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Elastic Scattering of Deuterons by O^{16}†*

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Thin targets of silicon dioxide on Formvar were bombarded with deuterons in order to study the yield of deuterons elastically scattered from O^{16}. The incident deuteron energy was varied in approximately 20-kev steps from 4.6 to 7.2 Mev for observations at 130 degrees, and from 4.6 to 7.0 Mev for observations at 90 degrees. The absolute cross section was determined by comparisons with the known O^{16} elastic proton cross section. The yield shows resonant structure; in particular, at least eight maxima occur at 130 degrees, and five of these appear at 90 degrees. The resonances are not isolated but indicate overlapping levels.

I. INTRODUCTION

The F^{18} nucleus has been investigated previously by several reactions involving deuterons incident on O^{16}. Stratton *et al.*[1] obtained the absolute cross sections and excitation functions for $O^{16}(d,p)O^{17}$ and $O^{16}(d,p)O^{17*}$ up to 10.9-Mev excitation. These same reactions have also been observed by Heydenburg and Inglis[2] up to an excitation of 10.4 Mev. The yield of F^{17} from the reaction $O^{16}(d,n)F^{17}$ has been obtained by Newson[3] and by Bonner[4] up to an excitation of 11.9 Mev. Previous reliable level assignments[5] extend up to about 10.8-Mev excitation in F^{18}.

Browne[6] has examined the $O^{16}(d,\alpha)N^{14}$ reaction from an excitation in F^{18} of 12.4 to 14.2 Mev, obtaining the yield of alpha particles to the ground state and to the first and second excited states of N^{14}. These data do not show discrete level structure but apparently show dense overlapping levels. The reactions $O^{16}(d,\alpha)N^{14}$ and $O^{16}(d,d)O^{16}$ involve only particles of zero isotopic spin and, hence, should excite only those levels in F^{18} that have isotopic spin zero, provided that the isotopic-spin selection rule holds. The (d,α) reaction, however, does go to the first excited $(T=1)$ state of N^{14}, and the yield shows a resonance-like behavior suggesting $T=1$ levels in F^{18}. To test this hypothesis, it would be of interest to investigate the yield of this forbidden group in a region of narrow isolated levels.

It was the purpose of the present experiment to use the elastic scattering of deuterons from O^{16} to investigate the level structure of F^{18} in the region of excitation covered by Browne and then to continue the investigation down to a lower excitation where it was hoped the dense overlapping level structure might be resolved into well-defined isolated levels. Level positions and widths might then be determined.

II. EQUIPMENT AND PROCEDURE

The source of deuterons used in this work was the MIT-ONR Van de Graaff generator. Bombarding energies from 4.6 to 7.2 Mev were used corresponding to excitations of 11.6 to 13.9 Mev in F^{18}. The slit systems of the beam deflecting magnet were adjusted to limit the deuteron energy spread to about 0.1%.

Deuterons scattered at 90 degrees or at 130 degrees were detected with a scintillation counter installed at a fixed radius in the broad-range magnetic spectrograph.[7] The spectrograph and counter slits determined the solid angle which was about 3.6×10^{-4} steradian.

The scintillation counter consisted of a polished CsI(Tl) crystal 0.8-mm thick cemented with Araldite to the face of an RCA 6199 multiplier phototube. The tube was operated at -500 volts bias and fed a standard Los Alamos Model 100 preamplifier-amplifier combination. The resultant pulses were counted by two scale-of-64 counters. The discriminators of these two scalers were adjusted to give a single channel that recorded deuterons and discriminated against protons having the same momentum as the elastic deuteron group. The proton background never exceeded 10% of the deuteron yield. Alpha-particle background coincident with the O^{16} elastic deuteron group would give approximately the same pulse heights as the deuterons and would be counted with them. Nuclear-track plates were exposed in the spectrograph at several points on the yield curve and the alpha background counted. This background was less than half a percent of the deuteron group. A lead shield of approximately 3π geometry and average thickness of 3 cm reduced gamma background intensity at the crystal sufficiently so that no counting correction was necessary for gamma background.

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[3] H. W. Newson, Phys. Rev. **51**, 624 (1937).

