Elastic Scattering of Deuterons from Mg, Al, Ti, V, Cr, Co, Ni, and Cu†

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Angular distributions of deuterons elastically scattered from Mg, Al, Ti, V, Cr, Co, Ni, and Cu have been measured at laboratory energies of 3.32 and 4.07 Mev. The measured cross sections show a smooth decrease below the Rutherford cross section for scattering angles greater than some critical angle which increases with increasing A and decreasing deuteron energy. Cross sections calculated with an optical model show satisfactory agreement with the measurements. The dominant feature of the model is the large imaginary part of the potential, implying strong absorption of deuterons interacting with the nucleus. From the measurements, however, it does not appear possible to identify the reaction mechanism giving rise to this absorption.

THE elastic scattering of protons,[1] neutrons,[2] and alpha particles[3–7] has been studied now for a wide range of incident energies and target nuclei and the results have been found to be generally consistent with the predictions of an optical model.[8–10] Only a few measurements of elastic deuteron scattering have been reported.[11–15] Nishida[16] has fitted the data of Rees and Sampson[12] assuming that electric breakup of the deuteron is the only important interaction. On the other hand, Sowle[17] reports that some unpublished measurements by Wall can be adequately fitted by using an optical model calculation.

The present measurements were intended as a survey of elastic deuteron scattering at the energies available in this laboratory. The analysis of these results indicates that an optical model can provide an adequate fit to the data, though the actual reaction mechanism involved in the scattering is not clear.

APPARATUS

The University of Rochester variable-energy cyclotron was used to provide a deuteron beam in the energy range of 3.2–4.2 Mev. The layout of the machine and associated equipment is shown in Fig. 1. The beam is extracted by an electrostatic deflector and after passing through an iron shield in the fringing field of the cyclotron, is focused on slit A by a pair of quadrupole lenses. A wedge analyzer magnet then focuses part of the beam through slit B into two scattering chambers in tandem. The magnetic field in the analyzer is monitored by a proton resonance probe. The calibration of particle energy *vs* resonance frequency was obtained from measurements with Cm^{244} alpha particles and by observing the (p,n) thresholds on Be^{9} and C^{13}, and is believed accurate to $\pm 0.7\%$.

Most of the present measurements were in the second of the two scattering chambers, a 36-in. diameter chamber containing 2 counters which could be independently rotated from outside the chamber. The zero of the angular scale for each counter was checked by observing Rutherford scattering each side of the beam and was determined to $\pm\frac{1}{4}°$. The angular position of one of the counters could be measured to $\pm 0.1°$. The angular scale of the other counter was less accurate and may have been in error by $\pm 0.5°$ at large angles. With the procedure used in these measurements, even this large an uncertainty would introduce negligible error in the measured cross sections. An adjustable slit C at the entrance to this chamber defined the beam spot on the target. This was followed by an antiscattering baffle C' which removed particles scattered by more than about 4° at the slit edges. The beam was collected in a lead-lined Faraday cup and measured with a conventional dc feedback amplifier. Normally this circuit was used only to adjust the cyclotron operating conditions. The beam intensity was monitored by a CsI crystal and photomultiplier mounted in a port on the scattering chamber at an angle of 45° to the incident beam direction. For measurements at forward angles, where very low beam intensity was needed, a gridded ionization chamber mounted on one of the rotating arms was fixed at an angle near 15° and was used as a monitor.

Detectors

For most of the measurements a CsI crystal bonded to a Dumont 6291 photomultiplier was used to detect the scattered deuterons. The multiplier was mounted on one of the rotating arms in the scattering chamber

