Angular Distributions of Protons from the (*d,p*) Reaction with Deuteron Energies below the Coulomb Barrier*

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Cross sections and angular distributions for the (*d,p*) reaction to a known $l=1$ single-particle state of the captured neutron have been measured for seven target nuclides between Ti and Ni. Targets with effective thicknesses of several hundred kev were used with deuteron bombarding energies of 3.8 and 4.5 Mev. The angular distributions were found to be similar, with approximately 2:1 forward peaking and a broad maximum at about 60°. In addition, a sharp but relatively weak peak was observed at about 25° for the lighter of the target nuclides. This is the angle at which the theory of Butler would predict a maximum for neutron capture with $l_n=1$. Analysis of the proton spectra and angular distributions indicates that compound nucleus formation contributes less than 25% to the reaction yield at these deuteron energies.

INTRODUCTION

ANGULAR distributions from (*d,p*) reactions have served as a very useful tool in nuclear spectroscopy since, as was first pointed out by Butler,[1] a unique angular distribution corresponds to a particular value of the orbital angular momentum of the captured neutron. Thus the angular momenta of many states have been determined by measurements of (*d,p*) angular distributions. One of the limitations of the Butler theory is, however, that it fails to take the Coulomb field into account. Thus it is to be expected, as both theory and experiment have shown, that at incident deuteron energies below the Coulomb barrier angular distributions would not follow the shape predicted by Butler.[2]

In recent experiments[3] we have studied the proton spectra from the (*d,p*) reaction in a series of nuclei between Ti and Ni and have found a well-separated level or group of levels which was identified with the $2p_{\frac{3}{2}}$ single-particle or shell-model state of the captured neutron. In the present experiment we have attempted to study the angular distribution of this group of protons at deuteron energies of 3.8 and 4.5 Mev, which are below the Coulomb barrier (~5–6 Mev) for these nuclei.

RESULTS

The deuteron beam of the Argonne Van de Graaff accelerator was used to bombard thin-foil targets with thicknesses ranging from 2 to 7 mg/cm^2, corresponding to energy losses of several hundred kev at the deuteron energies used. A scattering chamber with collimating holes of 0.25-inch diameter at 7.5° intervals on a circle of 6-inch diameter was used. The detectors were CsI(Tl) scintillation crystals mounted on photomultipliers. Typical proton spectra, recorded in a 256-channel pulse-height analyzer, are shown in Fig. 1. The appropriate group of protons was selected from the spectrum and the number of counts in this group was computed at each angle. Data points were obtained between 15° and 135° at 15° intervals, and one point was obtained at 157.5° for each target. On some targets a measurement was also made at 22.5°. The angular distributions at the two bombarding energies are shown in Fig. 2. The statistical errors in the points were always negligible compared to the instrumental errors and the errors in determining the exact shape of the proton group. Absolute cross sections are given in Table I.

DISCUSSION

The following observations can be made regarding the data:

1. The angular distributions for the lighter target nuclides show a fairly sharp maximum around 22°–30°. This might well correspond to the peak at 22° in the angular distribution predicted by the Butler theory for

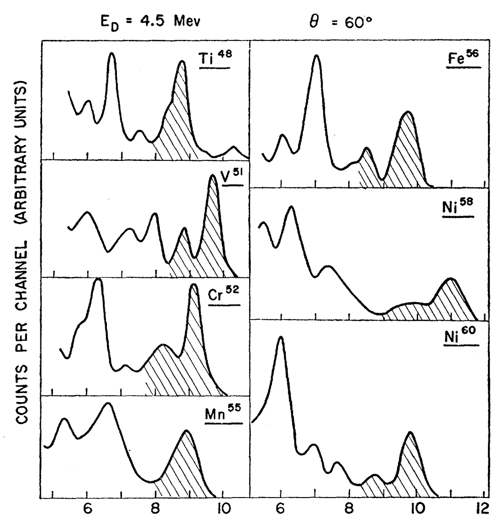

FIG. 1. Typical proton spectra as observed in a 256-channel pulse-height analyzer. The proton energy scale is approximate. Statistical errors are always less than twice the width of the line. The shaded areas indicate the portion of each spectrum that was used for the angular distributions.

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[1] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).
[2] See for example W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955).
[3] Schiffer, Lee, and Zeidman, Phys. Rev. **115**, 427 (1959).

