Differential Cross Sections for Tritium-Induced Reactions on C^{12}

G. D. GUTSCHE,*† H. D. HOLMGREN,‡ L. M. CAMERON, AND R. L. JOHNSTON†
Nucleonics Division, U. S. Naval Research Laboratory, Washington, D. C.
(Received September 1, 1961)

The differential cross sections for the ground-state proton group from the $C^{12}(t,p)C^{14}$ reactions, and for the ground-state and first-excited-state alpha-particle groups from the $C^{12}(t,\alpha)B^{11}$ reactions, have been studied as functions of the angle of emission and the bombarding energy in the region from 0.800 to 2.025 Mev. The elastically scattered tritons have also been studied in the energy region from 1.000 to 1.950 Mev. The angular distributions of all reaction groups are complex. The basic structure of the angular distributions for the ground-state alpha-particle group is retained throughout the energy region studied; however, it shifts toward higher angles with increasing bombarding energy. The structures of the angular distributions for the first-excited-state alpha-particle group and the ground-state proton group shift smoothly toward lower angles with increasing energy. The first-excited-state alpha-particle group exhibits a resonance at 1.13 Mev at which the total cross section increases by a factor of 4. The width of this resonance is about 50 kev. The angular distributions of this group are not affected by the resonance, and the effects of this resonance are negligible in the other reaction channels. The total cross sections for all of the reaction groups increase rapidly between 1.5 and 1.7 Mev. This increase to some extent may be due to a broad anomaly in the region of 1.8 Mev. The total cross sections for the ground-state and first-excited-state alpha-particle groups at 1.95 Mev are 330 and 30 mb, respectively. The $C^{12}(t,\alpha)B^{11}$ reactions may proceed by a "direct cluster exchange interaction" in which the distortion effects may play an important part.

INTRODUCTION

SEVERAL years ago a study of the mechanisms of nuclear interactions was started in the Nucleonics Division, U. S. Naval Research Laboratory, and several papers concerning the experimental observations of the interactions of He^3 particles with light nuclei have been published.[1–7] Recently the scope of this program has been expanded to include the study of the interactions of tritons with light nuclei.

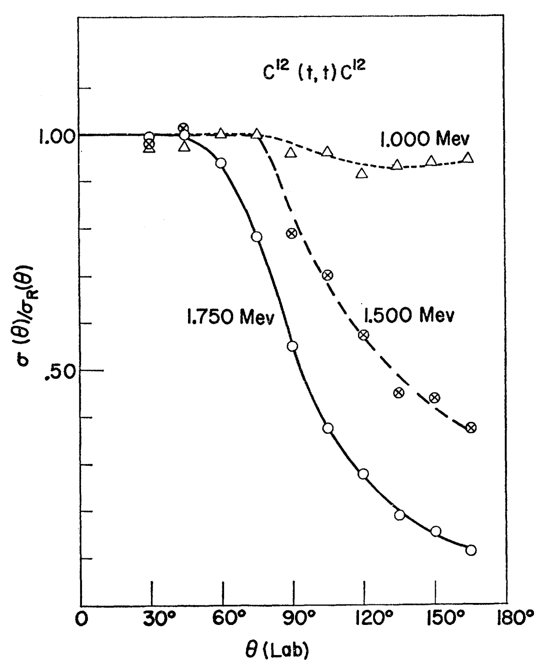

FIG. 1. The ratio of the differential cross sections for the elastic scattering of tritons from C^{12} to the Rutherford cross section at 1.000, 1.500, and 1.750 Mev.