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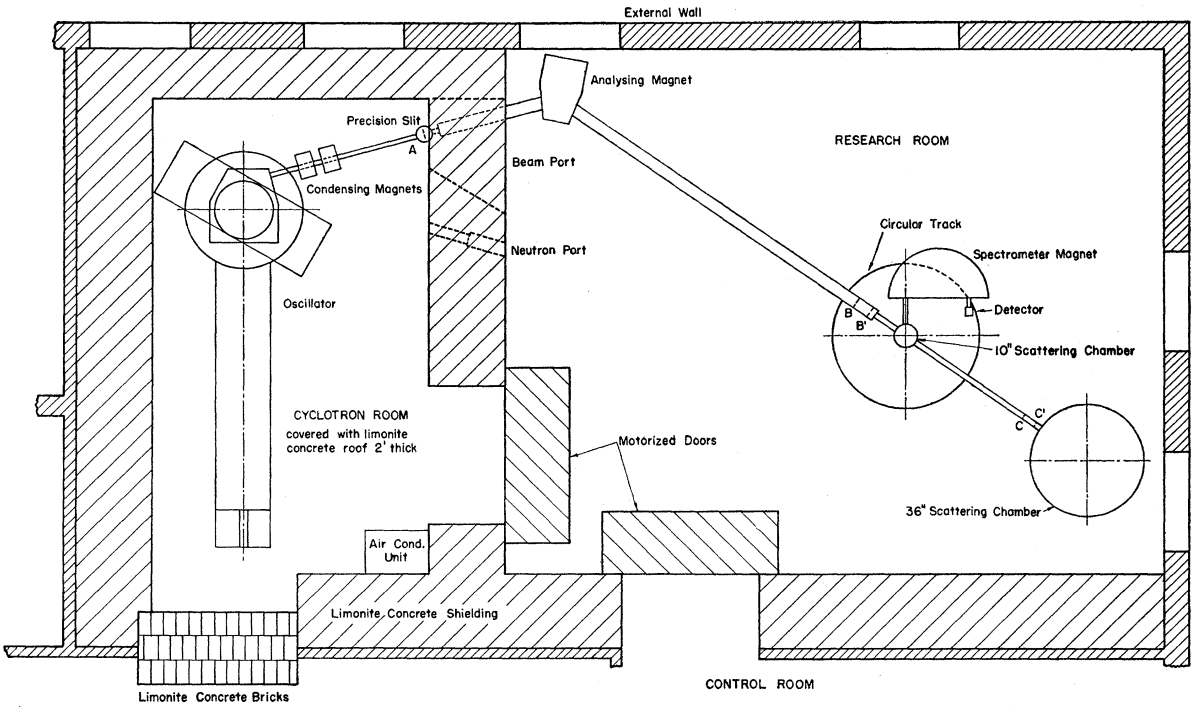

FIG. 1. The University of Rochester 27-in. cyclotron and associated equipment.

and could be set anywhere in the angular range from 7.5° to 170°. The angular resolution of this counter was 0.6°. Signals were amplified in a conventional fast amplifier and analyzed with a commercial 100-channel pulse-height analyzer (RIDL Model 3300). The resolution of the detector was about 4%, allowing easy separation of the desired group from background, mainly protons from (d,p) reactions in the target. Typical spectra are shown in Fig. 2.

For some of the measurements on Mg and Al it was necessary to use a magnetic spectrometer as will be described later. This instrument is a 180°, double-focusing instrument similar to that described by Snyder *et al.*[18] It can be rotated about a small scattering chamber from 0° to 150° and can be attached to the chamber by means of ports located every 15°. A CsI crystal at the exit slit was used to detect particles focused through the spectrometer, so that both the energy and momentum of the scattered particles could be measured.

Targets

It was desired to investigate deuteron scattering from as wide a range of target nuclei as possible, but two limitations were apparent. For $A>70$ the cross sections deviate very little from Rutherford, while for $A\leq 16$ it has been shown that resonant compound-nucleus effects are important at our energies.[19,20] Within this range of A, most elements that could be formed into thin, self-supporting stable foils were investigated. Aluminum, titanium, nickel, and copper were obtained as thin foils from commercial sources. Impurities in the form of heavy elements were stated to be less than 0.1%. Groups from carbon and oxygen contamination were never more than 1% of the elastic group from the target element at back angles where they were resolved. Other targets were made as follows:

Magnesium.—Commercial foil 0.001 in. thick was electropolished in a bath comprised of phosphoric acid (60%) and ethyl alcohol (40%) to about 20% of the original thickness. The resultant foil showed many pinholes but these were small compared with the dimensions of the beam spot and were uniformly distributed over the foil. Magnesium showed the greatest contamination of any target used. Carbon and oxygen groups had an intensity of about 4% of the magnesium elastic group at back angles.

