$$^1V_c^- = -100 \text{ Mev for } n\text{-}p \text{ data at 0–90 Mev}$$
$$= -100 \text{ Mev for } n\text{-}p \text{ data at 156 Mev}$$
$$= -150 \text{ Mev for } n\text{-}p \text{ data at 310 Mev},$$
$$^1\mu_c^- = 1.0\times10^{13} \text{ cm}^{-1}.$$

The potentials $^3V^-$ and $^1V^+$ are given in reference 1, and are (for Yukawa shapes):

$$^3r_0^- = 0.4125\times10^{-13} \text{ cm}, \quad ^1r_0^+ = 0.4\times10^{-13} \text{ cm},$$
$$^3V_c^- = 0 \text{ Mev}, \quad ^3\mu_c^- \text{ is not relevant},$$
$$^3V_T^- = -22 \text{ Mev}, \quad ^3\mu_T^- = 0.8\times10^{13} \text{ cm}^{-1},$$
$$^3V_{LS}^- = 7317.5 \text{ Mev}, \quad ^3\mu_{LS}^- = 3.7\times10^{13} \text{ cm}^{-1},$$
$$^1V_c^+ = 425.5 \text{ Mev}, \quad ^1\mu_c^+ = 1.45\times10^{13} \text{ cm}^{-1}.$$

IV. DISCUSSION

The most obvious defect in the fits to n-p data found in the present work is that the differential cross sections are slightly low in the forward direction at 90 and 156 Mev. This means that there is a small amount of attractive potential $^3V_c^-$ in the interaction (more at 90 than at 156 Mev).[6] At 310 Mev, it is definitely not desirable to have any $^3V_c^-$, either in the n-p or p-p problem. Here again, it is probable that an effect of a diffuse core in the potential $^3V^-$ shows itself.

---

[6] Definite depths for Yukawa-shaped $^3V_c^-$ of range $^1\mu_c^- = 1.5\times10^{13}$ cm^{-1} are: $^3V_c^- = 40$ Mev at 90 Mev, $^3V_c^- = 10$ Mev at 156 Mev, $^3V_c^- = 0$ at 310 Mev.

PHYSICAL REVIEW VOLUME 107, NUMBER 5 SEPTEMBER 1, 1957

Study of Reaction Mechanisms Involved in the $Ca^{40}(d,p)Ca^{41}$ Reaction*

L. L. Lee, Jr., and J. P. Schiffer
Argonne National Laboratory, Lemont, Illinois

(Received May 23, 1957)

Excitation functions and angular distributions for the $Ca^{40}(d,p)Ca^{41}$ (ground state) reaction have been measured from 1.50- to 4.15-Mev bombarding energy. Strong resonance effects are observed in the excitation functions, indicating that at least 20% of the reaction proceeds through compound-nucleus formation. Angular distributions were measured at 7.5° intervals between 0° and 157.5° in the laboratory system. Although these show strong fluctuations over resonances, a general forward peaking is apparent throughout the energy region studied.

INTRODUCTION

For reactions in which the bombarding energy exceeds the Coulomb barrier, observed angular distributions from (d,p) and (d,n) reactions to discrete final states have been adequately interpreted by the simple deuteron stripping theory.[1] Various attempts[2] to extend the theory to bombarding energies below the Coulomb barrier have met with some success, but have not been entirely satisfactory. Many of these interpretations have assumed that the reaction proceeds entirely by a direct-interaction mechanism without formation of a compound nucleus. In this case one would expect the excitation function for a (d,p) or (d,n) reaction to a particular final state to be a slowly varying function of energy, exhibiting none of the resonances characteristic of compound-nucleus formation. Experiments on light nuclei[3] have revealed pronounced resonance effects. These effects have been interpreted in terms of interference between resonant compound-nucleus and nonresonant direct-interaction contributions to the interaction.

In order to observe whether or not resonance effects persist in medium-weight nuclei, the $Ca^{40}(d,p)Ca^{41}$ reaction leading to the ground state of Ca^{41} has been studied. One does not expect to observe isolated resonances at such high excitation in medium-weight nuclei but, if the reaction proceeds appreciably by compound-nucleus formation, the effects of closely spaced resonances should be observed. The deuteron energies used were well below the 5.8-Mev Coulomb barrier in this case, so the simple stripping theory is not expected to give an adequate picture of the angular distributions.