Since the experience with the He^3-induced reaction studies indicated that C^{12} was the most serious contamination on almost all targets after a period of bombardment, the triton interactions with C^{12} were chosen as the first to be studied. In addition, the lower energy levels of the residual nuclei are not only well known, but are sufficiently well separated so that the identification of the groups can easily be made. An examination of the Q values for these reactions reveals that two proton groups and four alpha-particle groups are energetically possible in the region of bombarding energy available; however, only one of these proton groups and two of the alpha-particle groups were observable with apparatus used in this experiment. Measurements were made on the proton group leading to the ground state of C^{14} ($Q_0=4.635$ Mev), and on the alpha-particle groups leading to the ground state and first-excited state of B^{11} ($Q_0=3.853$ Mev, and $Q_1=1.728$ Mev). Differential cross sections for all three reactions were measured as functions of the bombarding energy for several angles and as functions of the angle of emission at seven different energies in the region from 0.900 to 2.000 Mev. The differential cross sections for the elastically scattered tritons were also studied as functions of the angle at three energies in this region, and as functions of the bombarding energy at 90° and 150°.

* NSF Science Faculty Fellow during a portion of this study.
† Present address: Science Department, U. S. Naval Academy, Annapolis, Maryland.
‡ Present address: Physics Department, University of Maryland, College Park, Maryland.

[1] H. D. Holmgren, M. L. Bullock, and W. E. Kunz, Phys. Rev. **104**, 1446 (1956).
[2] H. D. Holmgren, Phys. Rev. **106**, 100 (1957).
[3] H. D. Holmgren, E. H. Geer, R. L. Johnston, and E. A. Wolicki, Phys. Rev. **106**, 102 (1957).
[4] E. G. Illsley, H. D. Holmgren, R. L. Johnston, and E. A. Wolicki, Phys. Rev. **107**, 538 (1957).
[5] R. L. Johnston, H. D. Holmgren, E. A. Wolicki, and E. G. Illsley, Phys. Rev. **109**, 884 (1958).
[6] H. D. Holmgren, E. A. Wolicki, and R. L. Johnston, Phys. Rev. **114**, 1281 (1959).
[7] E. A. Wolicki, H. D. Holmgren, R. L. Johnston, and E. G. Illsley, Phys. Rev. **116**, 1585 (1959).

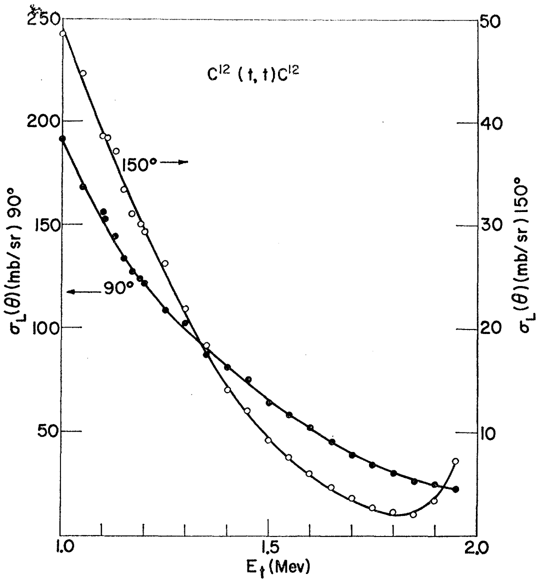

FIG. 2. The differential cross sections for the elastic scattering of tritons from C^{12} at 90° and 150° as functions of the bombarding energy.

PROCEDURE

Tritons with energies up to 2.025 Mev were accelerated with the Nucleonics Division 2-Mv Van de Graaff accelerator. The beam was magnetically analyzed in a 90° magnet and then focused on the target by means of a strong focusing lens. A mass analysis of the beam at 1.50 Mev indicates that the relative intensity of the mass-3, mass-2, and mass-1 beams were 1.00, 0.013, and 0.12. The ionized atomic hydrogen beam is known (under the conditions used) to be about 5 times more intense than the triatomic beam; thus, contributions of HHH^+ and HD^+ ions to the mass-3 beam were negligible.

