PHYSICAL REVIEW VOLUME 114, NUMBER 3 MAY 1, 1959

Inelastic Scattering of 21.6-Mev Deuterons*

J. L. Yntema and B. Zeidman
Argonne National Laboratory, Lemont, Illinois

(Received October 16, 1958)

The inelastic scattering of 21.6-Mev deuterons by Ni, Cu, Zn, Rh, Ag, Sn, Gd, Ta, Pt, and Au has been measured. A NaI(Tl) crystal sandwich was used for the detection of the scattered particles. The calculated energy scale of the spectrum was checked by observing the inelastic spectrum from Mg. The angular distribution shows a pronounced peaking in the forward direction. At background angles there is no increase in cross section with increasing excitation, showing that compound-nucleus processes do not contribute to the cross section. Up to an excitation of 10 Mev, the inelastic scattering cross section for 21.6-Mev deuterons scattered at 60° by Au is not measurably different from that for 22-Mev protons. However, the inelastic deuteron cross sections for Ni, Cu, and Zn are about half of the corresponding 22-Mev proton cross sections at 60°. The gross structure found by Cohen in the inelastic spectrum is also observed in the present experiment. However, the gross structure in Ta and Gd appears to be considerably more pronounced in the deuteron spectrum than in the proton spectrum.

I. INTRODUCTION

SEVERAL experiments on the inelastic scattering of protons and alpha particles with energies between 20 and 40 Mev have been reported in the past few years. In general these experiments showed that (a) the inelastic spectrum gives an angular distribution peaked sharply in the forward direction, (b) at backward angles, the number of inelastically scattered particles per Mev increases with the excitation of the residual nucleus, and (c) in the inelastic spectrum of many elements there exists a gross structure between 2 and 3 Mev excitation of the residual nucleus.

The purpose of the present work was to obtain some information on the inelastic scattering of deuterons. In view of the small binding energy of the deuteron and the strong competition of the (d,p) process and (for heavier elements) of the electrodisintegration of the deuteron in the Coulomb field of the nucleus, one might expect the total cross section to be exceedingly small, especially compared to protons of the same energy. Furthermore, since the cross section for direct interaction processes in the backward hemisphere is small, one might hope to get some measure for the magnitude of compound nucleus processes. Furthermore, it appeared to be of interest to see whether the "anomalous scattering" observed by Cohen[1] with 22-Mev protons would appear for the same elements and at the same excitation energies for deuterons.

II. EXPERIMENTAL ARRANGEMENT

The experiment was done with the 60-in. scattering chamber using the 21.6-Mev external deuteron beam of the Argonne 60-in. cyclotron.[2] The experimental equipment was the same as that described previously.[3,4] The targets were placed at an angle of 45°±0.1° to the incident deuteron beam. The detection system used consisted of a NaI(Tl) sandwich with crystal thicknesses of 0.010 in. and 0.070 in., and of 0.010 in. and 0.180 in. Particles were identified by the system described previously. Great care was taken to insure that the deuteron pulses from the pulse-multiplier circuit were independent of the energy of the incident deuterons. Excellent resolution between protons and deuterons was obtained. No attempt was made to eliminate tritons. However, a separate experiment was performed to identify triton groups. Several spectra were obtained which showed strong peaks at positions corresponding to inelastic deuterons which had excited the target nuclei to approximately 7 Mev. In order to determine whether the observed peaks were deuteron or triton peaks, the spectra were taken using a higher base line on the discriminator, since this tended to decrease the deuteron to triton ratio for the particles observed. The spectra obtained in this manner were compared with the spectra obtained during normal operation and the relative intensities of several peaks were observed to have changed markedly, indicating the presence of triton groups. Inasmuch as the tritons appear as lower energy deuterons and only the lowest two or three states of the residual nucleus are strongly excited, it was a relatively simple matter to omit these peaks from subsequent calculations.

Energy Calibration.—Initially, deuterons which were elastically scattered through a small angle by gold were detected without the use of absorber. This provided a peak at the position corresponding to the full deuteron energy. Absorbers were then inserted in small increments, resulting in peaks of successively smaller pulse heights corresponding to successively lower deuteron energies. Sufficient absorber was inserted to allow the elastic peak to be barely observed. From the published range-energy relations for deuterons, it was then possible to determine the effective thickness of the material between the absorber foils and the E crystal [i.e., the

---

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] B. L. Cohen, Phys. Rev. **105**, 1549 (1957).

