Angular Distributions for the $C^{13}(d,n)N^{14}$ Reaction*

ERICH H. WILLEN,† P. W. KEATON, AND GEORGE E. OWEN
Department of Physics, The Johns Hopkins University, Baltimore, Maryland
(Received 2 October 1963)

Angular distributions of neutrons corresponding to transitions to the ground, first (2.31-MeV) and second (3.94-MeV) excited states have been measured at incident deuteron energies between 1.3 and 2.5 MeV. A single stilbene crystal spectrometer utilizing pulse-shape discrimination was employed to separate the ground and first excited states. The second excited-state neutron group was measured with a double crystal time-of-flight spectrometer using the associated gamma ray as a trigger. An analysis in terms of the plane-wave heavy-particle stripping theory was performed to describe the relatively high intensity of neutrons in the backward direction.

INTRODUCTION

THE reaction $C^{13}(d,n)N^{14}$ has been the subject of several experimental studies in the past few years. Zdanis[1] measured the angular distribution for the transition to the first and second excited states at a beam energy of 1.3 MeV. Deshpande[2] measured the distribution to the ground state for the energy range 3.2–4.1 MeV. His results are presented in terms of the absolute differential cross section. Both authors make stripping theory calculations in an attempt to fit the experimental data.

The purpose of this paper is to present the results of angular distribution measurements in the energy range 1.3 to 2.5 MeV. Angular distributions to 150° with respect to the beam direction were measured for the transitions leading to the ground, the first excited and the second excited states. In addition, a value for the absolute differential cross section was obtained.

The neutrons to the ground and first excited states were detected with a single-crystal spectrometer using pulse-shape discrimination[3] to minimize gamma-ray background. A double crystal time-of-flight spectrometer was constructed to detect the neutrons due to transitions to the second excited state. The low energies of the second excited-state neutrons rendered the single-crystal spectrometer ineffective except at forward angles. The cross section of the time-of-flight spectrometer was too low to measure the very weak intensity of first excited-state neutrons. The need for a coincidence gamma ray to start the timing cycle likewise prohibited its use in measuring the ground-state neutrons.

The time-of-flight spectrometer utilized the gamma ray associated with the decay of the 2.312-MeV state as a trigger. Since this gamma ray represents the decay of a spin-zero state, the $n-\gamma$ correlation is isotropic; an angular distribution taken in coincidence with this gamma ray thus represents a true angular distribution.

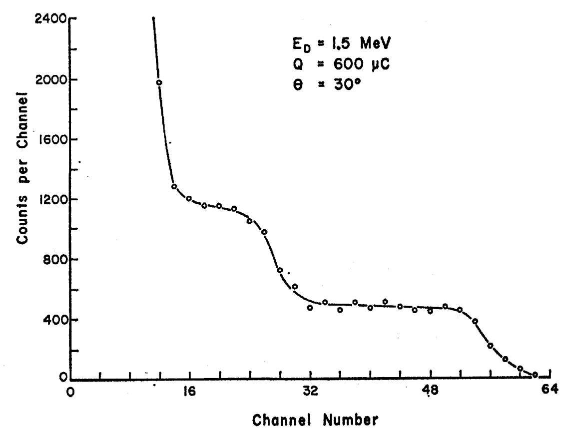

FIG. 1. A typical recoil proton pulse-height spectrum in stilbene. The plateaus represent the neutrons from the ground and first excited states of the reaction $C^{13}(d,n)N^{14}$.

EXPERIMENTAL ARRANGEMENT

The single-crystal spectrometer consisted of a single stilbene crystal $1\frac{1}{2}$ in. in diameter by 0.469 in. thick mounted on a 6810-Å photomultiplier. The front of the crystal was positioned 8 in. from the target. The linear signal was taken from the 11th dynode and analyzed in a 256-channel analyzer. The output of the pulse-shape discriminator was used to gate the analyzer. Gamma rejection efficiencies of better than 1000:1 were obtained using the pulse-shape discriminator.

