Differential Cross Sections for the $C^{12}(He^3,p)N^{14}$ Reaction

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(Received September 5, 1957)

The differential cross sections of the three highest energy proton groups from the $C^{12}(He^3,p)N^{14}$ reaction were measured at six angles as a function of incident He^3 energy from 2.0 to 5.0 Mev. Broad resonances were observed at 3.0, 3.6, 4.4, and 4.8 Mev in addition to those previously observed. The angular distributions are rather complex and not easily attributable to either a compound nucleus or a direct interaction. The differential cross sections have been measured at closely spaced angular intervals from 7 to 158 degrees in the center-of-mass system for bombarding energies of 2.0 and 4.5 Mev.

INTRODUCTION

THE $C^{12}(He^3,p)N^{14}$ reaction has been studied by Bromley *et al.*[1] in the energy region from 1.0 to 2.8 Mev. We have studied the $C^{12}(He^3,p)N^{14}$ reaction in the energy interval from 2.0 to 5.0 Mev using a 2-Mv Van de Graaff accelerator and the 6-Mv Van de Graaff accelerator of the U. S. Naval Research Laboratory. The differential cross sections of the three proton groups, leaving N^{14} in its lowest states, were studied as functions of the bombarding energy, and of the angle at 2.0 and 4.5 Mev.

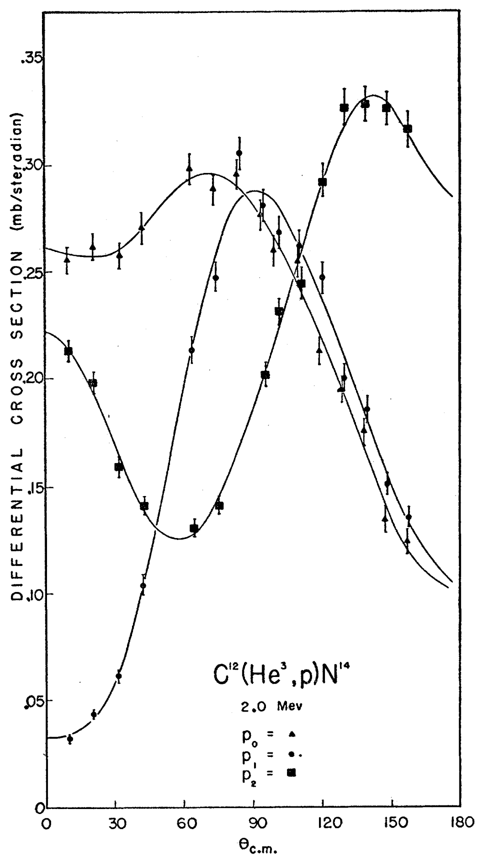

FIG. 1. The differential cross section as a function of angle in the center-of-mass system for the ground-state (p_0), first-excited-state (p_1), and second-excited-state (p_2) proton groups at 2.0-Mev incident He^3 energy.

PROCEDURE

The nuclear-emulsion reaction chamber used in determining the differential cross sections as functions of angle at 2.0 and 4.5 Mev has been previously described.[2] The targets were prepared by heating a 5-μin. foil in the presence of methyl iodide (CH_3I) vapor, depositing the carbon onto the foil. The target used at 2.0 Mev was about 180 kev thick for the incident He^3 particles, and that used at 4.5 Mev was about 200 kev thick for the incident He^3 particles. The reaction chamber

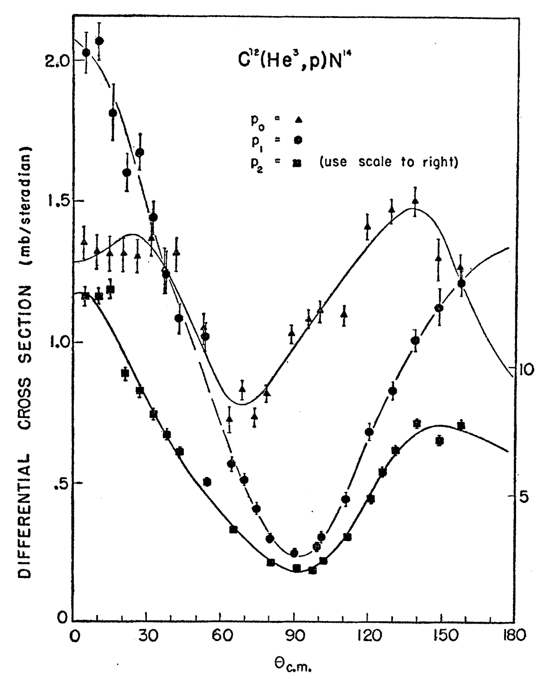

FIG. 2. The differential cross section as a function of angle in the center-of-mass system for the ground-state (p_0), the first-excited-state (p_1), and the second-excited-state (p_2) proton groups at 4.5-Mev incident He^3 energy.