[2] W. Ramler and G. Parker, Argonne National Laboratory Report ANL-5907 (unpublished).

[3] J. L. Yntema, Phys. Rev. **113**, 261 (1959).

[4] J. L. Yntema, Argonne National Laboratory Report ANL-5890 (unpublished).

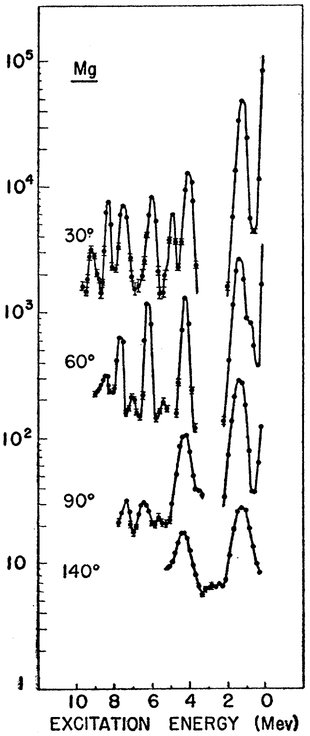

FIG. 1. Spectra of deuterons inelastically scattered from magnesium at 30°, 60°, 90°, and 140°. The spectra at the various angles have not been normalized to each other. The spectra show the accuracy of the energy calibration. Peaks are observed at excitation energies of 1.37, 4.2, 4.9, 6.2, 7.6, 8.5, and 9.4 Mev.

NaI(Tl) crystal used for the determination of energy E]. The knowledge of the effective minimum absorber thickness allowed determination of the residual energy of the particle entering the E crystal. By using the range-energy relations and the position of the elastic peak, under the assumption of linearity of response for the crystal, a curve of pulse height *vs* initial deuteron energy was calculated. The curve was checked by comparing the positions of the peaks obtained by inserting absorbers with the positions predicted by the calculated curve. As a further calibration, spectra at several angles from the inelastic scattering of deuterons by magnesium were examined. Taking into account the variation of deuteron energy with scattering angle, the spectra were plotted as functions of excitation energy. The accuracy of the calibration is shown by the magnesium spectra shown in Fig. 1, where the peaks correspond to the known levels of Mg^{24}.

TABLE I. List of elements and angles investigated.

Target	30°	60°	90°	140°
Nickel	*X*	*X*	*X*	*X*
Copper	*X*	*X*	*X*	*X*
Zinc	*X*	*X*	*X*	*X*
Rhodium	*X*	*X*	*X*	*X*
Silver	*X*	*X*	*X*	*X*
Tin	*X*			
Gadolinium	*X*			*X*
Tantalum	*X*			
Platinum	*X*	*X*	*X*	*X*
Gold	*X*	*X*	*X*	*X*

Since the pulse height in the E crystal is not a linear function of the energy of the incident particle (because of the presence of the dE/dx crystal), and since the energy of a given deuteron group varies with scattering angle, a constant difference in pulse height does not correspond to a constant difference in excitation energy. The experimental points have, therefore, been adjusted so as to compensate for this and the spectra shown in Figs. 1 through 6 are plotted as functions of the excitation energy on a linear scale.

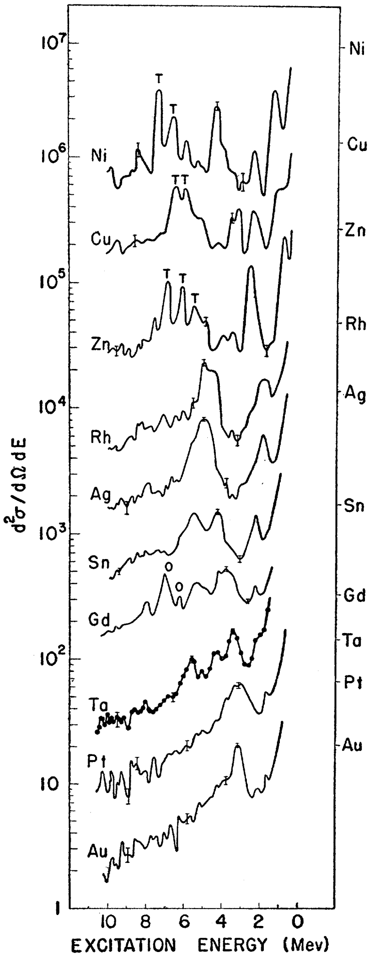

FIG. 2. Spectra of inelastically scattered deuterons for all elements at 30°. The marks at the right-hand edge of the figure indicate the point at which the differential cross section for each element is 10.0 mb/sterad Mev. The curves are drawn through the experimental points. Each distribution contains approximately 80 points. The experimental points have been omitted except for Ta. The standard deviation of the number of counts is shown for a few points. T indicates triton peak; O indicates deuteron peak due to oxygen contamination.