The gamma detector in the double crystal time-of-flight spectrometer consisted of a Pilot B scintillator $1\frac{3}{4}$ in. in diameter by $1\frac{1}{2}$ in. long mounted on a 56 AVP photomultiplier, positioned $3\frac{1}{2}$ in. vertically under the target. A 12-in.-long by 2-in.-diam Pilot B scintillator mounted on a second 56 AVP served as a neutron detector. This detector, with its long axis tilted 10° from the perpendicular to the plane of the reaction, was placed 75 cm from the target at the lower beam energies but was placed 1 m from the target at 2.5 MeV in order to achieve better energy resolution. The signals from both photomultipliers were sent to double differ-

* Supported in part by the U. S. Atomic Energy Commission.
† Present address: Department of Physics, Brookhaven National Laboratory, Upton, New York.
[1] R. Zdanis, G. E. Owen, and L. Madansky, Phys. Rev. 121, 854 (1961).
[2] V. K. Deshpande, NYO-10252, The University of Rochester, Rochester, 1962 (unpublished).
[3] W. Daehnick and R. Sherr, Rev. Sci. Instr. 32, 666 (1961).

entiating circuits using regenerating tunnel diodes to detect the point of zero crossing.[4] The output of the tunnel diode circuits was used to generate a square wave. The amount of overlap of the two square waves was measured with a transistorized time-to-pulse

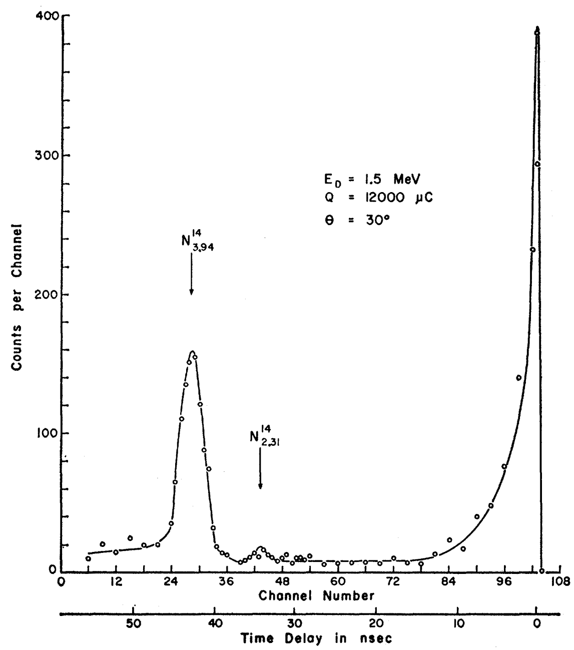

FIG. 2. A typical coincidence spectrum obtained with the time-of-flight system utilized in the experiment.

height converter,[5] the output of which was analyzed in a 256-channel analyzer.

Side gating was employed with both detectors. The gamma side gate was used to restrict the accepted

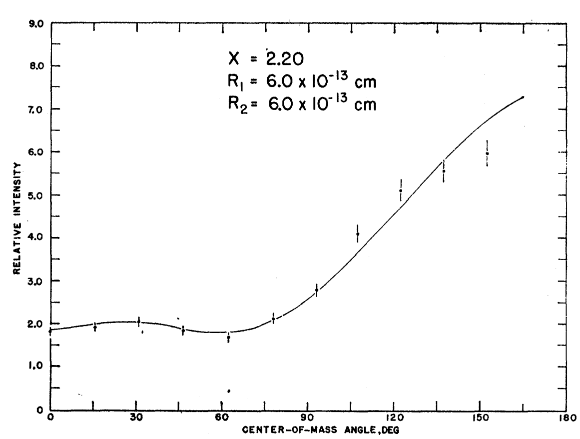

FIG. 3. Ground-state angular distribution at E_d=1.3 MeV.

[4] A. E. Bjerke, Q. A. Kerns, and T. A. Nunamaker, UCRL-9838, University of California Lawrence Radiation Laboratory, Berkeley, California, 1961 (unpublished).

[5] P. C. Simms, Rev. Sci. Instr. **32**, 894 (1961).