The reactions were studied in two phases. The differential cross sections of the proton group and the ground-state alpha-particle group were studied first in a sliding-seal reaction chamber[8] using a thin (0.02-in.) CsI crystal to detect the reaction products. The sliding-seal chamber allowed the angle of the CsI crystal counter to be varied continuously from 0° to 130°. A fixed monitor counter at 163° to the axis of the beam allowed an additional observation to be made at this angle. For angles below 20° the collector cup was removed and the beam was stopped on a 200-microinch nickel foil which was inserted behind the target. The ranges of the observed reaction products were sufficiently large so that these particles could pass through this foil without excessive straggling. In addition, the mean scattering angle of these particles, produced by this foil, was small compared to the details of the angular distributions; thus, the insertion of the foil near the target did not materially affect the observed angular distributions. The current to the foil was measured; however, the beam was actually monitored by the 163° monitor counter during this period, since no means of collecting or repelling secondary electrons was provided. The pulse-height spectra from the CsI crystal counter were recorded with a 256-channel analyzer.

Differential cross sections for the ground-state and the first-excited-state alpha-particle groups, and for the elastically scattered tritons, were measured in a reaction chamber with fixed-angle exit ports at 15° intervals in the angular region from +0° to +105° in one quadrant, and from −75° to −165° in another quadrant. The particle energies were observed with solid-state ionization chambers in this phase of the experiment. As before, the pulse-height spectra were recorded in a 256-channel analyzer. The differential cross sections of the ground-state alpha-particle group determined with both chambers were the same within the experimental uncertainties.

The target used during the first phase of the experiment was prepared by the cracking of methyl iodide vapor on a hot 10-microinch nickel foil. The target used during most of this phase had a 0.15-mg/cm² carbon deposit (98% C^{12}). The target thickness was determined from the comparison of the observed yields of the protons elastically scattered at several angles with the differential cross sections measured by Jackson *et al.*[9] During the second phase of the experiment, thin self-supporting foils of carbon were used as targets. The thicknesses of these targets were determined from the

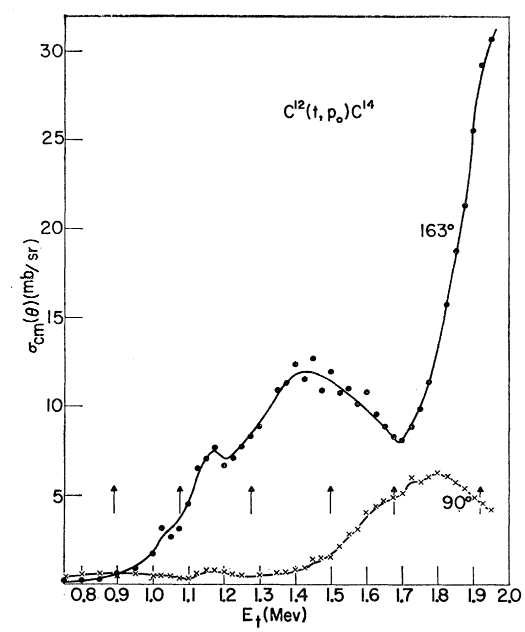

FIG. 3. The differential cross sections for the ground-state proton group from the $C^{12}(t,p)C^{14}$ reaction at 90° and 163° as functions of the bombarding energy.

[8] F. I. Louckes, Jr., Rev. Sci. Instr. 28, 468 (1957).

[9] H. L. Jackson, A. I. Galonsky, F. J. Eppling, R. W. Hill, E. Goldberg, and J. R. Cameron, Phys. Rev. 89, 365 (1953).