Vanadium—Commercial foil 0.001 in. thick was electropolished in a mixture of 85% concentrated hydrochloric acid with 15% concentrated hydrofluoric acid. This foil also showed pinholes when polished to 20% of original thickness. Light-element groups showed about 2% of the intensity of the V elastic group.

Chromium.—Foils were prepared by electroplating chromium to the desired thickness on thin copper foils. After annealing by heating gently in a Bunsen flame, the copper backing could be dissolved in dilute nitric acid to yield foils from 0.1 to 2.5 mg/cm² in thickness.

Cobalt.—This was electroplated onto a polished

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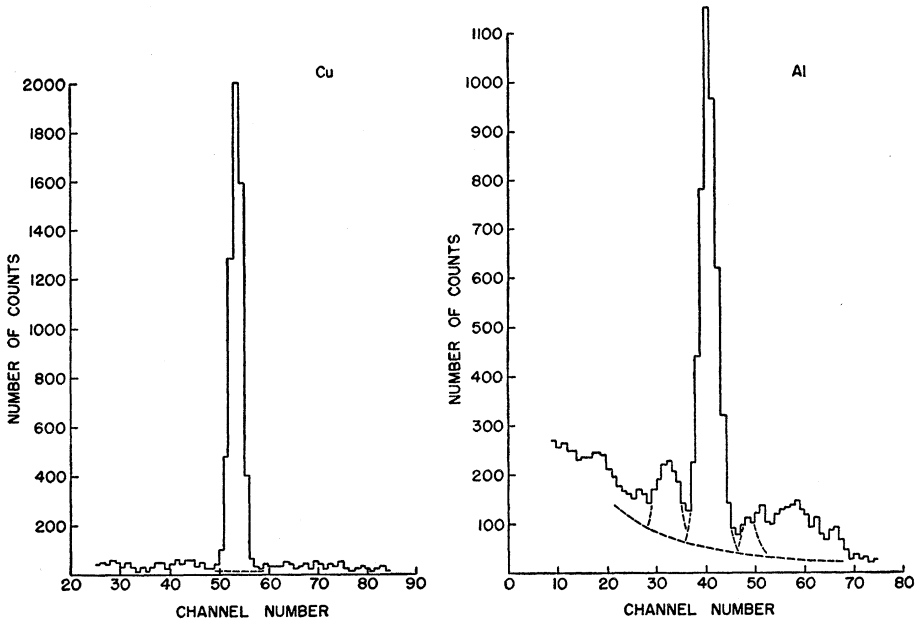

FIG. 2. Pulse-height spectra from Al and Cu.

molybdenum sheet from which it could readily be peeled.

Copper.—To look for possible isotope effects, copper foil enriched to 99.85% in Cu^{63} [21] was prepared by evaporating metallic copper onto a molybdenum sheet, from which it was later peeled.

Carbon and oxygen groups from the chromium, cobalt, and copper targets showed no more than 1% of the intensity of the elastic group from the target element. Contamination from heavier elements was believed negligible. The data on the targets used in the measurements are summarized in Table I.

PROCEDURE

Initial measurements of the elastic scattering of deuterons from gold were made to check the zeros of the angle scales for the detectors in the 36-in. scattering chamber. These measurements were continued to large angles and it was found that the elastic scattering from gold from 25° to 165° followed the Rutherford law to within the accuracy of the measurements. The curves labelled "Au" in Figs. 3 and 4 show the measured cross section multiplied by $\sin^4(\theta/2)$. All other cross sections were then measured in terms of the Rutherford cross section by using a comparison method. Target frames carrying a gold target plus two other foils were used, and at each angle the number of particles scattered from each of the targets of interest was compared with the number from the gold target for a given number of monitor counts. The ratio of the number of counts from the target of interest to that from gold then is proportional to the ratio of the cross section from the target to the Rutherford cross section, at that angle, with only a small correction for conversion to center-of-mass coordinates. The main advantages of the method are that it eliminates the need for very precise angle measurements at forward angles, and for accurate beam integration.