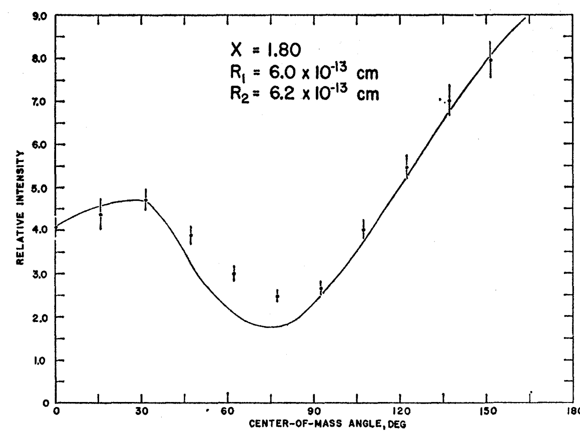

FIG. 4. Ground-state angular distribution at E_d=1.5 MeV.

Compton recoil electrons to the energy range 1.7–2.3 MeV while the neutron side gate was used to reject small pulses, just larger than the tunnel diode threshold, which are primarily responsible for slewing (time shifts). These side gate signals, in coincidence with each other and in anticoincidence with the output of a priority circuit, generated a pulse which gated the multichannel analyzer. The use of the priority circuit ensured that the signals from the gamma detector always preceded those from the neutron detector, thus

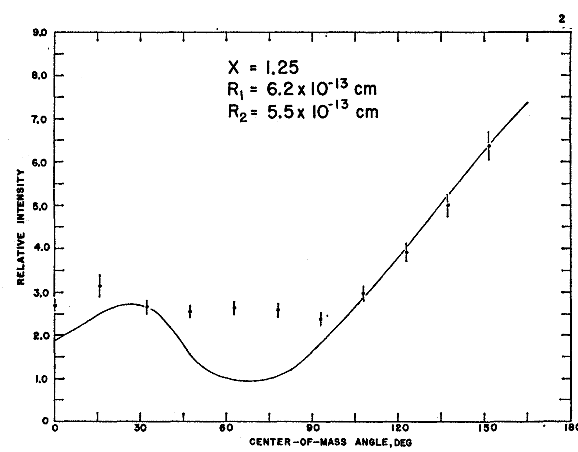

FIG. 5. Ground-state angular distribution at E_d=2.0 MeV.

reducing background by exactly one half. Time resolution (full width at half-maximum of neutron-gamma coincidence peak) of the time-of-flight spectrometer as used in the experiment was approximately 3 nsec.

Carbon targets were made for the time-of-flight experiment by heating 0.005-in. Ni blanks in an atmosphere of 55% enriched C^{13} methyl iodide with an rf induction heater.[6] Targets for the single-crystal

[6] G. C. Phillips and J. E. Richardson, Rev. Sci. Instr. **21**, 885 (1950).

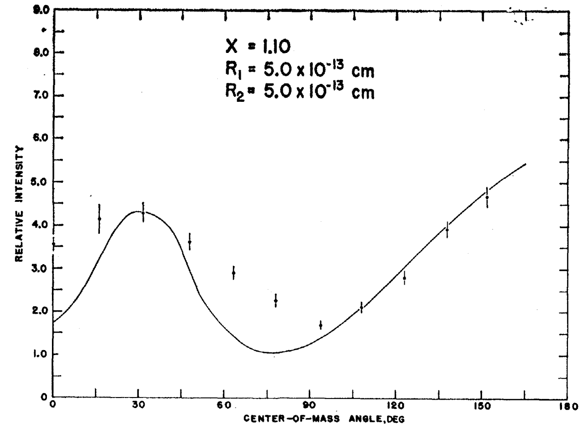

FIG. 6. Ground-state angular distribution at $E_d = 2.5$ MeV.

spectrometer were made by resistance heating of 0.00035-in. Ni foil in the same atmosphere. The use of thin foil backings in the latter case allowed the deuteron beam to traverse the foil without losing all its energy. The beam was stopped in a piece of tantalum heated to a dull red glow. This procedure avoided the buildup of deuterium and a subsequent $H^2(d,n)He^3$ reaction in the target backing. This must be avoided because the energy of these neutrons coincides with the energy of the first excited-state $C^{13}(d,n)N^{14}$ neutrons at forward angles.