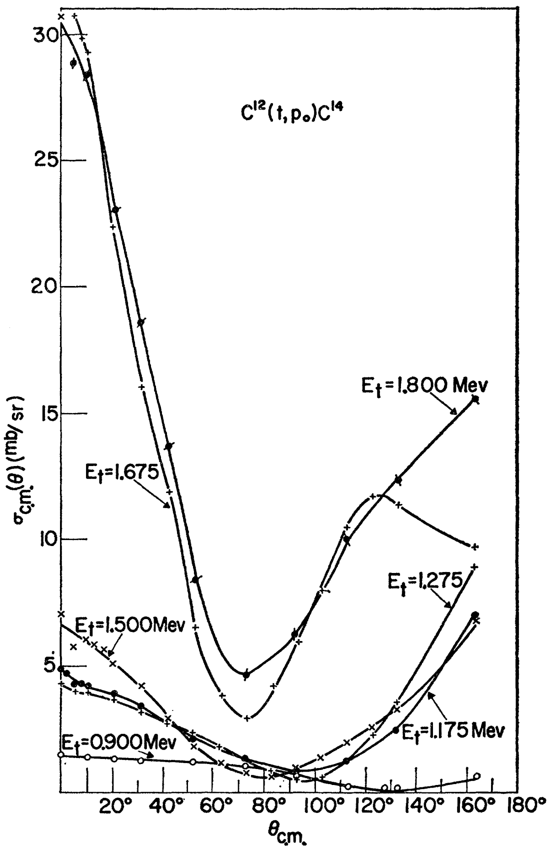

FIG. 4. The differential cross sections for the ground-state proton group from the $C^{12}(t,p)C^{14}$ reaction as functions of angle at various bombarding energies.

Rutherford cross section and from the observation of the tritons scattered at low angles. The absolute differential cross sections obtained in both phases of the experiment for the ground-state alpha-particle group agree to within 2%.

RESULTS

Elastic Scattering

The yields of the elastically scattered tritons were measured at 10 angles for incident triton energies of 1.000, 1.500, and 1.750 Mev. The ratios of the experimental yields to the calculated Rutherford scattering cross sections are shown in Fig. 1. These ratios were found to be constant at small angles for all energies. This constant was assumed to be unity. The determinations of the absolute differential cross sections for the second phase of this experiment are based on this assumption. The differential cross sections of the elastically scattered tritons at 90° and 150° are illustrated as functions of the bombarding energy in Fig. 2.

$C^{12}(t,p)C^{14}$ Reaction

The differential cross sections at 90° and 163° for the ground-state proton group from the $C^{12}(t,p)C^{14}$ reaction, measured as functions of the bombarding energy, are shown in Fig. 3. The measurements extend from 0.750 to 1.950 Mev, and data points were taken in approximately 25-kev intervals. The behavior of these differential cross sections suggests the possible existence of a weak resonance at E_t= 1.15 Mev and a broad anomaly in the neighborhood of 1.8 Mev. Above 1.8 Mev a marked increase appears in the yield at 163°, indicating strong backward peaking in the angular distribution. Angular distributions of the emitted protons leaving the residual nucleus, C^{14}, in the ground state have been measured at triton energies of 0.900, 1.100, 1.175, 1.275, 1.500, 1.675, and 1.800 Mev. These angular distributions were converted to the center-of-mass coordinate system, and in each case normalized to the 90°-differential-cross-section curve of Fig. 3 in order to obtain the differential cross sections as functions of the angle shown in Fig. 4. Strong forward and backward peaking is exhibited at all energies and the curves are not symmetrical about 90° at any energy. The total cross section obtained by integrating the differential cross sections is shown as a function of the bombarding energy in Fig. 5. The total cross section appears to increase rapidly up to about 1.1 Mev and then remains essentially constant to 1.5 Mev. Above this energy the total cross section again increases rapidly to about 1.7 Mev. The total cross section also approaches a constant value above this energy. The basic structure of the angular distributions is retained throughout the energy region studied except that it shifts towards smaller angles with increasing energy. This fact is most easily seen in the semilog plot of Fig. 6. The lines in these figures are smooth curves drawn through the data points.

