1/4}$ at which the observed cross section of elastic scattering of alpha particles from gold falls to 1/4 of the Rutherford value.

	Fixed energy or angle	$q_{1/4}\times 10^{13}$ (cm)	θ and E (Mev) for $q_{1/4}$	
Farwell and Wegner[a]	60°	10.05±0.16	60°	27.0
Farwell and Wegner[a]	96°	10.45±0.25	96°	20.4
This work	27.5 Mev	10.20±0.20	84°	27.5

[a] See reference 1.

Porter[6] has attempted to explain the deuteron data theoretically by assuming that the main effect that lowers the cross section below the Coulomb value is absorption of the deuteron from the incident beam. This same theory applied to the elastic scattering of alpha particles[1–3] gives quite good agreement[6] for the following parameters; $d\sim 2\times 10^{-13}$ cm and $R/l_0\sim 3$–4, with R assumed to be given by

$$R=(1.51\times A^{\frac{1}{3}}+1.2)\times 10^{-13}\text{ cm},$$

where d is a measure of the thickness of the diffuse edge of the nucleus, R is the interaction radius, and l_0 is the mean free path near the center of the nucleus.

For the deuteron scattering shown in Fig. 3 the best fit[6] is obtained for $R=14\times 10^{-13}$ cm, $d=3.5\times 10^{-13}$ cm, and $R/l_0\sim 1$. It is pointed out[6] that interpretation of the data is somewhat uncertain in view of the possibility of electric breakup of the deuteron.

[10] E. T. Clark, Phys. Rev. **71**, 187 (1947).
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[12] Massachusetts Institute of Technology (LNSE) Progress Report, July, 1950 (unpublished).