Elastic Scattering of 13.5- and 15-Mev Deuterons by Nuclei

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15-Mev deuterons from the MIT Cyclotron were elastically scattered by a number of elements, including Al, Ti, Fe, Cu, Ni, Rh, Pd, Sn (natural and monoisotropic), Ta, Au, and Pb. The angular distributions were measured in the MIT cyclotron 24-in. scattering chamber, by means of a NaI(Tl) scintillation detector. The crystal was thick enough to stop 15-Mev deuterons but too thin to stop protons of the same energy, thus, permitting measurement of the (d,d) cross sections for light elements, where (d,p) reactions play an important role. The obtained distributions differ sharply from the Rutherford formula $\sigma_C \propto \csc^4(\theta/2)$; most of them, especially those for medium and lighter elements, show pronounced diffraction-like maxima and minima.

The energy of the beam was degraded to 13.5 Mev and the angular distributions for Ni, Sn (natural), and Au measured, showing the same general characteristics.

I. INTRODUCTION

THE existence of a phenomenological optical model to describe nucleon-nucleus elastic scattering[1] has raised the question of application of the same sort of analysis to deuteron and other complex particle scattering.[2] It may be expected that a deuteron phenomenological optical model is more easily interpretable in terms of the known nucleon-nucleus scattering parameters because of the low deuteron binding energy. With this in mind, as well as the need for more data to be able to fully understand elastic deuteron scattering, we undertook the experiments described below.

Prior to these experiments there was some unpublished data at 15 Mev by Darden and Wall,[3] data by Gove[4] at the same energy, and data at about 4 Mev by Alford and Slaus[5] as well as some 11-Mev experiments by Rees and Sampson.[6]

Recently Yntema[7] has published a set of very accurate experiments at 21.6 Mev. Most of these data as well as the present 15-Mev elastic deuteron experiments are analyzed in a paper to be published by Andro and Melkanoff in terms of an optical model and in that paper the significance of these data is discussed. In this paper we shall only present the 13.5 Mev and 15-Mev experimental results.

II. EXPERIMENTAL APPARATUS AND TECHNIQUES

The 15.1±0.1-Mev deuteron beam from the 42-in. MIT cyclotron was used in these experiments. The overall experimental arrangement, including a pair of strong-focussing quadrupole lenses, a slit system and the MIT 24-in. scattering chamber have been described in detail elsewhere.[8] A movable target holder with four target positions made possible the measurement of angular distributions for two elements simultaneously. The remaining two positions were occupied by a Au target and an empty frame. The measurements herein described were made combining a comparison method using Au as a reference target,[9] and the multiplication of the normalized number of counts by $\sin^4\theta_{\text{c.m.}}/2$. The differential cross section for Au was measured quite accurately as described below. Although the size of the beam spot was usually of the order of $\frac{1}{4}$ in.$\times\frac{1}{8}$ in. (as compared to the 1 in.$\times$1 in. size of the target), the empty frame served as a double check that slit scattered beam was not hitting the massive target frame and target holder. The angular resolution of the detecting system was that of a 1/50-in. aperture about 5 inches away from the target for angles up to approximately 45° and a $\frac{3}{32}$-in. aperture at the same distance for greater angles. The effects of the finite aperture and target spot size have not been "unfolded" from the experimental data since at all angles these corrections never exceeded several percent.

The targets were commercially obtainable thin metal foils, the thickness of which varied from 1–5 mg cm^2. The energy loss in the targets was of the order of 100–200 kev. The effect of the multiple scattering was calculated[10] and was shown to be negligible. Experimentally, this was confirmed by observing the difference between the angular distributions from two Pb targets of 0.8 and 0.3 mil thickness, respectively; the difference was inside the limits of the total experimental error. Nevertheless, care was taken that all the targets run simultaneously were of approximately the same thickness.

A NaI(Tl) scintillation counter was used both as a

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[1] H. Feshbach, C. E. Porter, and W. F. Weisskopf, Phys. Rev. **96**, 448 (1954).

[2] An extensive list of papers on charged particles elastic scattering is given by H. Feshbach, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Palo Alto, California, 1958), Vol. 8.

[3] C. W. Darden and N. S. Wall (private communication).

[4] H. E. Gove, Phys. Rev. **99**, 1353 (1955).

[5] W. P. Alford and I. Slaus (to be published).

[6] J. Rees and D. Sampson, Phys. Rev. **108**, 1289 (1957).

[7] L. Yntema, Phys. Rev. **113**, 216 (1959).

[8] H. J. Watters, Phys. Rev. **103**, 1763 (1956).