Targets.—The targets used were thin metallic foils of normal isotopic abundance. Most of the foils were obtained commercially, but the Sn, Gd, and Ta foils had to be rolled down to the desired thickness by the Metallurgy Division.[5] Observation of the spectra indicated that a detectable amount of either C, O, or N contamination was present only in the gadolinium. The contaminant was found to be oxygen. This contribution is noted on the Gd spectra. The targets were punched

---

[5] The techniques used for rolling Gd were developed by Mr. Frank Karasek and Mr. Robert E. Macherey of the Argonne National Laboratory Metallurgy Division.

out of the foils and the thickness was determined by weighing on a microbalance. Since the diameter of the target is 33.49 mm and the diameter of the incident beam is 3 mm, nonuniformities in target thickness can easily lead to large errors in the calculated cross sections. Accordingly, cross sections were determined for the elastic scattering peaks. For Ni, Cu, Zn, Rh, Ag, Pt, and Au, these were compared with the accurately determined elastic scattering cross sections obtained by Yntema.[3] The elastic scattering cross sections obtained in the two manners agreed with each other to within a few percent, indicating that if the thickness varies it increases smoothly across the foils so the thickness at the center is close to the average value. For Sn, Gd, and Ta, elastic scattering cross sections were calculated under the assumption that the ratio to Rutherford scattering was similar to that of nearby elements. The elastic scattering cross sections obtained in this fashion agreed with the experimental ones to within 20%. Since the assumption made concerning the elastic scattering cross sections is somewhat questionable, particularly for Gd and Ta, all indicated cross sections have been determined using the target thickness determined by weighing.

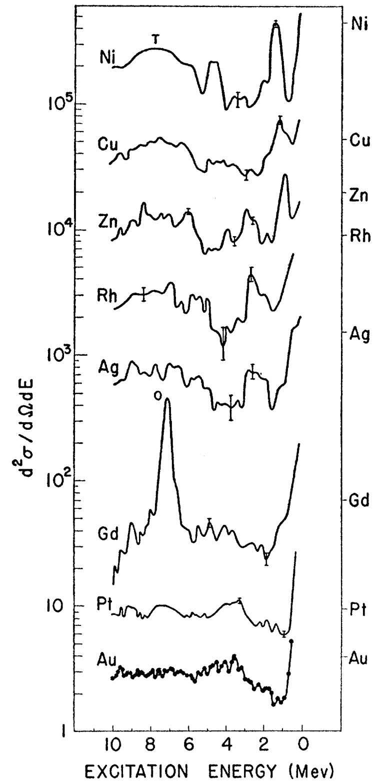

FIG. 3. Spectra of inelastically scattered deuterons at 140°. The marks at the right-hand edge of the figure indicate the point at which the differential cross section for each element is 0.1 mb-sterad Mev. The curves are drawn through the experimental points. The experimental points have been omitted except for Au. The statistical errors are indicated for several points on each curve.

III. EXPERIMENTAL RESULTS

A list of targets and the laboratory angles at which they were examined is given in Table I. The differential scattering cross sections at laboratory angles of 30° and 140°, plotted as functions of the excitation energy of the residual nucleus are shown in Figs. 2 and 3 for all elements. The curves have been drawn directly through the experimental points and statistical errors are indicated at several positions. At the right of the figures, markings indicate the point at which the absolute cross section for each element is either 10.0 millibarns per steradian per Mev at 30° or 0.1 millibarn per steradian per Mev at 140°. The error in the absolute cross section is estimated to be less than 5%, except for Sn, Gd, and Ta for which the error is estimated to be less than 30%. In Figs. 4, 5, and 6, energy spectra at laboratory angles of 30°, 60°, 90°, and 140° are shown for Zn, Ag, and Au. The ordinates indicate the absolute differential cross sections in millibarns per steradian per Mev and the abscissae are excitation energy in Mev. All curves have been drawn directly through the experimental points and statistical errors are indicated at several positions. The spectra from Ni and Cu resemble those of Zn, while the spectra from Rh and Pt are similar to those of Ag and Au, respectively. In Figs. 2, 3, and 4, the letters T and O appearing near peaks indicate that these peaks result from either tritons (T) or oxygen contamination