* A portion of this research was the basis of a thesis submitted to the Graduate School of the University of Maryland in partial fulfillment of the requirements for the degree of Master of Science by R. L. Johnston.
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[1] Bromley, Almqvist, Gove, Litherland, Paul, and Ferguson, Phys. Rev. **105**, 957 (1957).
[2] Holmgren, Bullock, and Kunz, Phys. Rev. **104**, 1446 (1956).

employed for measuring the cross sections as functions of bombarding energy had apertures at 7, 30, 60, 90, 120, and 150 degrees in the laboratory system which subtended a solid angle of 0.013 steradian at the target. The protons were detected with thin CsI(Tl) crystals mounted on multiplier phototubes. In this portion of the experiment, a thin (about 40 kev thick for 2-Mev He^3 particles) evaporated target was used. This target was weighed in order to determine the absolute differential cross section.

RESULTS

The differential cross sections as functions of angle in the center-of-mass system at 2.0- and 4.5-Mev incident He^3 energy are shown in Figs. 1 and 2, respectively. The uncertainties indicated include an uncertainty of 1% in the measurement of the solid angle, an estimated uncertainty in counting the tracks of 1%, and the standard statistical deviations. The curves are the least-squares fit to the data of Legendre polynomial expansions including the sixth degree. The coefficients of the Legendre polynomials in these expansions and the total cross sections, are presented in Table I.

The laboratory differential cross sections as functions of bombarding energy for the ground, first excited, and second excited states are shown in Figs. 3, 4, and 5, respectively. The uncertainty in the determination of the absolute cross section arises largely from the uncertainty in the measurement of the thickness of the target and was estimated to be 20%. An independent check of the determination of the target thickness was made by measuring the differential cross section of the $C^{12}(d,p)C^{13}$ reaction leaving C^{13} in the ground state and comparing this value with the published values. The differential cross sections determined for the (d,p) reaction, using the weighed target thickness, were about 20% lower than those obtained by Bonner *et al.*[3]

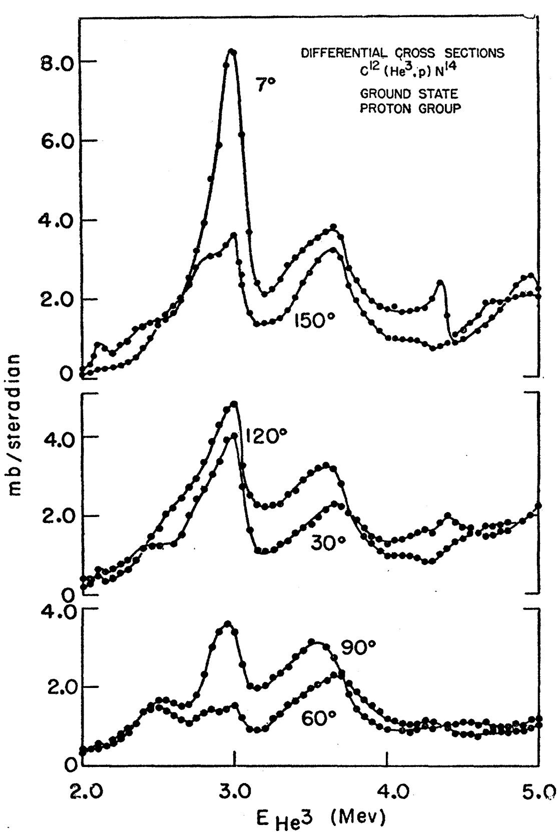

FIG. 3. The differential cross section of the ground-state proton group in the laboratory system as a function of incident He^3 energy from 2.0 to 5.0 Mev.