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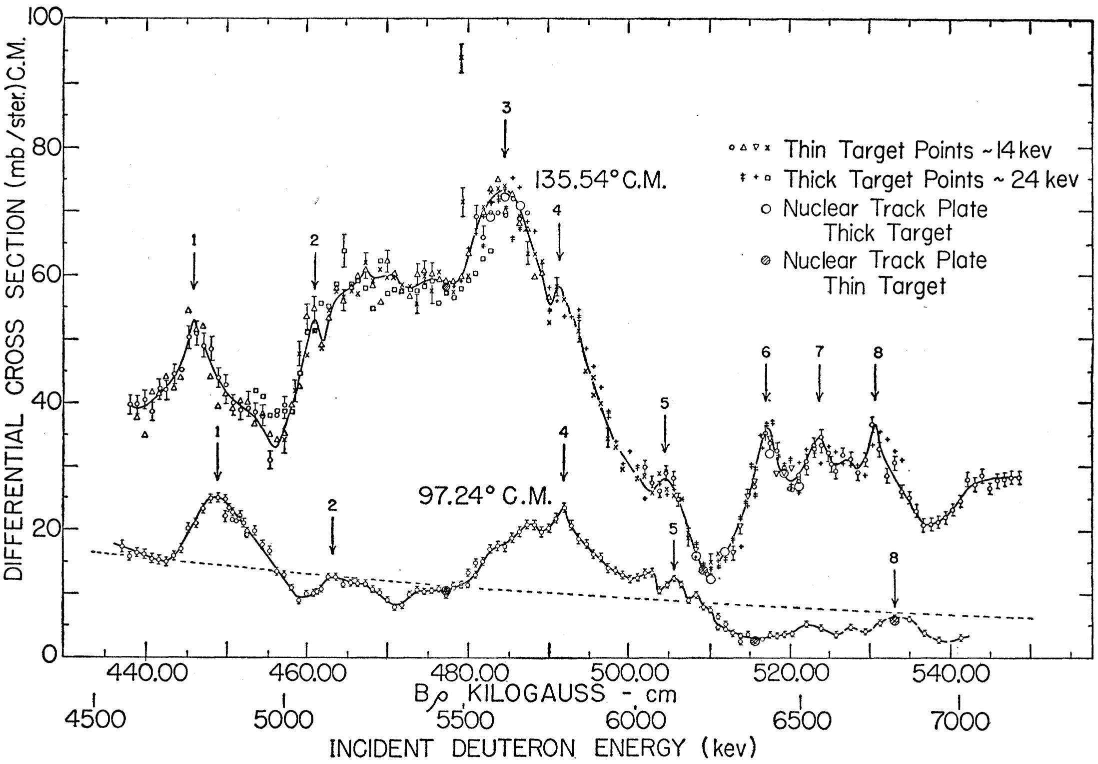

FIG. 1. Center-of-mass differential cross section for the elastic scattering of deuterons from O^{16} *vs* laboratory deuteron momentum ($B\rho$) and energy at 130- and 90-degree laboratory angles (135.5 and 97.2 degrees center of mass). The solid lines are best fits to the thinner target data. Classical 90-degree Rutherford cross section is shown as a dotted line. The numbered arrows mark peaks listed in Table II. The point above the 130-degree curve at $E_d=5.449$ Mev was observed with a target of about 12-kev thickness and must be regarded as an unexplained counting anomaly, since it occurred on only one of the four runs over this point.

The deuteron beam passing through the target was collected by a Faraday cup with a secondary electron suppressor biased to −300 volts. An electronic integrator[8] was used to measure the beam charge collected by the Faraday cup. Two targets of SiO_2 evaporated onto Formvar were used, which had thicknesses such that the energy spread of the scattered deuterons was 14 and 24 kev, respectively, including the effect of beam inhomogeneity. The energy spread was determined at 6.25-Mev incident energy from the width of the elastic groups recorded on nuclear-track plates in the spectrograph, using the known spectrograph dispersion. All energy determinations are based on the polonium alpha-particle calibration of the broad-range magnetic spectrograph and subsequent calibration of the deflecting magnet.

Data were taken by observing the number of counts per 20 micro-coulombs of incident deuterons in the case of the 130-degree runs and 100 micro-coulombs at 90 degrees for a given incident energy. The input energy was changed in 20-kev steps, and the spectrograph field was changed to keep the deuteron group centered on the counter. Experience in taking momentum distributions, by varying the spectrograph field with a fixed input energy, showed that the width of the deuteron group was sufficiently narrow compared with the counter slit to allow adequately for the slight uncertainty in the position of the group caused by uncertainty in input energy. Thus, it was possible to use the value calculated for the spectrograph field for each input energy without taking numerous momentum distributions.

Target stability and over-all consistency of the counter data were checked by exposing nuclear-track plates at eleven input energies spaced along the yield curve.

The relative yield was converted into an absolute cross section by comparison with the cross section for elastic scattering of protons from O^{16} measured by Eppling.[9] The comparison of the deuteron and the proton elastic yields was made by using nuclear-track plates in the spectrograph.