For Ti, V, Cr, Fe, Co, Ni, and Cu, data were taken down to small angles until the measured ratio of the counting rates became constant and the small-angle points were then normalized to unity. For Mg and Al this ratio did not become constant until such small angles that corrections for finite beam size and multiple scattering became quite large. For this reason the normalization of the Al and Mg curves was done by comparing the yields from thick targets of these elements with that from copper using the magnetic spectrometer.

Measurements on all targets were made at incident energies of 3.32 and 4.07 Mev. Results are shown in

TABLE I. Data on the targets used in the measurements.

Target	Thickness mg/cm²	Contamination[a]
Mg	1.28±0.2	4%
Al	0.68±0.05	1%
	1.36±0.05	
	2.40±0.1	
Ti	2.20±0.1	1%
V	1.84±0.15	1%
Cr	1.88±0.1	1%
Co	2.10±0.1	1%
Ni	1.13±0.05	0.2%
	2.26±0.1	0.2%
Cu (natural)	1.13±0.05	0.2%
Cu^{63} (99.85%)	1.0±0.1	0.5%

[a] Contamination refers to the intensity of carbon and oxygen groups relative to the elastic group from the target element at backward angles.

[21] Obtained from Stable Isotopes Division, Oak Ridge National Laboratory.

Figs. 3 and 4 which show the ratio of the measured cross section to Rutherford cross section *versus* c.m. angle. Because of the more complex structure in the angular distributions for Mg and Al, another measurement was made on these targets with deuterons of lab energy 3.73 Mev. These results, along with the initial measurements for comparison, are shown in Fig. 5. The c.m. energy at the center of each target is indicated beside each curve. Data were taken about every 5° and each point was measured at least twice. Measurements for Al and Ni were also taken with targets of different thicknesses as indicated in Table I. Within the accuracy of the measurements, no change in the distributions could be observed when the target thickness was changed. Angular distributions from Cu^{63} and natural copper were identical indicating that isotope effects are small at this energy.

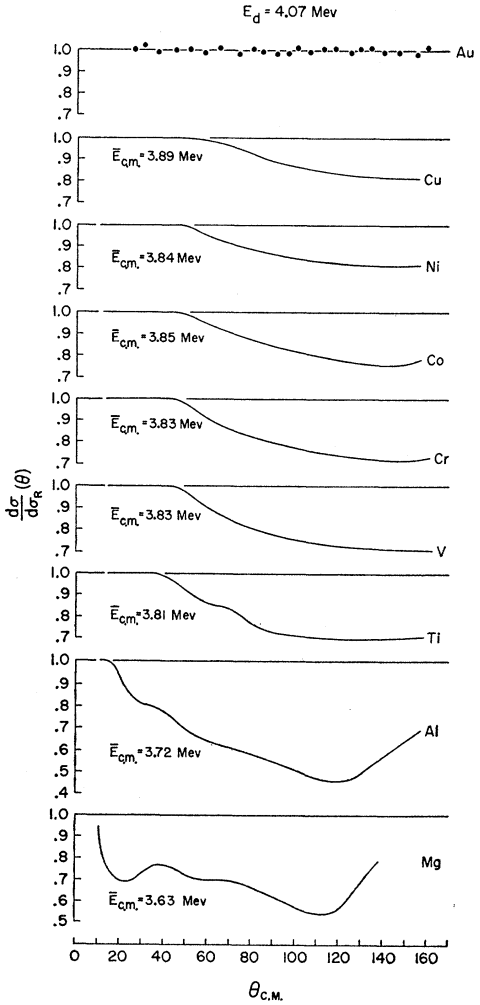

FIG. 3. Measured angular distributions at laboratory energy of 4.07 Mev. The center-of-mass energy is shown beside each curve.