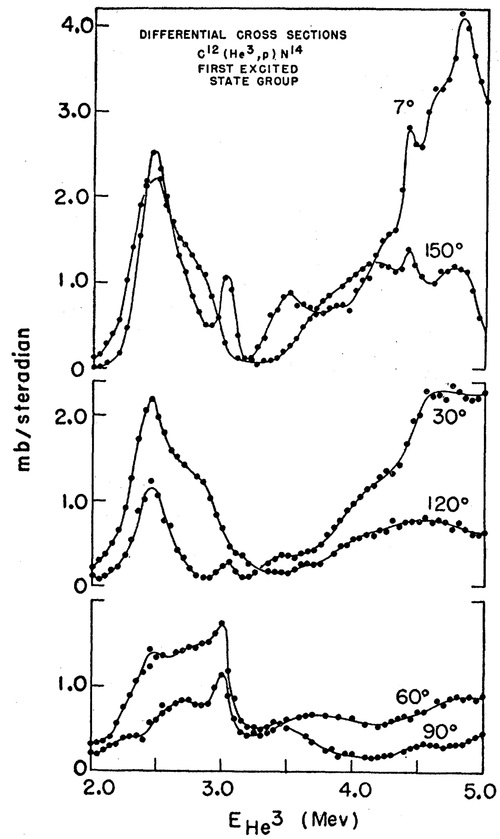

FIG. 4. The differential cross section of the first-excited-state proton group in the laboratory system as a function of incident He^3 energy from 2.0 to 5.0 Mev.

TABLE I. Coefficients of the Legendre polynomials from the least-squares fit to the data at 2.0 and 4.5 Mev. σ_0 is the integrated cross section in mb. $d\sigma/d\Omega=(\sigma_0/4\pi)[1+a_1P_1+\cdots+a_nP_n]$.

Group	σ_0	a_1	a_2	a_3	a_4	a_5	a_6
				2.0 Mev			
P_0	3.1	0.30	−0.30	0.01	0.01	0.03	0.02
P_1	2.5	−0.24	−0.78	−0.02	0.11	0.09	−0.02
P_2	2.7	−0.52	0.26	0.30	−0.05	0.08	−0.03
				4.5 Mev			
P_0	14.3	−0.15	0.25	0.34	−0.14	−0.02	−0.16
P_1	9.5	0.23	1.25	0.15	−0.10	0.08	0.12
P_2	25.1	0.10	1.08	0.27	−0.14	0.27	0.04

[3] Bonner, Eisinger, Kraus, and Marion, Phys. Rev. **101**, 209 (1956).

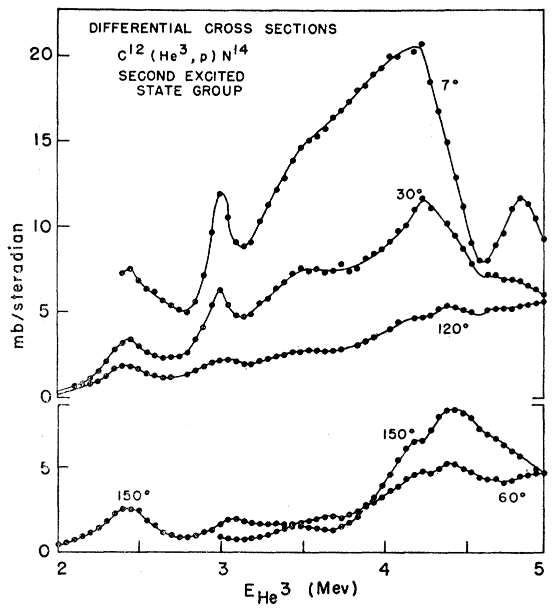

FIG. 5. The differential cross section of the second-excited-state proton group in the laboratory system as a function of incident He³ energy from 2.0 to 5.0 Mev.

and 5% lower than the results of Benenson *et al.*[4] The present results for the $C^{12}(He^3,p)N^{14}$ reaction, based on the weighed target thickness, are in good agreement with the measurements of Bromley *et al.*,[1] in the region in which they can be compared.

Angular distributions are given for selected energies in Figs. 6, 7, and 8 based on the observations at six angles. These illustrate the general trend in the neighborhood of observed resonances.

The differential cross sections of protons to the various states in N^{14} are an order-of-magnitude greater than those previously observed in other He^3-induced reactions[2,5–7].