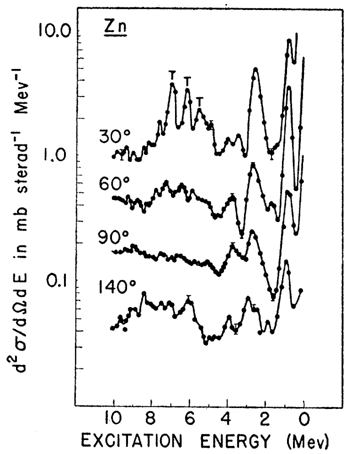

FIG. 4. Spectra of deuterons inelastically scattered from zinc at 30°, 60°, 90°, and 140°. The ordinate is the absolute differential cross section. The curves are drawn through the experimental points. The statistical errors are indicated for several points on each curve.

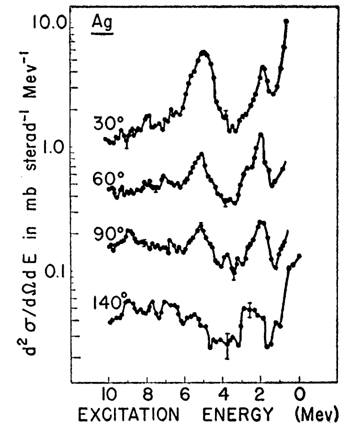

FIG. 5. Spectra of deuterons inelastically scattered from silver at 30°, 60°, 90°, and 140°. The ordinate is the absolute differential cross section. The curves are drawn through the experimental points. The statistical errors are indicated for several points on each curve.

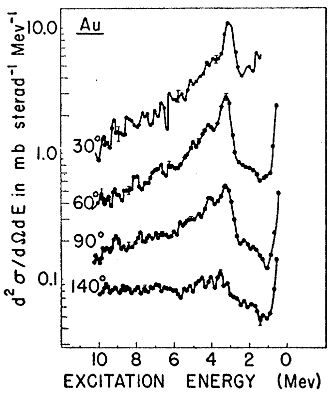

FIG. 6. Spectra of deuterons inelastically scattered from gold at 30°, 60°, 90°, and 140°, The ordinate is the absolute differential cross section. The curves are drawn through the experimental points. The statistical errors are indicated for several points on each curve.

(O). The relative cross sections shown in Figs. 4, 5, and 6 are estimated to be in error by less than 5%.

The energy dependence $\Delta\sigma/\Delta E$ of the inelastic scattering cross section for Ni, Cu, Zn, Rh, Ag, Pt, and Au is shown in Figs. 7, 8, and 9. To obtain this distribution, the energy spectra of the type shown in Figs. 4, 5, and 6 were divided into segments approximately 1 Mev wide. For each segment, it was assumed that the angular followed a smooth curve which passed through the known points at 30°, 60°, 90°, and 140°. This distribution was integrated over the section of the sphere between 30° and 180° with respect to the direction of the incident beam and provided the total cross section for scattering into an angle ⩾30° for each segment. From this, a total cross section may be found for the inelastic scattering of deuterons into angles greater than 30° for excitations from approximately 1 to 10 Mev. The results are shown in Table II.

The differential cross section $d\sigma(\theta)/d\omega$ for inelastic scattering of 21.6-Mev deuterons with final energies between approximately 11.5 and 20.5 Mev may be obtained by integrating over the energy at each angle. For each element, the distribution was assumed to be a smooth curve passing through the experimentally determined points at 30°, 60°, 90°, and 140° and the curves for Ni, Cu, Zn, Rh, Ag, Pt, and Au are shown in Fig. 10. The ordinates are in millibarns per steradian. These curves were integrated over the section of the sphere between 30° and 180° and the total cross sections which resulted from the calculation are shown in Table II. In addition, rhodium was investigated at angles up to 16°, where $d\sigma/d\omega$ reached 150 mb/sterad. If the smooth curve representing the angular distribution is drawn through the 16° point, then the total cross section for inelastic scattering of 21.6-Mev deuterons with final energies between 11.5 and 20.5 Mev into angles greater than 10° is 80 mb, as compared to the 42 mb for angles greater than 30°. Since the angular distribution appears to be rising very steeply with decreasing angle and the angular distributions for all elements are similar in appearance, it seems reasonable to estimate that the total cross sections for inelastic scattering between approximately 1 and 10 Mev are greater than twice the values obtained for the cross sections from 30° to 180°.