III. RESULTS

Figure 1 shows the yield curves obtained at 130 degrees and at 90 degrees. For elastic scattering, the conversion factor between the laboratory and center-

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[8] H. A. Enge, Rev. Sci. Instr. **23**, 509 (1952).

[9] F. J. Eppling, Ph.D. thesis, University of Wisconsin (1953) (unpublished) and private communication.

TABLE I. Cross-section ratios for various bombarding energies and the two angles of observation. The first number in the parentheses is the laboratory deuteron energy in Mev, while the second number is the center-of-mass angle of the scattered deuteron.

$\sigma(5.449, 97.2)/\sigma(5.449, 135.5)=0.178\pm0.007$
$\sigma(6.360, 97.2)/\sigma(6.203, 135.5)=0.201\pm0.008$
$\sigma(6.795, 97.2)/\sigma(6.203, 135.5)=0.423\pm0.017$

of-mass systems is independent of energy, so that the yield curve may conveniently be plotted as center-of-mass differential cross section *versus* laboratory deuteron energy. The center-of-mass angles in this experiment are 135.5 degrees and 97.2 degrees.

For the 130-degree runs, both targets were used and all experimental points are shown. The curve, however, is drawn through the points obtained with the thinner target. Several runs were required to cover the energy range, but a sufficient overlap was made to permit normalization where necessary. The track-plate data were taken in a single run and are seen to agree with the counter data. Three runs sufficed for the 90-degree curve, and no normalization was necessary.

The ratio of the yields at the two angles was determined at several points using nuclear-track plates. The values determined are given in Table I:

The results of the cross-section determinations are as follows:

$$\sigma_{\text{c.m}}=14.1\pm0.7 \text{ millibarns/steradian at } E_d =6.203 \text{ Mev}_{\text{lab}} \text{ and } 135.5°_{\text{c.m.}},$$

$$\sigma_{\text{c.m.}}=59.3\pm3.0 \text{ millibarns/steradian at } E_d =5.449 \text{ Mev}_{\text{lab}} \text{ and } 135.5°_{\text{c.m.}}.$$

These values are based on the following values for the proton elastic cross section determined by Eppling.[9]

$$\sigma_{\text{c.m.}}=95 \text{ millibarns/steradian at } E_p =2.999 \text{ Mev}_{\text{lab}} \text{ and } 122.2°_{\text{c.m.}},$$

$$\sigma_{\text{c.m.}}=93 \text{ millibarns/steradian at } E_p =2.999 \text{ Mev}_{\text{lab}} \text{ and } 134.4°_{\text{c.m.}}.$$

The cross-section scale assigned in Fig. 1 is based on the value of 14.1 millibarns/steradian at 135.5 degrees and $E_d=6.203$ Mev.

At 130 degrees, the cross section displays eight prominent maxima listed in Table II. In addition to the sharp peaks, there appears to be a broad resonance at 5.5-Mev deuteron energy, with an estimated width of 750 kev.

The cross section at 90 degrees is seen to vary about the Rutherford cross section. The maxima that occur are summarized in Table II, adjacent to those maxima at 130 degrees to which they appear to correspond.

TABLE II. List of observed resonance peaks with the corresponding excitation energy in F^{18}.

	$135.54°_{\text{c.m.}}$		$97.24°_{\text{c.m.}}$	
Peak	E_d in Mev ±10 kev	Excitation in F^{18} Mev	E_d in Mev ±10 kev	Excitation in F^{18} Mev
1	4.756	11.751	4.818	11.806
2	5.084	12.042	(5.133)	(12.086)
3	5.617[a]	12.516	...	...
4	5.771	12.653	5.788	12.688
5	6.088	12.934	6.115	12.958
6	6.401	13.212	...	...
7	6.566	13.359	...	...
8	6.735	13.509	(6.795)	(13.562)

[a] ±20 kev.

IV. ERRORS

If one assumes a Poisson distribution, the relative errors arising from the counting are shown directly on Fig. 1. For the curve at 130 degrees, the standard deviations shown are representative rather than exhaustive because of space limitations. All points at 130 degrees have a standard deviation of 5% or less from the counting errors.

The curves at the two angles are self-consistent to the standard deviations shown. The errors caused by current integration are considered negligible compared with counting errors.

The cross sections determined are subject to two dominant sources of error: target contamination and beam contamination. Target contamination results when the target chamber is brought to atmospheric pressure while changing angles and is noticed as an apparent increase in oxygen content of 3 to 10%. Beam contamination consisted of 0 to 9% deuteron content of the 6-Mev molecular hydrogen beam used to measure the 3-Mev yield of protons from the reaction $O^{16}(p,p)O^{16}$. In assigning the cross section to the yield data, 4.5% deuteron contamination was assumed, and each yield ratio was the mean of several to correct the target contamination to the first order.