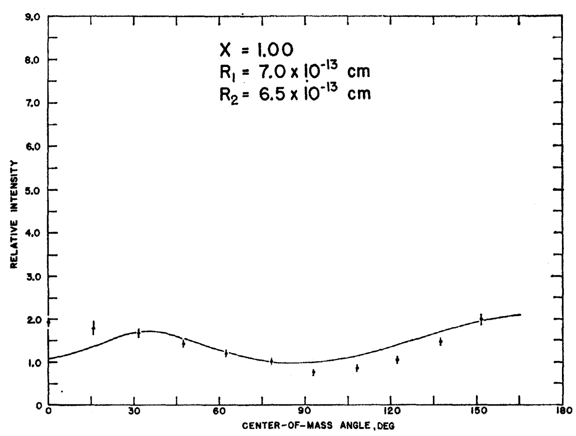

FIG. 7. First excited-state angular distribution at $E_d = 1.3$ MeV.

Typical spectra obtained with the two spectrometers are shown in Figs. 1 and 2.

ANALYSIS OF THE DATA

The plateau shaped neutron spectra obtained from the single-crystal spectrometer were corrected for the nonlinear pulse-height response of stilbene as well as the crystal end effect.[7] The integral plot was then a straight line which, extrapolated to the y axis gave the number of $n-p$ interactions in the crystal. This number was corrected for the relative crystal efficiency[7] and converted to a center-of-mass intensity.[8]

The effect on the integral spectrum of directional anisotropy[9] in the stilbene crystal was calculated. A variation of 10% in light output in a direction perpendicular to the direction of the incident beam will cause

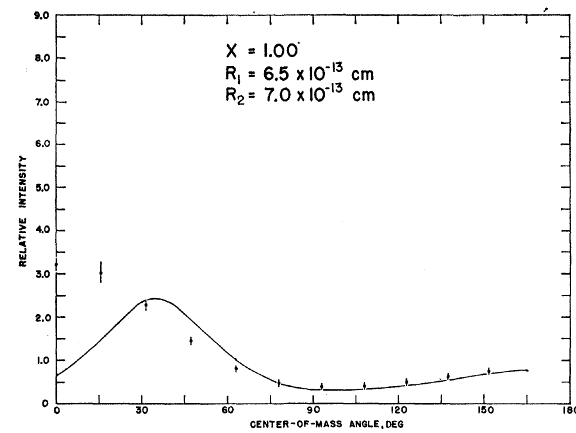

FIG. 8. First excited-state angular distribution at $E_d = 1.5$ MeV.

the intercept of the integral slot with the y axis to shift less than 1% for 8-MeV neutrons. Hence, this effect was neglected.

Background in the time-of-flight data presented an increasingly serious problem at the higher beam energies. The ratio of peak to background counts was better than 8 to 1 at 1.3 MeV whereas at 2.5 MeV, it

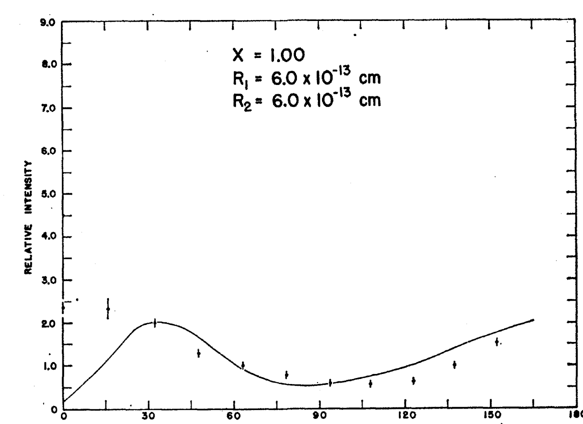

FIG. 9. First excited-state angular distribution at $E_d = 2.0$ MeV.