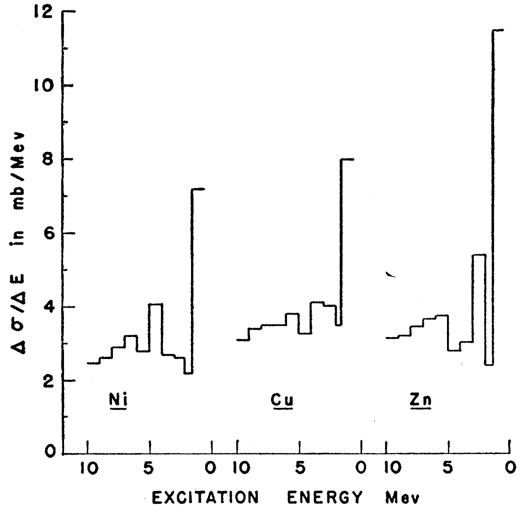

FIG. 7. Energy dependence of the cross sections for inelastic scattering into angles ⩾30° by Ni, Cu, and Zn.

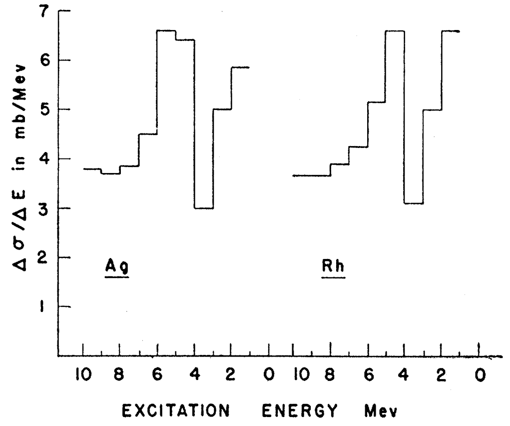

FIG. 8. Energy dependence of the cross sections for inelastic scattering into angles ⩾30° by Rh and Ag.

Inasmuch as the differential cross section for elastic scattering rises very rapidly as the scattering angle decreases below 30°, the effect of slit edge penetration by the elastically scattered deuterons giving rise to apparently inelastic deuterons was investigated. Using the method of Courant,[6] it was found that approximately 20% of the inelastically scattered deuterons at 16° were due to slit edge penetration. The percentage decreased to 10% at 20° and rapidly became negligible as the angle increased. The figures for the inelastic scattering cross section mentioned previously are the corrected values. Because of the high deuteron flux at forward angles, the possibility of nuclear reactions taking place in the NaI was also investigated and it was seen that this effect may be neglected.

---

[6] E. D. Courant, Rev. Sci. Instr. 22, 1003 (1951).

IV. DISCUSSION OF EXPERIMENTAL RESULTS

The inelastic scattering spectra obtained at all backward angles do not show an increase in cross section with increasing excitation. In this respect the inelastic scattering of deuterons differs markedly from the data on the inelastic scattering of alpha particles[7] and protons.[1,8]

The peaking of the cross section in the forward direction is essentially similar to what has been observed for protons and alpha particles. In particular, the ratio σ_{60}/σ_{30} for Au is the same for the present deuteron experiment as for the experiment with 31-Mev protons.[8] The measured cross section for the deuterons is, however, only 40% of that for 31-Mev protons. On the other hand, the ratio σ_{90}/σ_{60} is smaller for the 21.6-Mev deuterons than for the 31-Mev protons and the effect is even greater for the ratio σ_{135}/σ_{90}.

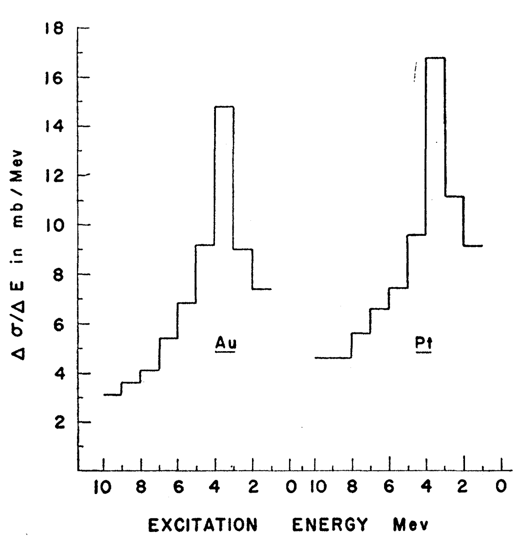

FIG. 9. Energy dependence of the cross sections for inelastic scattering into angles ⩾30° by Pt and Au.