[9] W. Waldorf, thesis, Massachusetts Institute of Technology, 1957 (unpublished).

[10] *Experimental Nuclear Physics*, edited by E. Segré (John Wiley & Sons, Inc., New York, 1953), Vol. 1, p. 282.

detector and a charged particle selector. This response was obtained by cutting the crystal just thick enough to stop 15-Mev deuterons; protons of the same energy could not be stopped completely and therefore gave less light output. For a 35-mil NaI(Tl) crystal the proton edge was 10.5 Mev and the 15-Mev (or less, due to energy loss by nuclear recoil) elastic deuteron peak could easily be discerned. The system did not possess high enough resolution to unambiguously discriminate against inelastically scattered deuterons. Although in many cases the cross section for this process was much smaller than for the elastic process, there were some cases (Cu and Fe) where the inelastic deuterons set the limit, in angle, to the experimental data.

The pulses obtained from the photomultiplier were inverted, amplified, and fed into an Atomic Instrument Company 20-channel analyzer; the elastic peak was

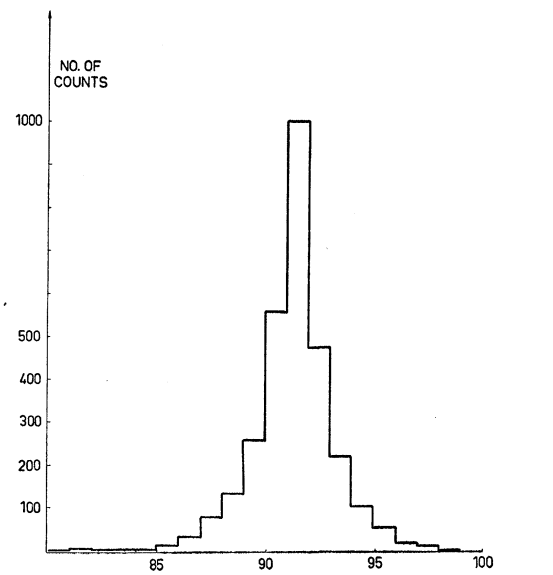

FIG. 1. A typical peak: 15-Mev deuterons scattered by Au at 35°.

usually displayed in 5–10 channels. The monitoring was performed by means of a second counter situated above the target at a fixed angle of 22°35′. This system of monitoring,[9] although not allowing one to obtain absolute cross sections, has been found to be of some convenience since it eliminates target nonuniformity corrections, geometrical corrections (caused by the fact that the beam spot was not exactly in the rotation axis of the target and the counter), the center-of-mass correction, and partly the Z^2 correction in making the comparison measurement to Au.

The absolute cross-section measurements or normalization to Rutherford scattering was obtained in the following way; first a very precise measurement of elastic scattering of deuterons from Au and a measurement of the zero of the angular range showed that this angular distribution was Rutherford within 4% up to

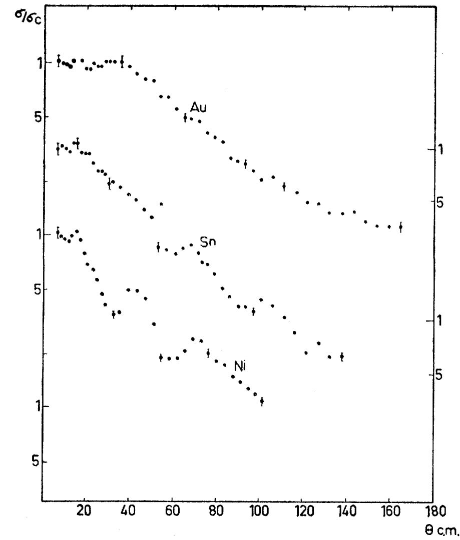

FIG. 2. Ratio to Coulomb cross section, σ/σ_C, for the elastic scattering of 13.5-Mev deuterons by Au, Sn (natural), and Ni.

$\theta=16°$. For other elements the aim was to go as far in forward angles as possible in order to find a region where the ratio to Au was fairly "flat" and identify this region with Rutherford scattering. Most of the angular distributions were "flat" up to about 10°. The main limitation for small angle measurements was the scattering from the slit system. For this and other reasons it was never possible to go beyond 5°. Mechanical arrangement limited the back angle measurements to 165°.