[7] C. D. Swartz, G. E. Owen, and O. Ames, NYO-2053, The Johns Hopkins University, Baltimore, Maryland, 1957 (unpublished); C. D. Swartz and G. E. Owen, in *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler (Interscience Publishers, Inc., New York, 1960), Part I, p. 211.

[8] J. B. Marion and A. S. Ginzberg, Research Report, Shell Development Company, Houston (unpublished).

[9] K. Tsukada and S. Kikuchi, Nucl. Instr. Methods **17**, 286 (1962).

was no better than 2 to 1. After subtraction of background, the time-of-flight data was corrected for the varying coincidence efficiency (due to fixed side gate settings) and $n-p$ cross section[10] as a function of angle. The data were then converted to the appropriate intensity in the center-of-mass system.[8]

The data for each distribution were normalized to a monitor which counted protons from the competing reaction $C^{13}(d,p)C^{14}$. This monitor and a beam current integrator always agreed to better than 10%.

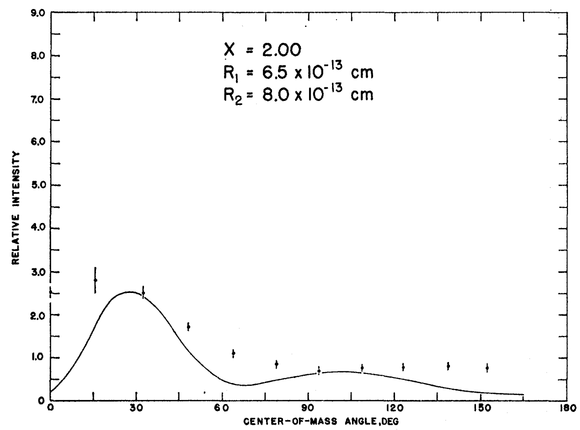

FIG. 10. First excited-state angular distribution at $E_d = 2.5$ MeV.

The corrected experimental data are presented in Figs. 3–14. The vertical scale is the same for all twelve graphs. One unit on the vertical scale corresponds to an absolute differential cross section of 0.51 ± 0.17 mb/sr. This number as well as the relative intensities of the three states were all obtained with the single-crystal spectrometer. The error bars on the data for the ground and first excited state represent the mean deviation in the intensities observed on the two sides of the beam direction. The error bars on the second excited-state intensity represent statistical error in the number of counts, including statistical error in the background.

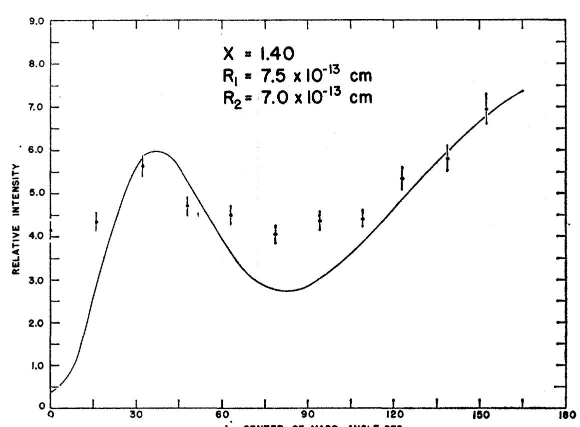

FIG. 11. Second excited-state angular distribution at $E_d = 1.3$ MeV.

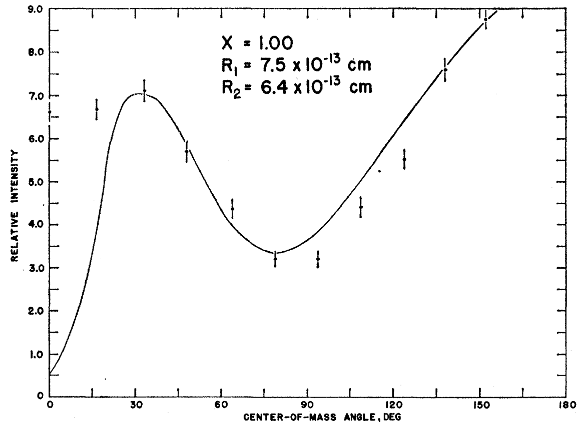

FIG. 12. Second excited-state angular distribution at $E_d = 1.5$ MeV.