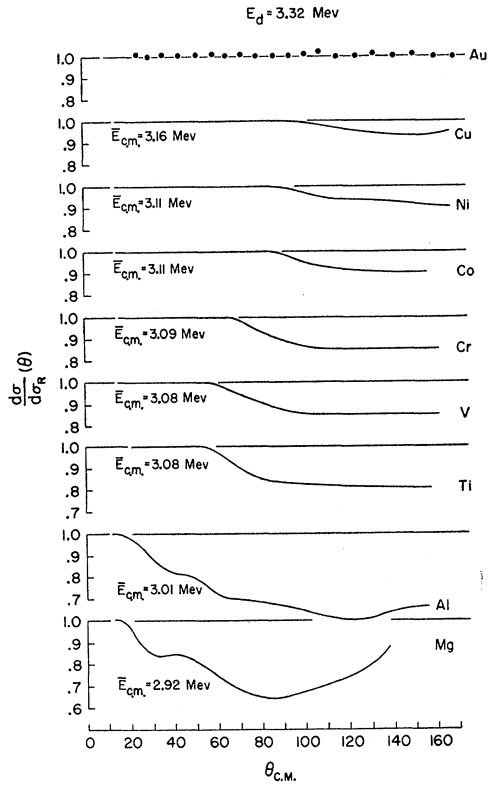

FIG. 4. Measured angular distributions at laboratory energy of 3.32 Mev. The center-of-mass energy is shown beside each curve.

ERRORS

Since the comparison method was used to measure cross sections relative to that of gold at each angle, errors arising from uncertainties in the angular position of the counter or from the finite size of the beam spot and detector aperture were negligible. In using this method it was necessary to assume that the scattering from gold does follow the Rutherford law, but this is certainly indicated by our measurements. For copper

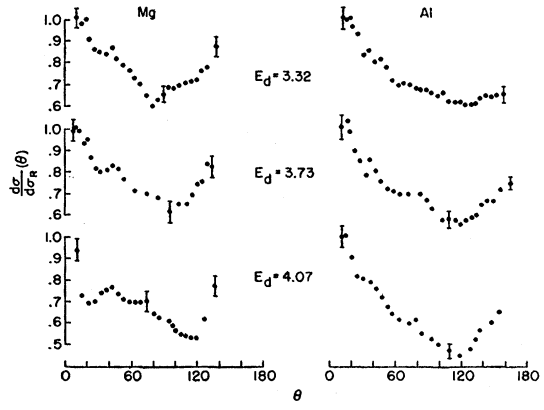

FIG. 5. Comparison of results for Al and Mg at 3.32, 3.73, and 4.07 Mev.

($Z=29$) at 4.07 Mev, the deviation from Rutherford scattering is less than 20% and is seen to be decreasing fairly rapidly with increasing Z. The measured points for gold showed a scatter of 2 to 3% at a given angle, even though counting statistics were much better than this. This was found to be caused by variations in beam intensity over the area of the beam spot on the target. Within the accuracy of this measurement, there was no evidence for any deviation from the Rutherford cross section in the scattering from gold.

A small correction for multiple scattering was necessary at forward angles, but the resultant uncertainty in the cross sections is negligible.

Measurements were affected by two different types of background, both of which were more serious with Mg than with other targets. As is seen in Fig. 2, pulse-height spectra showed a background from (d,p) reactions in the target. For the heavier targets this background was low, and showed no prominent groups. All data were taken with the multichannel pulse-height analyzer, and background could be accurately estimated and subtracted with an uncertainty no greater than 1%. For Mg and Al, definite proton groups can be seen in the pulse-height spectra and the uncertainty in background subtraction is estimated to be about 3% at backward angles. At forward angles, the elastic scattering is so intense that this background can be neglected.