For two elements, Al and Ti, it was not possible to find a "Rutherford region" of the angular distribution. Even at as small angles as 5°, due to the experimental error, it was not possible to ascertain by this method whether the cross section was Rutherford or not. A new

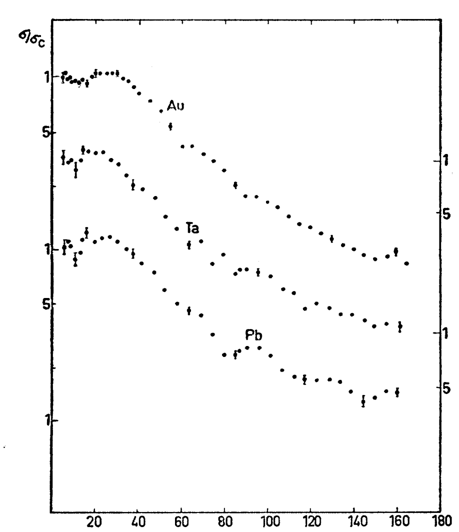

FIG. 3. Ratio to Coulomb cross section, σ/σ_C, for the elastic scattering of 15-Mev deuterons by Au, Ta, Pb.

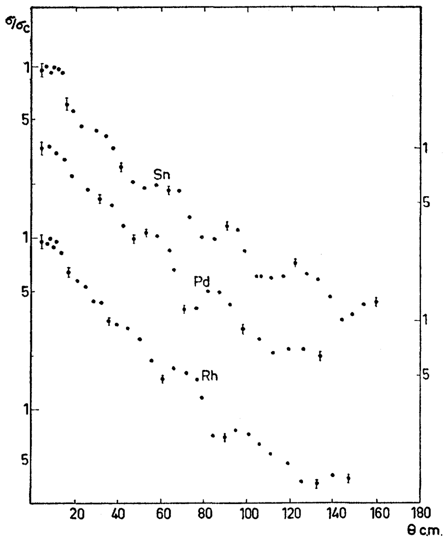

FIG. 4. Ratio to Coulomb cross section, σ/σ_C, for the elastic scattering of 15-Mev deuterons by Sn^{124}, Pd, and Rh.

measurement of the absolute cross section was therefore performed. A simple comparison method, using two targets in telescopic arrangement was employed. The second target was used as a monitor, and for the first target Al (or Ti) and then Au was used. Subsequently the number of particles scattered by Al (or Ti) targets was compared to the number scattered by Au against the same number of particles scattered from the second (monitor) Au target. Knowing the thickness of the two targets and the absolute cross section for elastic scattering by Au, a simple comparison gave the Al and Ti absolute cross section. The Au measurement was made by successive multiplying the experimentally observed differential cross section converted to the c.m. system by $\sin^4(\theta/2)$ and assuming that the small angle constant product was indicative of Rutherford scattering.

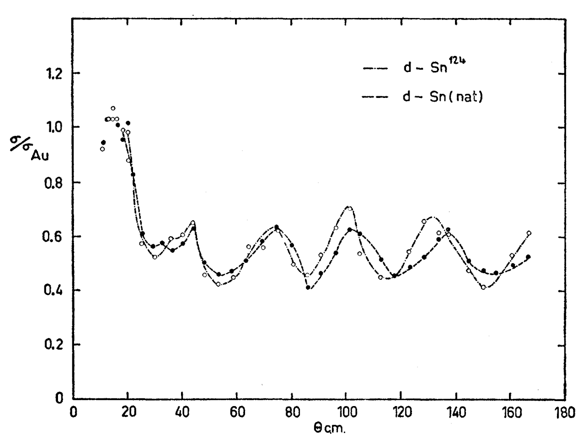

FIG. 5. The ratio of differential cross sections for the elastic scattering of 15-Mev deuterons by Sn^{124} and Sn (natural) to Au, σ_{Sn}/σ_{Au}. The figure shows a slight smearing out of the peaks for Sn (natural) as compared to those of Sn^{124}.

The resolution of the scintillation spectrometer was in the range of 2.5 to 3.5% (Fig. 1). The peak was usually clean and the amount of background was negligible. However, for back angles in lighter elements the number of inelastically scattered deuterons was sometimes comparable to the elastic peak. In such cases a graphical analysis allowing errors of the order of 10% was used. The area under the elastic peak was determined by the requirement of shape symmetry of both sides of the peak.

III. RESULTS

The elements used as targets represented a cross section through the periodic table. The lightest investigated was aluminum and the heaviest one lead. The bombarding energies were 13.5 and 15 Mev. The 13.5-Mev deuterons were obtained by degrading the 15-Mev beam with an Al absorber. The results are shown in Figs. 2 through 7.