THEORETICAL RESULTS AND DISCUSSION

The data were analyzed using the dual-mode stripping theory as developed by Owen and Madansky[11] and given by Edwards.[12] For the heavy-particle stripping mode, the "last" neutron is considered separated from the target nucleus and the residual core is captured by the deuteron with the relative orbital angular momentum l_c to form the final state. The shell-model configuration (neglecting the S state) for the ground state of the C^{13} target nucleus was taken to be $P_{1/2}(P_{3/2})$.[8] For the ground state of the final N^{14} nucleus, the shell-model configuration was taken as $(P_{3/2})^8(P_{1/2})^2$; for the first excited state, $(P_{3/2})^8(P_{1/2})^2$; for the second excited state, $(P_{3/2})^{-1}(P_{1/2})^{-1}$.[13] Assuming these configurations, the target neutrons participating in the reaction were taken to be the $P_{1/2}$ neutron for the

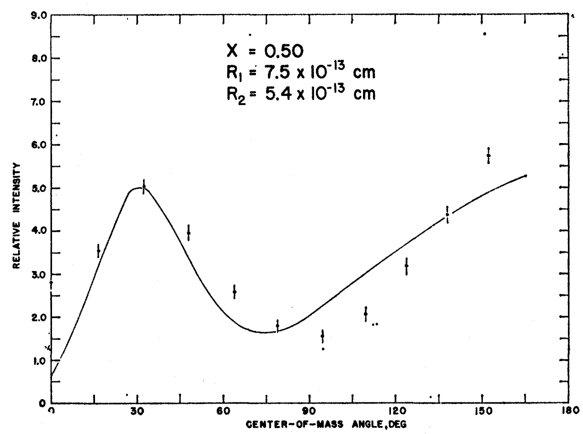

FIG. 13. Second excited-state angular distribution at $E_d = 2.0$ MeV.

[10] D. J. Hughes and R. B. Schwartz, *Neutron Cross Sections* (U. S. Government Printing Office, Washington, D. C., 1958).

[11] L. Madansky and G. E. Owen, Phys. Rev. **99**, 1608 (1955).

[12] S. Edwards, Phys. Rev. **113**, 1277 (1959).

[13] E. K. Warburton and W. T. Pinkston, Phys. Rev. **118**, 733 (1960).

ground state and the $P_{3/2}$ neutrons for the first and second excited states. The proton and core capture angular momenta were chosen as 1 and 0, respectively.

The theoretical curves, shown as solid lines in Figs. 3–14, were calculated from the expression

$$\frac{d\sigma}{d\Omega}\propto \sum_{\substack{\text{final}\\ \text{av initial}}}\left|C_1\Upsilon_D G_D(K_1)F_D(k_1R_1)-\frac{\Lambda_2}{\Lambda_1}C_2\Upsilon_H G_H(K_2)F_H(k_2R_2)\right|^2,$$

where the notation is similar to that of Ref. 12. The Υ's represent the appropriate sums over the Clebsch-Gordon coefficients. The values of $X=\Lambda_2/\Lambda_1$, R_1 and R_2, chosen to give the best fit to the data, are listed in Figs. 3–14. The numerical calculations were made with the aid of a program written for use on the IBM 7094 computer.

The theoretical results show that the general features of the experimental data can be reproduced by the dual mode theory. Distortion effects have not been explicitly included in the present calculation. Hence, the results presented are subject to possible modification by a more detailed distorted-wave analysis. Such a calculation has been carried out for this reaction at higher deuteron beam energies, the results showing poor agreement between theory and experiment.[2] The most realistic result is to be expected from a calculation which includes both distorted waves and the heavy-particle mode. Efforts in this direction have thus far been unsuccessful.