In general the experiments on inelastic scattering of protons and alpha particles show that the peaking of the cross sections is stronger for heavier elements and for lower excitation energies of the residual nucleus. In the present experiment the peaking is about the same for the Ag group as for the Au group, but slightly less for the Zn group. Of course, the (d,t) competition is much stronger for the latter than for the former. There is no marked difference in the angular behavior at different excitation energies. Possibly in the case of Au one might conclude that for higher excitations the peaking is less pronounced. This is, however, not the case for the two other groups.

If one compares the cross sections obtained for deuterons to those obtained for protons at 22 Mev at 60°, it is obvious that the results for heavy elements are in exceedingly good agreement. However, the cross section for elements with lower Z is about twice as large for protons as it is for deuterons (Table II). It would appear that the inelastic scattering of deuterons proceeds entirely without processes involving compound-nucleus formation, because of the absence of an increase in cross section with increasing excitation at backward angles and the extremely sharp forward peaking, even at high excitations.

TABLE II. Summary of cross sections. The column heading "Energy int." refers to integration of the histograms shown in Figs. 7, 8, and 9, while the column heading "Angle int." indicates integration over angles ⩾30° of the cross section for scattering into an excitation energy of 1 to 10 Mev. The proton inelastic scattering cross sections at 60° have been taken from B. L. Cohen and S. W. Mosko, Phys. Rev. **106**, 995 (1957).

Target	σ_{tot}30-180° (d,d') at 21.6 Mev Energy int.	Angle int.	$d\sigma/d\omega$ at 60° 21.6 Mev (d,d')	22 Mev (p,p')
Ni	30.5	31.0	4	12.4
Cu	38.0	37.5	4.7	10.4
Zn	38.7	39.0	5.2	10.0
Rh	42.8	42.0	6.0	
Ag	42.0	41.7	6.0	10.4
Pt	74.5	74.5	10.4	8.2
Au	63.6	65.6	9.6	9.2

The total cross sections obtained have a considerable uncertainty assigned to them. This is primarily due to the fact that the measurement of the cross section at angles smaller than 30° involves a quite considerable uncertainty and that the cross section rises so rapidly that, even though the solid angle becomes small, the major contribution to the cross section comes from this region.

The inelastic scattering spectrum obtained at forward angles shows a definite group structure similar to that observed by Cohen. However, it is to be pointed out that in some cases there appears to be a notable difference. In the case of Rh it is apparent that the energy at

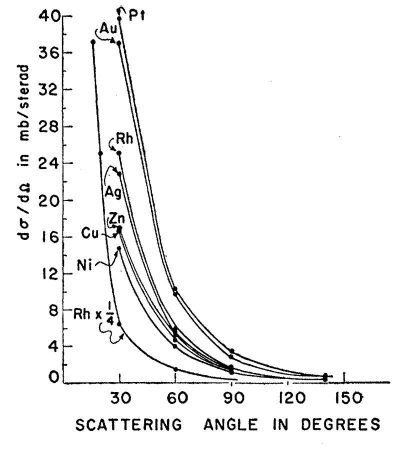

FIG. 10. Angular distributions for inelastic scattering of 21.6-Mev deuterons with final energies between approximately 1 and 10 Mev for Ni, Cu, Zn, Rh, Ag, Pt, and Au. The lines indicate gross structure of the distribution.

---

[7] G. Igo, Phys. Rev. **106**, 256 (1957).

[8] R. M. Eisberg and G. Igo, Phys. Rev. **93**, 1039 (1954).

which the group structure occurs (about 1.9 Mev), is appreciably smaller than that reported by Cohen. Furthermore, Cohen and Rubin[9] show only a very weak effect in Ta and Gd at 45°. Our data at 30° indicate that the 3-Mev peak in Ta is about as pronounced as the one for Au. The Gd peak is certainly present, even though it is less pronounced than some of the others. It is to be noted that both Rh and Ag produce a very pronounced second peak at about 5 Mev excitation. Tomasini[10] has proposed an explanation for the occurrence of the anomalous peak. His formula can predict the second peak successfully also. However, Tomasini's treatment seems to give a shift in excitation energy of the residual nucleus as a function of angle, which is not observed experimentally. Also, Tomasini predicts that "anomalous" scattering should not occur for Gd.