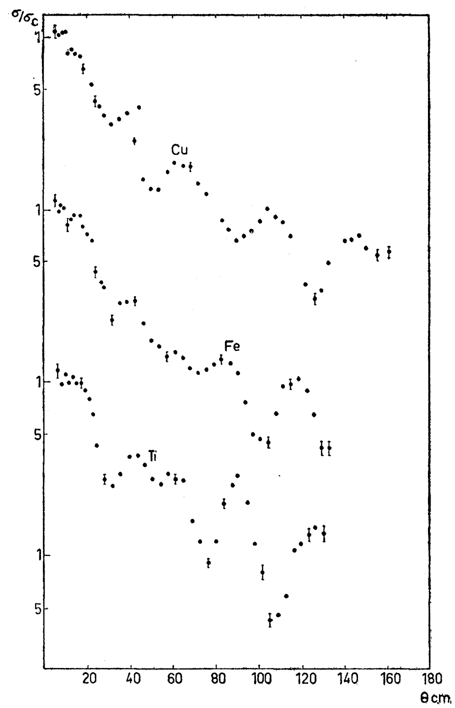

FIG. 6. Ratio to Coulomb cross section σ/σ_C for the elastic scattering of 15-Mev deuterons by Cu, Fe, and Ti.

A. 13.5 Mev

At this energy only three elements Ni, Sn (natural), and Au were investigated (see Fig. 2). The angular distribution for Au is in essence Rutherford up to about 35°, and then drops to about $\frac{1}{10}$ of the Rutherford cross section at 165°. The distribution does not show any pronounced diffraction pattern. The pattern is, however, clearly visible in Sn and especially in Ni.

B. 15 Mev

(1) *Heavy Elements: Pb, Au, and Ta*

There is a similarity between all the three angular distributions: All of them show a Rutherford angular distribution up to about 20°, a small but certain peak at about 30°, preceded by a less certain valley in between of 20° and 30°. The strong break-down from the Rutherford scattering cannot be ascertained better than within ±3.6°, but it seems that it drops from about 35±3.6° for Pb to about 30±3.6° for Ta. In all the cases the cross sections drop to approximately $\frac{1}{10}$ of the Rutherford at about 165°, and there are no pronounced diffraction peaks (Fig. 3).

(2) *Medium Heavy Elements: Sn, Pd, Rh*

The diffraction pattern, barely visible in the preceding group, starts being prominent in the angular distribution of deuterons elastically scattered by these elements (Fig. 4). It is of interest to compare the ratio of differential cross sections of both natural Sn and monoisotopic

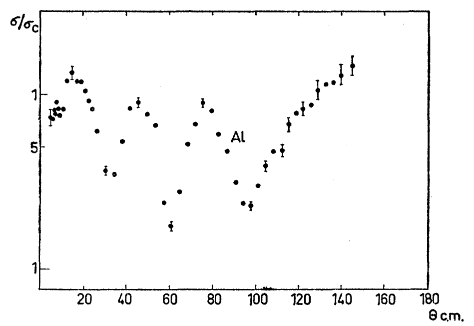

FIG. 7. Ratio to Coulomb cross section σ/σ_C for the elastic scattering of 15-Mev deuterons by Al.

Sn^{124} to Au. Figure 5 shows a slight displacement of the peaks for natural Sn as compared with those for Sn^{124}. Also the ratio of peaks to valleys is larger for Sn^{124}, whose peaks are somewhat sharper, especially in the back region. This could be qualitatively explained in terms of the simple diffraction theory. As the position of the peaks, according to this theory, is given by the expression $2kR\sin(\theta/2)$, where θ is the center-of-mass angle of scattering, it is feasible that the angular position of the peaks will differ for the different isotopes which constitute Sn-natural, thus smearing out the peaks, the shifts being the greatest for the largest angles. No quantitative conclusions were deduced from this comparison.

(3) *Group Cu, Fe, Ni*

In this group the diffraction pattern is quite prominent. It is of interest again to compare the position of the corresponding peaks (Fig. 6). Table I gives the position of the peaks: (The position is uncertain to ±3.6°.) The displacement of the maxima with respect

TABLE I. Position of the peaks.

Element	Angular location of maxima (in degrees).[a] 1st	2nd	3rd	4th	5th
Fe	17	43	84	118	
Ni		40(42)	81(81)	110(115)	
Cu	17	38(41)	66(78)	105(111)	144

[a] The numbers in parentheses are the positions of the peaks given by the diffraction theory, assuming Fe as standard to define the radius and neglecting the relative center-of-mass correction.

to A, and thereby the interaction radius R, is quite visible. The numbers in parentheses are the positions of the peaks given by the diffraction theory, assuming Fe as standard to define the radius and neglecting the relative center-of-mass correction. There is no quantitative agreement, and except in the case of Ni at 81° all the shifts are considerably larger than those given by the simple diffraction theory. The measurement of the absolute cross section for Ni (normalization to Rutherford) was unsatisfactory. For that reason only the positions of the peaks, which depend only on the relative cross sections, are given.