The cross sections read from the figure are estimated to have an absolute error of ±15% at 130 degrees and ±20% at 90 degrees. For small stepwise changes in beam energy, as used in this experiment, energy differences are known to 0.1%. The absolute error is estimated to be ±0.2%.

The resolution of the excitation function is considered to be 40 kev, since data were taken at intervals of about 20 kev.

V. DISCUSSION

The cross-section curves display structure that indicates compound-nucleus effects and undoubtedly interference effects between potential and Coulomb scattering. It is to be noted that, if the peaks listed in Table II for the 97.2-degree (c.m.) curve actually arise from the same levels as those listed for the 135.5-degree (c.m.) curve, the energy for the peak at 97.2 degrees is higher in each case. Such an effect might be expected on the basis of interference effects.

The work of Browne on the $O^{16}(d,\alpha)N^{14}$ reactions shows some correlation of the resonance structure with the present work. Again, however, as the yield appears to come from many overlapping levels, a comparison is difficult.

Rather than to attempt an analysis of the present work with its apparent overlapping resonance structure and its lack of information on level widths, it seems more reasonable to extend both the elastic scattering and (d,α) work to lower excitation energies. At the lower energies, a comparison might also be made with the (d,p) work of references 1 and 2.

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Zero-Energy Scattering of Neutrons by Optical Models

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If the imaginary part of the complex square-well potential is adjusted to produce the correct-sized giant resonances in the total cross sections of light nuclei, it is found to be too large to do the same for heavy nuclei and too small throughout most of the range of mass numbers to produce a suitable zero-energy strength function. Damping of giant resonances from optical potentials can generally be correlated with that of a zero-energy scattering amplitude, and the square well defects mentioned can all be studied with analytic simplicity at zero energy. When total cross-section data matching is performed for a square-well or a diffuse-edged potential, the imaginary part will be much less dependent on mass number if it is concentrated into a surface layer. However, once the parameters of any reasonable spherically symmetric potential have been determined from matching total cross sections, a general relationship prohibits complete experimental agreement with the zero energy strength function. For certain potentials, disregarding the data for those nuclei known to be distorted does result in excellent agreement.

I. INTRODUCTION

An "optical model" represents by a complex single-particle potential the interaction of an incident neutron with a target nucleus. The case in which the wavelength of the incident neutron is much larger than nuclear dimensions will be treated here. Since only S-wave scattering occurs and only one exit channel is determined, all the very low-energy implications of a model with a spherically symmetric potential can be studied through the real and imaginary parts of a single element of the resulting diagonal derivative matrix,

$$\mathcal{R}(R)=\mathcal{R}_{\mathrm{Re}}+i\mathcal{R}_{\mathrm{Im}}=\left[\psi\Big/\frac{\partial\psi}{\partial r}\right]_{r=R}, \qquad (1)$$

where the radius R is a distance outside of which the potential vanishes and $\psi(r,R)$ is the solution to the radial wave equation,

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial r^2}+(V-E)\psi=0. \qquad (2)$$

Like ψ, the potential $V(r,R)$ will depend in general on both R and r since each nuclide could conceivably have a different interaction. Several advantages result from working with the quantity $\mathcal{R}$ rather the dimensionless logarithmic derivative, $R/\mathcal{R}$, or the "potential scattering length,"[1] $R-\mathcal{R}_{\mathrm{Re}}$.

A comparison of the $\mathcal{R}$ of the *model* with properties of *nuclei* (for which $\mathcal{R}$ is always real and usually not diagonal) can be accomplished through the interpretation of Feshbach, Porter, and Weisskopf,[1] who show that at very low energy

$$\mathcal{R}_{\mathrm{Im}}=\tfrac{1}{2}\pi\hbar(2m)^{-\frac{1}{2}}\Gamma_n{}^0/D, \qquad (3)$$

where $\Gamma_n{}^0/D$, the "strength function,"[2] is the average ratio of the reduced level width, $\Gamma_n{}^0=\Gamma_nE^{-\frac{1}{2}}$, to spacing D at the epithermal energy E, which turns out to be negligible in Eq. (2). The general equations of scattering[1] yield for the "shape-elastic" and "compound nucleus formation" cross sections in the zero-energy limit:

$$\sigma_{SE}=4\pi[\mathcal{R}_{\mathrm{Im}}{}^2+(R-\mathcal{R}_{\mathrm{Re}})^2], \qquad (4)$$

$$\sigma_c=4\pi\mathcal{R}_{\mathrm{Im}}/k, \qquad (5)$$

where k is the incident wave number. Since the strength

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