ACKNOWLEDGMENTS

We wish to acknowledge the cooperation of W. Ramler and the Cyclotron group and the help of W. J. O'Neill in obtaining the data. We also wish to thank Dr. B. J. Raz for several stimulating discussions.

---

[9] B. L. Cohen and A. G. Rubin, Phys. Rev. **111**, 1568 (1958).

[10] A. Tomasini, Nuovo cimento **6**, 927 (1957).

PHYSICAL REVIEW VOLUME 114, NUMBER 3 MAY 1, 1959

Elastic Scattering of 21.6-Mev Deuterons by Separated Isotopes of Nickel and Copper*

J. L. Yntema
Argonne National Laboratory, Lemont, Illinois

(Received November 24, 1958)

The relative differential cross sections for the elastic scattering of 21.6-Mev deuterons by Ni^{58}, Ni^{60}, Cu^{63}, and Cu^{65} have been measured. The diffraction pattern shows a shift with atomic number. The shift from Ni^{58} to Ni^{60} is about the same as the one between Cu^{63} and Cu^{65}. The shift between Ni^{63} and Cu^{63} is about 1.5 times that of the others.

I. INTRODUCTION

THE elastic scattering of charged particles by nuclei in the neighborhood of nickel has indicated in some cases a rather abrupt change in the angular distribution. In the experiments by Waldorf and Wall[1] and Dayton and Schrank,[2] the cross section for Ni at backward angles is considerably larger than the one for Cu. The experiment by Waldorf and Wall indicates an odd-even effect in this respect for nuclei below Cu. An odd-even effect also has been found by Schiffer *et al.*[3] in the gross structure of the (d,p) reaction on elements in this region. Brussel and Williams[4] have scattered 40-Mev protons from Fe^{54}, Fe^{56}, Ni^{58}, Ni^{60}, and Cu^{65} and have found some indication of effects which they attribute to the closure of the $Z=28$ and $N=28$ shells. In the elastic scattering of deuterons at 21.6 Mev[5] there was no appreciable difference in the cross sections of Ni, Cu, and Zn at backward angles. The shift in the location of the maxima and minima in the diffraction patterns of Ni and Cu, however, appeared to be much larger than the one observed for Cu and Zn. Therefore, it seemed of interest to investigate the angular distribution of the differential cross section for the separated isotopes Ni^{58}, Ni^{60}, Cu^{63}, and Cu^{65} to determine whether there is a rather abrupt change in the pattern between Ni and Cu.

II. EXPERIMENTAL PROCEDURE

The experiment was done in the 60-in. scattering chamber[5] with the 21.6-Mev deuteron beam from the Argonne 60-in. cyclotron.[6] The experimental procedure has been described in detail in the previous paper.[5] The targets consisted of foils approximately 1 cm in diameter obtained from Atomic Energy Research Establishment, Harwell. However, the Ni^{60} foil was considerably smaller and had to be held in the foil holder by clamping it between two Al foils 0.0005 in. thick. Since some of the beam was scattered by the Al foil, the data at angles below 41° would have required a correction and therefore have been disregarded in this work. No contamination with elements of either high or low Z was observed.

Since it was to be expected that any shift would be fairly small, the experimental points were obtained at each given angle for all four targets. The targets did not have the same thickness, but it is unlikely that this would change the average energy by more than 100 kev. Such a change should not affect the distribution measurably. In the forward direction the detector was at

---

[*] Performed under the auspices of the U. S. Atomic Energy Commission.

[1] W. F. Waldorf and N. S. Wall, Phys. Rev. **107**, 1602 (1957).

[2] I. Dayton and G. Schrank, Phys. Rev. **101**, 1358 (1956).

[3] Schiffer, Lee, Yntema, and Zeidman, Phys. Rev. **110**, 1216 (1958).

[4] M. K. Brussel and J. H. Williams, Bull. Am. Phys. Soc. Ser. II, **3**, 50 (1958).

[5] J. L. Yntema, Phys. Rev. **113**, 261 (1959).

[6] W. Ramler and G. Parker, Argonne National Laboratory Report ANL-5907 (unpublished).