$C^{12}(t,\alpha)B^{11}$ Reactions

The differential cross sections for the $C^{12}(t,\alpha_0)B^{11}$ reaction leaving the residual nucleus in the ground state were measured as functions of the bombarding energy

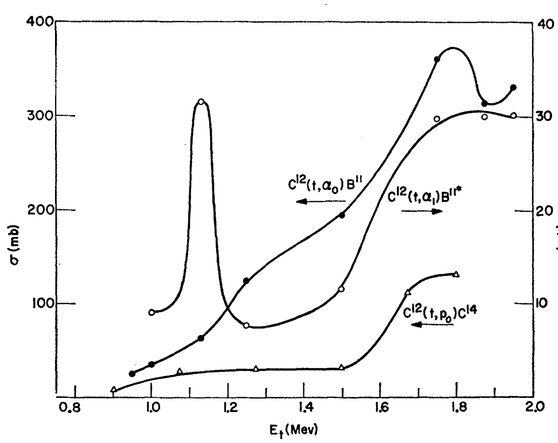

FIG. 5. Total cross sections for the ground-state and first-excited-state alpha-particle group from the $C^{12}(t,\alpha)B^{11}$ reactions and for the ground-state proton group from the $C^{12}(t,p)C^{14}$ reaction as functions of the bombarding energy. The values were obtained by integrating the differential cross sections as functions of angle at each energy.

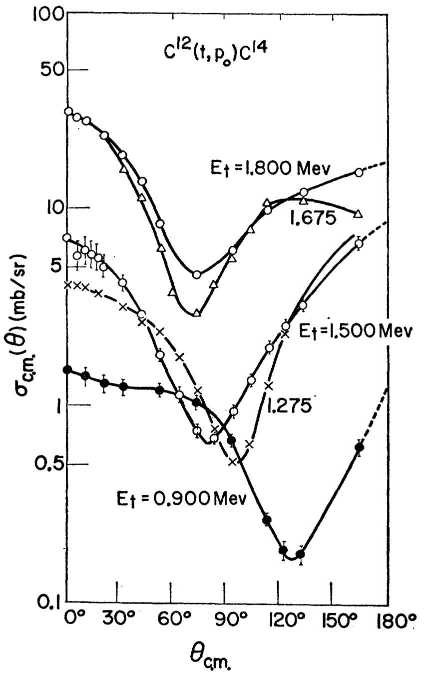

FIG. 6. Semilog plot of the differential cross sections as functions of the angle for the ground-state proton group from the $C^{12}(t,p)C^{14}$ reaction for various bombarding energies.

at laboratory angles of 90°, 150°, and 163° with respect to the beam axis. Measurements at 90° and 163° were made during the first phase of the experiment in the region of triton energies from 0.800 Mev to 2.025 Mev, and were taken at approximately 25-kev intervals. During the second phase, measurements were made at 90° and 150° in the range of bombarding energy from 1.000 Mev to 2.000 Mev at approximately 50-kev intervals. These data are shown in Fig. 7. The total cross section (obtained in the manner described previously) is shown as a function of the bombarding energy in Fig. 5; and, except for the broad anomaly in the region of 1.8 Mev, the total cross section appears to increase relatively smoothly with bombarding energy up to the energy of the Coulomb barrier. Although the data do not extend to sufficiently high energy, there may be some indication that the total cross section approaches a constant value above this energy. The total cross section for the emission of alpha particles leaving the residual nucleus in the ground state is more than an order to magnitude greater at most energies than the corresponding total cross sections for alpha emission leaving the residual nucleus in the first excited state, and about a factor of 3 more than that for proton emission (see Fig. 5). At 1.75 Mev the total cross section for the ground-state alpha-particle group is 360 mb, which is the largest known total cross section for a mass-3 induced reaction.[10]

The differential cross section for the $C^{12}(t,\alpha_1)B^{11}$ reaction leaving the residual nucleus in the first-excited state was measured at a laboratory angle of 150° at 50-kev intervals in the range of triton energies from 1.000 to 1.950 Mev. Also, the differential cross section at 105° was measured at 10-kev intervals near 1.13 Mev. The results are shown in Fig. 8. A pronounced resonance appears at a triton energy of 1.13 Mev, corresponding to an energy of excitation of 15.75 Mev in the $C^{12}+t$ system (N^{15}), and a strong peak occurs in the 150° yield at a bombarding energy of 1.85 Mev. The total cross section, shown in Fig. 5, also exhibits a rapid increase between 1.50 and 1.75 Mev as well as the strong resonance at 1.13 Mev where it increases by about a factor of 4. The behavior of the total cross section for this group between 1.5 and 1.9 Mev is similar to that of the other groups; however, this group is the only observed group which is significantly affected by the 1.13-Mev resonance.