PROCEDURE

Deuterons from the Argonne Van de Graaff generator were used to bombard Ca targets evaporated onto gold backings which were thick enough to stop the deuteron beam yet thin to the high-energy protons. The targets were mounted at 45° to the incident beam in the center of a scattering chamber of 6-in. diameter which had ports of $\frac{1}{4}$-in. diameter every 7.5°. Protons from reactions in the target passed through thin aluminum foil and were detected in CsI(Tl) scintillation counters.

---

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

[1] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).

[2] See for instance W. Tobocman, Phys. Rev. **94**, 1655 (1954); J. Yoccoz, Proc. Phys. Soc. (London) **A67**, 812 (1954).

[3] Stratton, Blair, Famularo, and Stuart, Phys. Rev. **98**, 629 (1955); Berthelot, Cohen, Cotton, Faraggi, Grjebine, Leveque, Naggiar, Roclawski-Conjeaud, and Sztensznaider, Compt. rend. **238**, 1312 (1954); Bonner, Eisinger, Kraus, and Marion, Phys. Rev. **101**, 209 (1956); McEllistrem, Jones, Chiba, Douglas, Herring, and Silverstein, Phys. Rev. **104**, 1008 (1956).

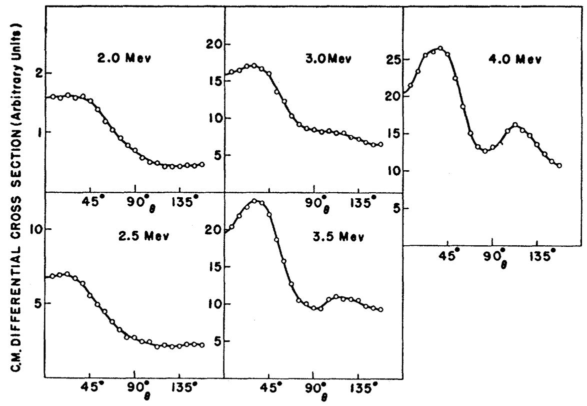

FIG. 1. Angular distributions for the $Ca^{40}(d,p)Ca^{41}$ reaction at the bombarding energies indicated. The Ca target used was 25 kev thick to 3-Mev deuterons and was evaporated on a thin Au backing. The angular resolution was 2.5°. Statistical errors are of the order of magnitude indicated by the size of the points, or less.

A carefully weighed CaF_2 target was used to obtain the absolute differential cross sections, since the metallic Ca targets oxidized too quickly to permit accurate weighing of the amount of Ca deposited.

Angular distributions were taken at 7.5° intervals using two counters which were carefully checked to have equal efficiencies. Excitation curves above 2.25 Mev were taken with four counters set at 0°, 45°, 90°, and 135° to the incident beam. Below 2.25 Mev, counters were set at 30°, 90°, and 150°. The biases on the single-channel pulse-height analyzers used were checked periodically by comparison with a 256-channel pulse-height analyzer to be sure that only protons from the ground state of Ca^{41} were detected.

RESULTS

Angular distributions in the center-of-mass system, measured at arbitrary half-Mev intervals with a target 25-kev thick to 3-Mev deuterons, are shown in Fig. 1. It is evident that there is a pronounced forward peaking at all of the energies chosen, probably indicating a direct-interaction process. At the higher energies there are indications of a peak at about 35° and a smaller backward peak at about 120°, but there is no appreciable change in the average front-to-back asymmetry. There is also evidence for this peak in the behavior of the ratio of the 45° yield to the 0° yield. When the data are averaged over a 0.25-Mev interval this ratio changes from 0.89 at 2.5 Mev to 1.15 at 3.5 Mev.