The other troublesome background came from oxygen and carbon contamination on the targets. As already mentioned, these groups had an intensity of about 1% of that of the elastic group at angles greater than 90°, except for magnesium which showed 4%. Measurements of the $O^{16}(d,d)$ cross section[19] show that it is never much smaller than Rutherford at 4 Mev for angles greater than 90°. Unless this cross section should increase very much above Rutherford at forward angles, target contamination would introduce no more than 1 to 2% error into the measured cross sections at forward angles. For all targets except vanadium, inelastic deuteron groups should have been resolved from the elastic peak, with the detector used in these measurements. In fact, no inelastic groups were observable above the proton backgrounds, so that even in the case of vanadium inelastic scattering is not believed to introduce any significant error.

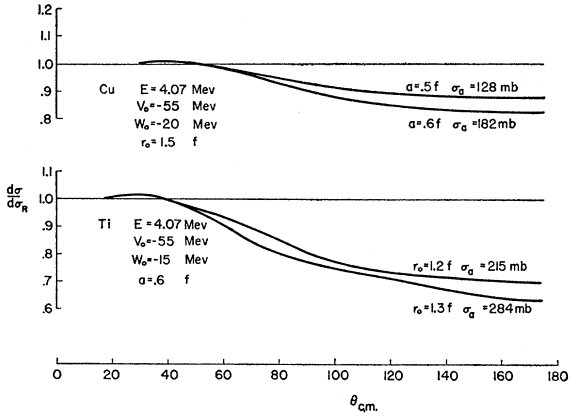

FIG. 6. Optical-model calculations for Ti and Cu, showing the effect of varying r_0 and a.

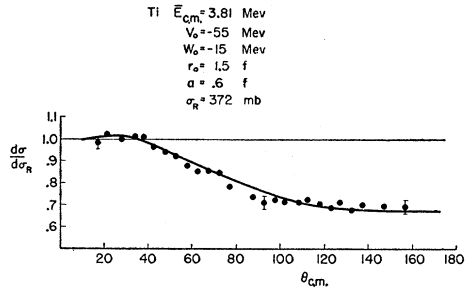

FIG. 7. Comparison of optical-model calculation with Ti results at 4.07 Mev.

For all elements except Mg and Al the over-all accuracy of the measurements show in Figs. 3 and 4 is believed to be about 3%. For Al and Mg the relative accuracy of the measured points in an angular distribution is about 5%. The absolute differential cross sections for these two elements, as normalized with the thick-target technique, are believed to be accurate to about 10%.

CALCULATIONS

The most striking features of the distributions for Ti and heavier elements are their over-all similarity and regular variation as a function of atomic number and deuteron energy. This behavior suggests that any resonance effects arising from compound nucleus formation are averaged over many states and that the measurements reflect some general properties of the deuteron-nucleus interaction. A program for optical model calculations using an IBM-650 computer was available here, and an attempt was made to use it to fit the data. There is little *a priori* justification for the application of an optical model to deuteron scattering, but its success in fitting alpha scattering measurements encouraged us to try it.

An arbitrary potential may be used in the program but for most calculations the usual Woods-Saxon well was used:

$$V=V_c+(V_0+iW_0)\left[1+\exp\left(\frac{r-r_0A^{\frac{1}{3}}}{a}\right)\right]^{-1}.$$

V_c was taken as the electrostatic potential of a uniformly charged sphere of radius $r_0A^{\frac{1}{3}}$. The program integrates the radial Schrödinger equation out to $kr=5.8$, and matches the wave function to the Coulomb wave function at that point to obtain the phase shifts for partial waves through $l=4$. More partial waves could have been included but usually the real part of the phase shift for $l=4$ was less than 1°, with a correspondingly small imaginary part. In addition to the angular

distribution, the program calculated the reaction cross section for each partial wave. The program requires about 40 minutes to compute an angular distribution for a given set of parameters.