The angular distributions of the emitted alpha particles leaving the residual nucleus in the ground state and first-excited state were measured at triton energies of 1.000, 1.128, 1.250, 1.500, 1.750, 1.875, and 1.950 Mev. Those for the ground-state alpha-particle group were also measured at 0.950 Mev. These angular distributions were converted to differential cross sections by the aforementioned procedure and are shown in Figs. 9 and 10, respectively. The essential features of the shape of the angular distributions for the ground-state alpha-particle group do not exhibit any marked changes in the energy region studied except for a de-

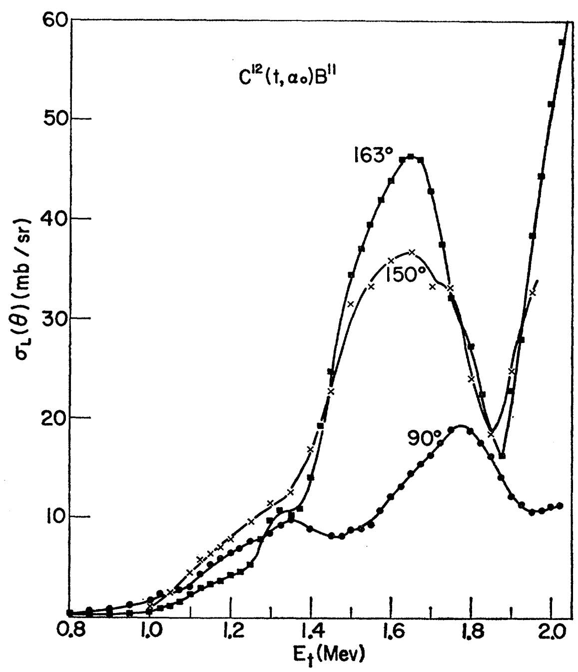

FIG. 7. The differential cross sections for the ground-state alpha-particle group from the $C^{12}(t,\alpha)B^{11}$ reaction at 90°, 150°, and 163° as functions of the bombarding energy.

[10] If one considers the $He^3(d,p)He^4$ reaction as a mass-3 induced reaction, then the cross section for this reaction at the 0.43-Mev resonance is actually larger than the $C^{12}(t,\alpha_0)B^{11}$ cross section at 1.75 Mev.

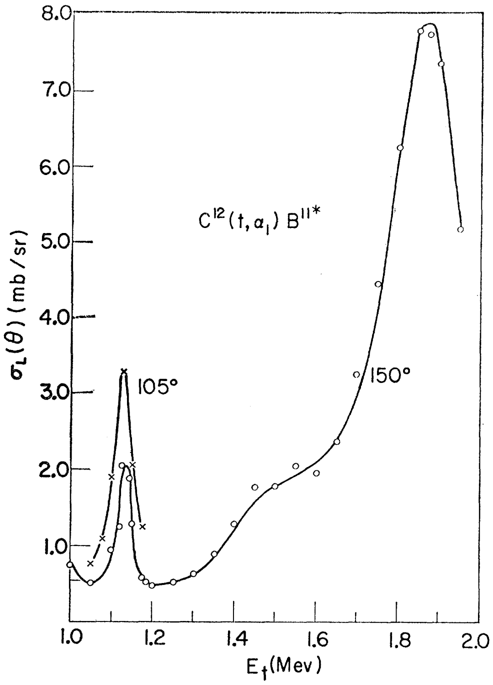

FIG. 8. The differential cross sections for the first-excited-state alpha-particle group from the $C^{12}(t,\alpha)B^{11}$ reaction at 105° and 150° as functions of the bombarding energy.