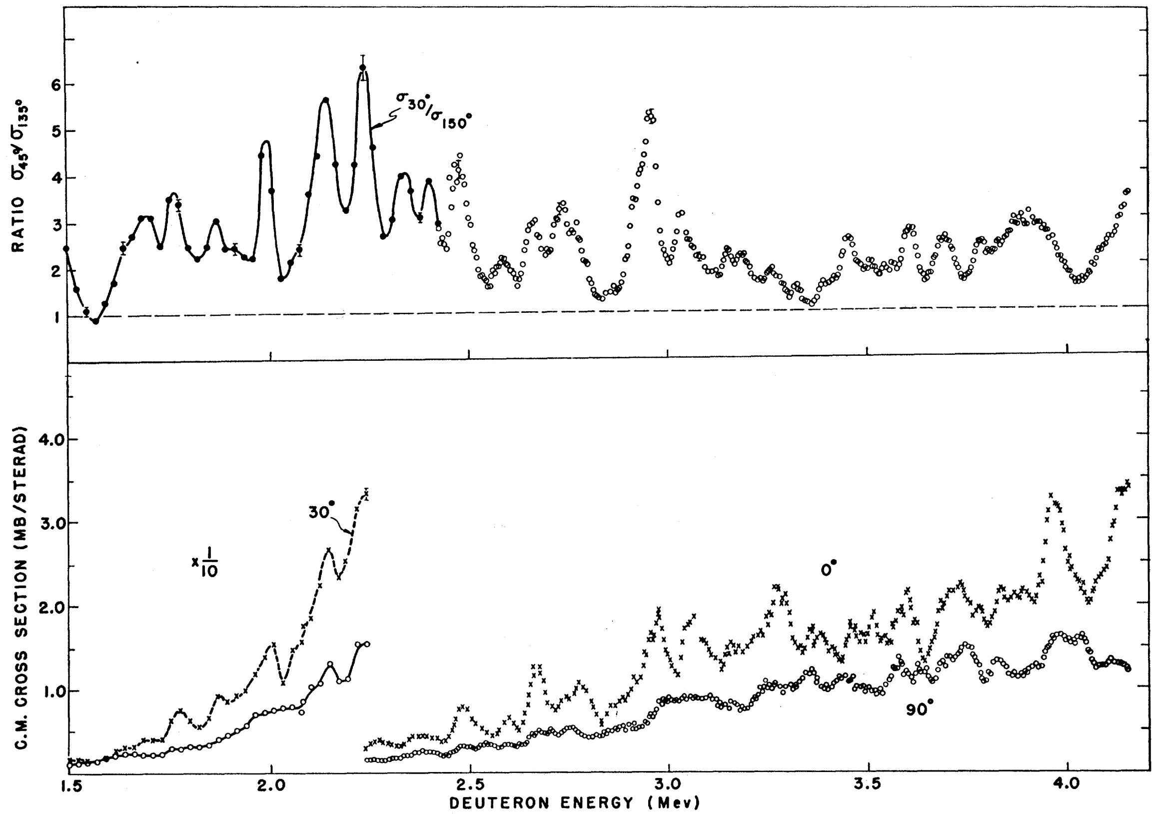

FIG. 2. Excitation functions for the $Ca^{40}(d,p)Ca^{41}$ reaction using the same target as for the measurements in Fig. 1. The cross sections were measured by using a weighed CaF_2 target, and are believed to be accurate to about 30%. The lower portion shows excitation curves at 90° and 0° (30° below 2.25 Mev). The upper part shows the ratio of the 45° cross section to the 135° cross section (30° to 150° below 2.25 Mev). Statistical errors are indicated only for a few points in regions where they are larger than the size of the points.

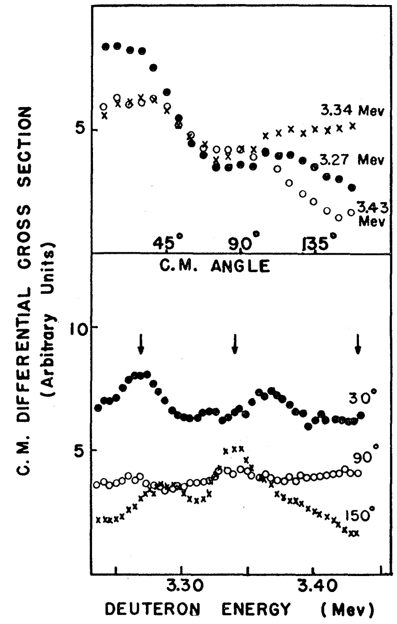

FIG. 3. Angular distributions for the $Ca^{40}(d,p)Ca^{41}$ reaction at bombarding energies of 2.37, 3.34, and 3.43 Mev. The target was the same as the ones used for the measurements in Figs. 1 and 2. The lower portion of the figure shows detailed measurements of the excitation function in this region. The arrows indicate the energies at which angular distributions were measured. The statistical errors are of the same order of magnitude as the size of the points, or less.