Because of the running time required, it was not possible to make an exhaustive search for sets of parameters providing "best fits" to the data. Rather, initial calculations were made to estimate the dependence of the calculated distributions on the various model parameters. It was immediately found that the general form of the experimental curves could be reproduced if W_0 was made large. A value of $W_0=-15$ Mev completely damped out any diffraction structure for all elements heavier than aluminum, and a further increase to $W_0=-20$ Mev had no effect on either the angular distribution or the absorption cross section. The other parameters were important mainly in so far as they affected the height of the Coulomb barrier at the nuclear surface. Increasing r_0 or a increased the barrier penetrability and decreased the backward scattering as illustrated in Fig. 6. Another pair of calculations used identical potentials for $r>r_0A^{\frac{1}{3}}$, but real central potentials differing by a factor of two for smaller r. The results were identical for the two cases.

With these results as a guide, several calculations were made for titanium and copper at the higher deuteron energy. The best fits obtained are shown in Figs. 7 and 8. The agreement is seen to be good for the Ti measurements, but the experimental points for Cu seem to be consistently below the calculated curve. Still better agreement for the Cu could probably be obtained by increasing r_0 or a or both, but the matching of the wave functions at $kr=5.8$ made it impossible to handle larger values with the present computer program.

In connection with this analysis, a determination of the absorption cross section for 4-Mev deuterons on Cu^{63} was made. This measurement, which is described in detail elsewhere,[22] gave the result $\sigma_{abs}=149\pm22$ mb, in fair agreement with the calculated value of 171 mb. An increase in r_0 or a would increase the calculated σ_R, but

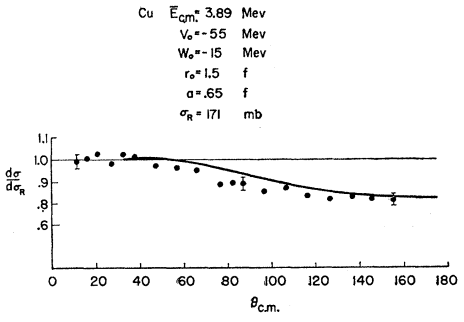

FIG. 8. Comparison of optical-model calculation with Cu results at 4.07 Mev.

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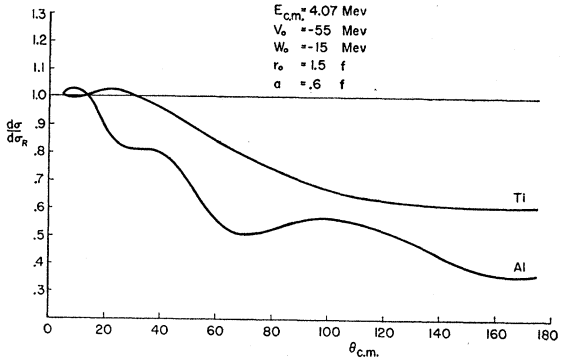

FIG. 9. Optical-model calculations for Ti and Al at 4.07 Mev, showing the more complex angular distribution for Al.

it is not clear whether better agreement for the angular distribution could be obtained without serious disagreement on σ_R.

DISCUSSION

The angular distributions for Mg and Al are clearly more complex than those for heavier elements, and seem to show a more marked variation with energy. As a result, no serious attempt was made to fit these data with an optical model. It is interesting to note, however, that an early calculation for Al showed a more complex angular distribution than did one for Ti using the same parameters (Fig. 9). It might be possible to fit these measurements at forward angles but it probably would be difficult to fit the rise in the curves in the backward direction. It was observed that the cross section for inelastic scattering was much greater for Al and Mg than for any other elements studied, and it may be that this backward rise is an indication of appreciable compound elastic scattering for these two nuclei.

The most significant feature of these results, aside from the data for Al and Mg, is the monotonic decrease in the cross sections below Rutherford as the scattering angle increases. In the optical-model calculations, this behavior was found to require a large value for W_0, but the actual values chosen for W_0 and V_0 were not important. This means that the principal information derived from the optical-model analysis is an estimate of the deuteron-nucleus interaction radius, plus the fact that deuterons reaching this nuclear surface are strongly absorbed. In particular, we do not learn much about the reaction mechanism involved in this absorption. The use of an optical model might seem to imply that we assume that the particles are absorbed by compound-nucleus formation. Since the calculations are insensitive to V_0, however, and since the dominating feature of our optical-model well is the large imaginary part that we are required to choose, it may be simply that such a well gives a satisfactory phenomenological description of absorption arising from stripping or electrical breakup.