DISCUSSION

The two detailed "off-resonance" angular distributions (2.0 and 4.5 Mev) do not exhibit the characteristic features of either a simple compound-nucleus formation or a simple direct interaction. A study of the yield curves taken at six angles indicates in general that the off-resonance angular distributions vary slowly as functions of energy. They have approximately the same shape above and below a resonance and are not symmetric about 90°. The trend of the angular distributions is to become more strongly peaked at the forward and backward angles with increasing bombarding energy. This peaking is enhanced on the resonance. The first-excited-state group at 3.0 Mev, Fig. 7, may be symmetrical about 90° allowing it to be attributed to the excitation of a single level in the compound nucleus.

Bromley *et al.*[1] observed resonances in the 90° yield curve at bombarding energies of 1.21, 1.3, 2.15, 2.5, and 2.7 Mev for one or more of the proton groups. In addition to these we have observed resonances at 3.0, 3.6, 4.4, and 4.8 Mev corresponding to excited states in O^{15} of 14.5, 15.0, 15.6, and 15.9 Mev, respectively. At the two higher energies, the tendency is for only the forward and/or the backward angles to exhibit the effects of the resonance.

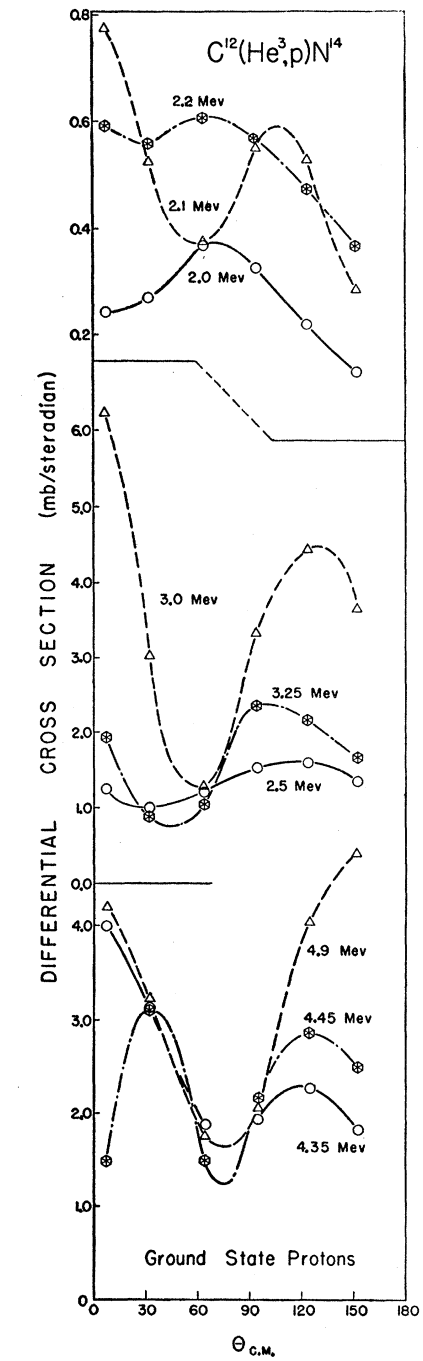

FIG. 6. The differential cross sections of the ground-state proton group in the center-of-mass system as a function of angle on and near the 2.1-, 3.0-, and 4.4-Mev resonances.

[4] Benenson, Jones, and McEllistrem, Phys. Rev. **101**, 308 (1956).
[5] H. D. Holmgren, Phys. Rev. **106**, 100 (1957).
[6] Holmgren, Geer, Johnston, and Wolicki, Phys. Rev. **106**, 102 (1957).
[7] Illsley, Holmgren, Johnston, and Wolicki (to be published).