Excitation functions, taken at 0° and 90° to the incident beam with a 25-kev Ca target, are shown in the lower half of Fig. 2. For deuteron energies below 2.25 Mev the forward counter was at 30° instead of 0°. Although the average cross section increases with energy, many resonances are evident in the excitation curve, with widths apparently determined by the target thickness. The resonance effects are most pronounced at the small and large angles and weaker around 90° in agreement with the work on lighter nuclei where it was possible to observe the effects of isolated resonances. Using the 45°, 90°, and 135° yields to obtain the approximate variation of the total reaction cross section, the contribution from compound-nucleus formation is estimated to be at least 20% of the reaction in the energy region studied.

The ratio of forward to backward cross sections is shown in the upper portion of Fig. 2. Except for one or two energies, where apparent symmetry is approached, there is pronounced fore-and-aft asymmetry, as might be expected from a direct-interaction mechanism, with the forward yield always exceeding that in the backward direction. It is evident that since the resonances have considerable effect on the fore-and-aft asymmetry these cause drastic changes in the angular distribution.

It was not practical to measure angular distributions over all of the numerous resonances observed in the excitation curves. Angular distributions taken at a few closely spaced energies are shown in Fig. 3. One can see that, although the 90° yield changes little over the energy range studied, there are marked variations in the angular distributions which must be attributed to compound-nucleus formation.

A small portion of the excitation curve which was investigated with a target about 5-kev thick at the deuteron energy used is shown in Fig. 4. With the thinner target, the resonance effects are more pronounced and the angular distribution varies quite sharply. In particular there is the very sharp change from a 7:1 forward asymmetry to near isotropy for bombarding energies differing by only 35 kev. The apparent width of some of the resonances is about 15 kev, considerably larger than the target thickness, giving a measure of the natural widths of these states in Sc^{42}.

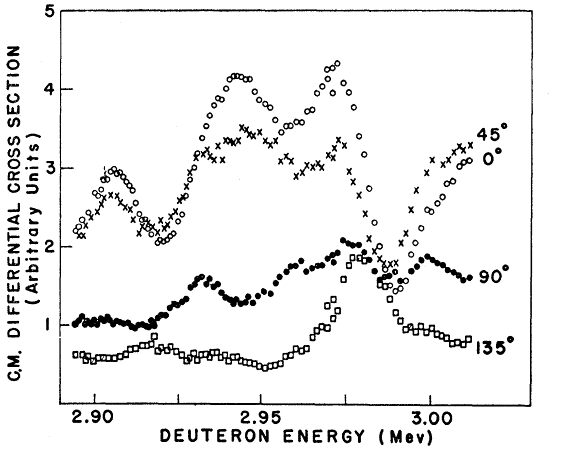

FIG. 4. Excitation function for the $Ca^{40}(d,p)Ca^{41}$ reaction over a limited region of bombarding energy. The target is evaporated Ca metal, about 5-kev thick to the incident deuterons.

DISCUSSION

Measurements at the Massachusetts Institute of Technology[4] and at Liverpool,[5] using 7.0- and 8.0-Mev deuterons, are fit fairly well by the simple stripping theory when $l=3$ is used for the captured neutron, in good agreement with the shell theory assignments for the $1f_{7/2}$ neutron shell. For 3-Mev bombarding energy the simple stripping theory predicts a maximum at about 60° for $l=3$ neutron capture. Our measured angular distributions do not show this peak, nor can one expect to improve agreement by adding a Coulomb correction, which broadens the theoretical peak and shifts it to larger angles.[6] The peak that is observed at about 35° at the higher energies might indicate a transition to the type of angular distribution observed in references 4 and 5.

It would appear that in addition to compound-nucleus formation a direct-interaction process, other than simple deuteron stripping, produces forward peaking in the angular distributions at energies well below the Coulomb barrier. Because of this process, and the effects of resonances, l-value assignments based on angular distributions at single bombarding energies near or below the Coulomb barrier might easily be incorrect.

---

[4] C. K. Bockelman, Bull. Am. Phys. Soc. Ser. II, **1**, 223 (1956).

[5] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 565 (1953).

[6] W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955).