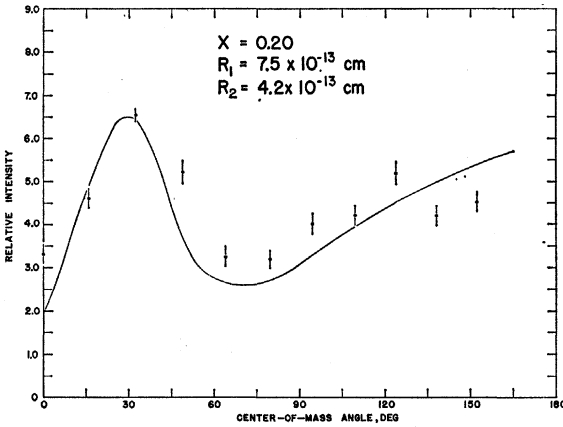

FIG. 14. Second excited-state angular distribution at $E_d=2.5$ MeV.

PHYSICAL REVIEW VOLUME 133, NUMBER 4B 24 FEBRUARY 1964

Energy Dependence of Elastic and Inelastic Scattering from C^{12} for Protons between 14 and 19 MeV*

W. W. DAEHNICK† AND R. SHERR
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received 4 October 1963)

Differential cross sections $\sigma(E,\theta)$ for elastic and inelastic (4.43 MeV) proton scattering by C^{12} have been obtained as a continuous function of bombarding energy for 15 scattering angles between 15° and 160°. The energy resolution was approximately 200 keV, and the angular resolution was chosen as $\Delta\theta\leq 2°$. The data show several resonance-like variations for $\sigma(E)$, <300 to 500 keV wide for all angles observed. Changes in the elastic and inelastic (4.43 MeV) differential cross sections are closely correlated and are strongest near 15 and 17.6 MeV. In the experiment, use was made of the fact that in a thick target the incident energy is reduced by ionization so that scattering occurs over a range of energies ΔE. Consequently, the energy spectrum of the scattered protons can be used to obtain continuous excitation functions $\sigma(E)$ over the energy interval ΔE. In the present measurements, polystyrene targets of $\Delta E=1.6$ MeV were used. A discussion of the thick-target method is presented. Normalizations and cross checks for the thick-target excitation functions were obtained by conventional thin-target cross section measurements. The latter runs also yielded some cross sections for scattering to the 7.66- and 9.64-MeV states in C^{12}. Scattering to the 0^+, 7.66-MeV state showed strong energy dependence while scattering to the 3^-, 9.64-MeV state showed fluctuations of not more than 15%. The scattering cross sections are compared with optical model calculations by Nodvik, Duke, and Melkanoff,[13] and $C^{12}(p,p'\gamma)C^{12}$ γ-yield measurements by Warburton and Funsten.[24]

I. INTRODUCTION

OF various methods to account for and predict nuclear elastic scattering at intermediate proton energies, the optical model has been most successful. With the aid of 4 to 7 empirical parameters, experimental angular distributions can be fitted, qualitatively correct predictions can be made,[1–4] and often polariza-

* This work was supported by the U. S. Atomic Energy Commission, the Higgins Scientific Trust Fund, and the U. S. Office of Naval Research.

† Present address: Department of Physics, University of Pittsburgh, Pittsburgh, Pennsylvania.

[1] M. A. Melkanoff, J. D. Nodvik, D. S. Saxon, and R. D. Woods, Phys. Rev. **106**, 793 (1957).

[2] A. E. Glassgold, W. B. Cheston, M. L. Stein, S. B. Schulott, and G. W. Erickson, Phys. Rev. **106**, 1207 (1957); A. E. Glassgold and P. J. Kellogg, Phys. Rev. **107**, 1372 (1957).

[3] F. Bjorklund, *Proceedings of the International Conference on the Nuclear Optical Model*, Florida State University Studies No. 32 (Florida State University, Tallahassee, 1959); F. Bjorklund and S. Fernbach, Phys. Rev. **109**, 1295 (1958).

[4] F. Perey and B. Buck, Nucl. Phys. **32**, 353 (1962).