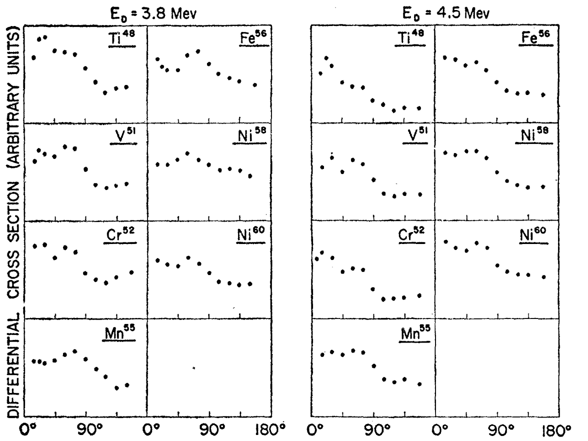

FIG. 2. Angular distributions of the (d,p) reaction with the deuteron energies and target nuclides indicated on the figure. The statistical uncertainties in the points are less than the diameter of the points; other errors are generally less than 10%.

$l=1$ stripping. The cross section under this peak is less than 10% of the total cross section.

2. All the angular distributions show a tendency for more yield forward of 90° than backward. This effect seems to decrease with heavier target nuclei and lower bombarding energies. The asymmetries are illustrated in Fig. 3(a).

3. All the angular distributions seem to show a rather broad maximum at about 60°–70°. The height of this maximum relative to the total cross section does not seem to vary appreciably for the various target nuclei and the two bombarding energies used. This is demonstrated in Fig. 3(b).

From the persistent lack of symmetry about 90° in the angular distributions it follows that the (d,p) reaction at these energies and for these target nuclei still proceeds, at least in part, by a direct reaction mechanism. The thickness of the targets and the number of target nuclei and bombarding energies studied insures that the features described above are not due to interferences between resonance levels in a compound nucleus. However, as had been observed in another experiment,[4] it is still likely that an appreciable fraction of the cross section can be accounted for by the reaction proceeding through a well defined compound nucleus. Since in the present experiment this part of the cross section would have to be symmetrical about 90°, it would be difficult to say what fraction of the cross section was due to compound nucleus formation. The maximum fraction of the cross section which could be symmetric about 90° varies from about 25% for Ti at 4.5 Mev to 75% for Ni at 3.8 Mev. These percentages then represent an upper limit for the fraction of the (d,p) reaction which could proceed through a compound nucleus, as calculated from our data.

Information regarding the amount of compound nucleus formation contributing to the (d,p) reaction can also be obtained from the proton spectra alone. It is evident from Fig. 1 that the gross structures in the proton spectra are very similar to those observed at higher bombarding energies in reference 3. Such gross structure is possible only if the reaction proceeds by a direct stripping process where the probability of populating a given state of the final nucleus is determined by the probability of a neutron being captured by the target nucleus. This is certainly not true for the part of the (d,p) reaction which proceeds by way of a compound nucleus. Since gross-structure effects definitely are present, one can estimate that the compound nucleus process contributes less than 25% to the proton spectra. This independent estimate is then consistent with the one derived from the angular distributions.

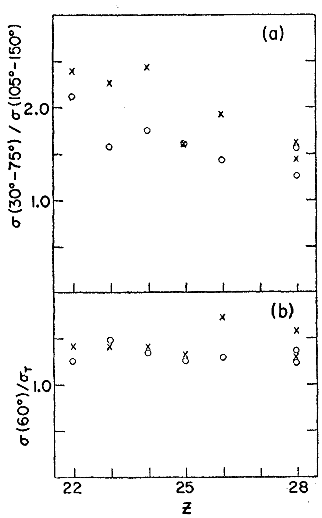

FIG. 3. (a) The ratio of forward to backward yields in the angular distributions as a function of atomic number. The 75°, 60°, 45°, and 30° yields were averaged for the forward yields; the 105°, 120°, 135°, and 150° yields were averaged for the backward yields. Circles and crosses are used to designate the 3.8- and 4.5-Mev data, respectively. (b) The ratio of the cross section at 60° to the total cross section as a function of atomic number.

These estimates are also in agreement with the amount of compound nucleus contribution that was found in the study of the $Ca^{40}(d,p)Ca^{41}$ reaction in reference 4. There it was concluded from a study of resonances in the excitation function that the compound nucleus contribution was at least 20% of the total for the same region of bombarding energies as in the present work.

Tobocman's[2] calculations of (d,p) angular distributions include the effects of the Coulomb field as well as the interactions of the deuteron and the proton with the nucleus. It remains to be seen whether these calculations can fit the observed cross sections and angular distributions.

TABLE I. Total cross sections.

Target nucleus	Total cross sections[a] (10^{-27} cm^2) E_d = 3.8 Mev	E_d = 4.5 Mev
Ti^{48}	17	25
V^{51}	11	17
Mn^{55} [b]	5	10
Fe^{56}	10	17
Ni^{58}	5	8

[a] The uncertainty in these cross sections for the $2p_{3/2}$ proton group is estimated to be approximately 30%.
[b] From reference 4 this group is expected to have a smaller intrinsic intensity than the others since the $p_{3/2}$ shell in Mn^{55} was determined to be partially filled.

[4] L. L. Lee and J. P. Schiffer, Phys. Rev. **107**, 1340 (1957).