(4) *Al and Ti*

There were considerable difficulties in normalizing the angular distributions for these two elements. It was not possible to find a "Rutherford region"; even at such angles as 10° for Ti and 5–10° for Al the ratio to Coulomb scattering was not quite "flat." For that reason an absolute measutment of the differential cross sections was necessary. The method was described in Sec. II. Although the error in the relative position of the points for Al and Ti distributions (Figs. 6 and 7) was not large, the normalization of the results was rather inaccurate due to errors in weighing the targets and other errors. As a consequence in both distributions there may be an error of about ±10% in the absolute cross section.

The distribution for Ti is of the kind we have already met for heavier elements, although the diffraction pattern is more pronounced. Al presents a completely different situation. First, even at such small angles as 5° the cross section is only about 0.8 of the Coulomb one. Second, the peaks are very pronounced and the ratio to Coulomb cross section lies in the vicinity of 1, even exceeding 1 for the peak at 20° c.m. Third, the backward region shows an increasing peak (of the ratio to Coulomb scattering). Care was taken to make sure that the relatively increasing number of particles at back angles did not come from the inelastic contributions. Protons were eliminated by cutting a somewhat thinner crystal for back angles, where the energy loss due to recoil was considerable, and the distribution was measured up to only 145° where the contribution of the inelastically scattered deuterons was quite discernible from the elastic peak. Even with such precautions the last points allow an error of 8–15%.

C. Errors

Several sources of error contributed to make the total error in measuring the cross section. Some of the contributions were discussed in Sec. II. The contribution of the statistical error was always under 3%. The main source of error was the angular uncertainty error, due to the particular method of normalization. After ascertaining the "flat" Rutherford region, the normalized (by monitor setting) and center of mass corrected number of counts was multiplied by $\sin^4(\theta_{\text{c.m.}}/2)$. This factor was very sensitive to the angular error (the relative error being proportional to $\cot\theta_{\text{c.m.}}/2$). The zero of the angular distribution was usually determined by observing the angular distribution of elastic scattering by Au on both sides of the scattering chamber. Assuming total symmetry, the zero angle was determined to 0.36°. This gave a severe error at forward angles, which rapidly decreased at backward ones. The experimental points at the most forward angles (up to 15°) are therefore rather scattered, and should be taken with an average error of 8%. For medium and back angles the main contribution to the overall error came from the statistical error. The total error varied from element to element, with an average value of about 5% for heavy and medium heavy elements. For lighter elements beginning with Cu a new source of error appeared: the contribution from the inelastic deuterons from the first excited state. In many cases the uncertainty of resolving these two contributions was the limitation (in angle) of the experiment. Since the differentiation generally became more difficult with increasing angle, the overall error for such elements at back angles (usually larger than 100°) increased. For Fe, where this contribution was very marked, the last point in the distribution (at 135° c.m.) has an error 14%. In general an error of about 10% was allowed in this region.

IV. DISCUSSION

An extensive analysis of the above experimental results in terms of the optical model using the Saxon potential is to be published in a paper by N. Cindro and M. A. Melkanoff).

Preliminary results of this analysis are given by Melkanoff.[11]

It is however of interest to compare the results of these experiments with a recent attempt by Nishida[12] to explain the deviation of deuteron elastic scattering by heavy elements as a result of electric break-up. One of the results of Nishida's theory is that for heavy elements and intermediate energies, where the Coulomb parameter $Ze^2/\hbar v \gg 1$ the problem can be treated in terms of classical orbits; and the angle of break-down from the Rutherford distribution does not depend on Z. For 15 Mev deuterons this angle should be 27.4°. The results for Pb, Au, Ta, and Sn, which all fulfill this condition contradict these conclusions. The "break-down" angles, corresponding to impact parameters where the Coulomb field is strong enough to overcome the binding energy of the deuteron, are markedly different for Sn and Pb, the former being about 17°, the latter about 35°. The experimental uncertainty of $\pm 3.6°$ in the position could hardly explain such a large difference.

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[11] M. A. Melkanoff, Proc. Florida Optical Model Conference, 123 (1959).

[12] Y. Nishida, Prog. Theoret Phys. (Kyoto) **19**, 389 (1958).