It would be expected that the shape of the potential well should be different for these different reaction mechanisms. As long as the absorption is strong, however, it will take place largely at the surface and the calculations will be insensitive to the details of the shape. It seems more likely that useful information about the reaction mechanism could be obtained from the energy and angular distributions of the reaction products, rather than from the elastically scattered particles.

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Direct Radiative Capture of Protons by O^{16} and Ne^{20}*

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A study has been made of the $O^{16}(p,\gamma)F^{17}$ and $Ne^{20}(p,\gamma)Na^{21}$ reactions by counting the positron activities of F^{17} and Na^{21} following proton bombardment of oxygen and neon targets. The $O^{16}(p,\gamma)F^{17}$ cross section was measured at a proton bombarding energy of 616 kev to be 0.29 ± 0.03 microbarn and the $Ne^{20}(p,\gamma)Na^{21}$ cross section was measured at 1100 kev to be 1.3 ± 0.7 microbarns. These cross sections are consistent with the reaction process in each case being one of direct radiative capture. In addition, the energy dependence of the $O^{16}(p,\gamma)F^{17}$ cross section from 275 kev to 616 kev was also consistent with the direct-capture hypothesis.

Both of these reactions are believed to be important at the thermal energies effective in stars. For such energies the cross-section parameter S_0 was estimated to be $S_0=5\pm1$ kev-barns for $O^{16}(p,\gamma)F^{17}$, and $S_0\sim80$ kev-barns for $Ne^{20}(p,\gamma)Na^{21}$.

1. INTRODUCTION

THE $O^{16}(p,\gamma)F^{17}$ reaction is distinguished by a completely smooth yield curve up to a proton bombarding energy of 3 Mev,[1] and by a $\sin^2\theta$ angular distribution[2] for the γ radiation to the first excited state of F^{17}. As Warren *et al.*[2] have suggested, these facts are consistent with the direct radiative capture of p-wave protons. However, the explanation of the ten to one favoring of transitions to the first excited state ($J=\frac{1}{2}^+$)[3] over transitions to the ground state ($J=\frac{5}{2}^+$) is not obvious, since both are electric dipole for incident p-wave protons.

The calculations of Christy and Duck[4] predict both the absolute cross section and intensity ratio with remarkable accuracy. It was noted that the favoring of the excited state transition was a result of the low proton binding energy (100 kev) of this state which leads to a considerable extension of the proton wave function beyond the customary nuclear radius. This suggested that $Ne^{20}(p,\gamma)Na^{21}$ should also have a large direct radiative capture cross section, as Na^{21} has an excited state[5] of $J=\frac{1}{2}^+$ bound by 26 kev with respect to $Ne^{20}+p$. In addition, this state in Na^{21} is believed to have a large proton reduced width,[6] which is undoubtedly a necessary condition for a large cross section.

Both of the reactions $O^{16}(p,\gamma)F^{17}$ and $Ne^{20}(p,\gamma)Na^{21}$ are believed to be important in determining the element abundances in stars.[7] The oxygen reaction is effective in returning any leakage through $N^{15}(p,\gamma)O^{16}$ from the C-N cycle by $O^{16}(p,\gamma)F^{17}(\beta^+\nu)O^{17}$ followed by the fast reaction $O^{17}(p,\alpha)N^{14}$.

The Ne^{20} reaction is the first step of the Ne-Na cycle and is principally interesting as the process for generating Ne^{21}. Ne^{21} owes its importance to the exoergic reaction $Ne^{21}(\alpha,n)Mg^{24}$ which is proposed by Burbidge *et al.*[7] as the main source of neutrons for building heavy elements through neutron capture processes.

2. EXPERIMENTAL

As the cross sections for both reactions are quite small, the yields were observed by delayed counting of

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