The region of excitation of the compound nucleus O^{15} investigated extends from 13.7 to 16.1 Mev. It is expected that in this region the energy levels of the compound nucleus are rather closely spaced[8] and overlap to a large extent. This overlapping of energy levels

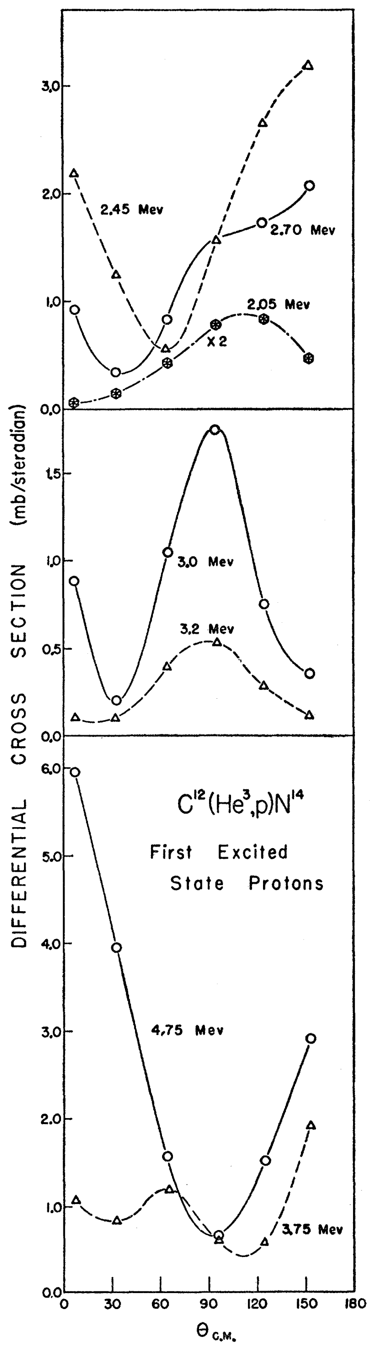

FIG. 7. The differential cross sections of the first-excited-state protons in the center-of-mass system as a function of angle on and near the 2.45-, 3.0-, and 4.75-Mev resonances.

[8] This statement is based upon the assumption of similarity between O^{15} and its mirror nucleus N^{15}. F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 27, 77 (1955).

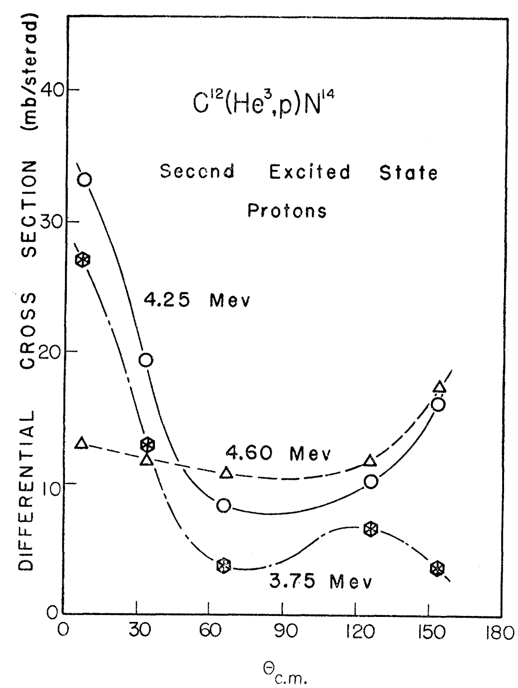

FIG. 8. The differential cross section of the second-excited-state protons in the center-of-mass system as a function of angle at three selected energies.

could account for the nonsymmetrical angular distributions observed. The observed separation of the resonances, about 500 kev, appears to be much larger than the expected level spacing. This may not be unreasonable since the wave function describing the incident He^3 particle and the target nucleus may have a strong overlap with only a select group of states in the compound nucleus.

At first it appears that this reaction could be accounted for almost entirely by the compound-nucleus model. On the other hand, the persistence of the forward and backward peaking with increasing bombarding energy and the enhancement of the peaks on the resonances (similar to deuteron-induced reactions[3,4]) strongly suggest that direct interactions do contribute to this reaction. This is particularly true when one considers the exchange type of direct interaction proposed by Owen and Madansky.[9] The relative importance of heavy-particle stripping, leading to backward peaking, may be expected to be greater for He^3-induced reactions than for deuteron-induced reactions due to the larger binding energy per nucleon in the He^3 particle.

The relatively large magnitude of the observed cross sections as compared to those for other He^3-induced reactions may be due to the low Q value (4.771 Mev) which limits the availability of residual levels. The low Q value, together with the lower excitation in the compound nucleus, may account for the appearance of relatively larger resonance effects in this reaction.

[9] G. E. Owen and L. Madansky, Phys. Rev. 105, 1766 (1957).