crease in the backward maximum in the region of the 1.8-Mev anomaly, and a shift towards larger angles with increasing bombarding energy. The fact that the essential structure of the angular distribution for the ground-state group is retained is better illustrated in the semilog plot of Fig. 11. The strong forward maximum shifts away from 0° for triton energies greater than 1.50 Mev. As before, the solid lines represent smooth curves through the data points, and no attempt has been made to obtain a theoretical fit. The essential features of the angular distributions for the first-excited-state group also appear to be retained throughout the energy region studied, even on the 1.13-Mev resonance. To show this effect in the region of the resonance, the angular distributions at 1.000, 1.128, and 1.250 Mev, normalized to their peak value, are plotted in Fig. 12. The shift of the characteristic structure of the angular distribution for this group is however towards lower angles with increasing bombarding energy (see Figs. 10 and 12).

In order to illustrate the shifts of the structure of the angular distributions, the angular positions of a characteristic feature of each angular distribution have been plotted as functions of the bombarding energy in Fig. 13. These points lie on relatively smooth curves; however, their rates of angular shift decrease with bombarding energy. The similarity of the shifts for the $C^{12}(t,\alpha_1)B^{11}$ and the $C^{12}(t,p_0)C^{14}$ reactions and the shift for the $C^{12}(t,\alpha_0)B^{11}$ reaction in the opposite direction are apparent in this figure. The points for the $C^{12}(t,\alpha_0)B^{11}$ reaction in the region 1.8 Mev are the only ones which deviate significantly from a smooth curve.

DISCUSSION

For the range of bombarding energies used in this experiment, the $C^{12}+t$ system corresponds in energy to excitation energies of N^{15} extending from 15.5 to 16.5 Mev. Five anomalies occurring in the neutron yield from the $B^{11}+\alpha$ system in this region of excitation (corresponding to triton energies of 0.95, 1.34, 1.35, 1.43, and 1.49 Mev) have been interpreted as energy levels of N^{15}.[11] None of these anomalies appears significantly in the present experiment; however, the two aforementioned anomalies, at bombarding energies of 1.13 and 1.8 Mev, were observed. This difference in the number and location of the observed resonances in the two reactions suggests that not only the configurations of the two systems are different, but that the nature of the interactions differs as well.

The exact nature of the anomaly at 1.8 Mev is difficult to determine on the basis of the present experiment; however, the effects of this anomaly are clearly seen. Although the angular distribution of the ground-state alpha-particle group shows the most pronounced change in the region of 1.8 Mev, the angular distributions of all groups exhibit the effect of this anomaly to some extent, especially for the yields at high angles.

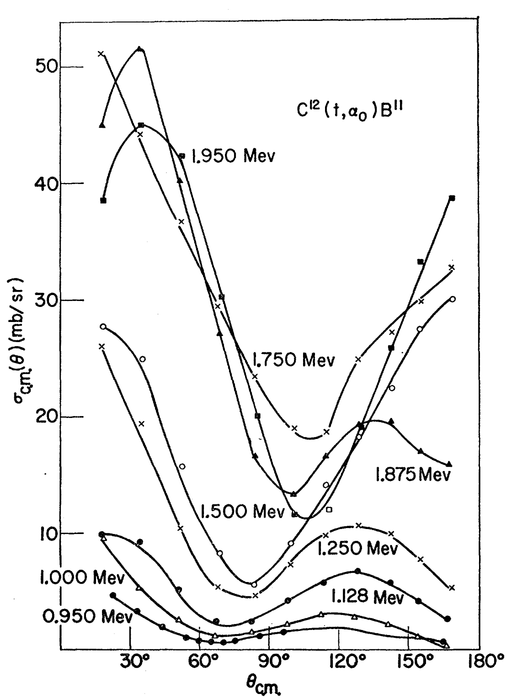

FIG. 9. The differential cross sections for the ground-state alpha-particle group from the $C^{12}(t,\alpha)B^{11}$ reaction as functions of the angle at various bombarding energies.

[11] Haddad Perry, and Smith, see F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. 11, 179 (1959).

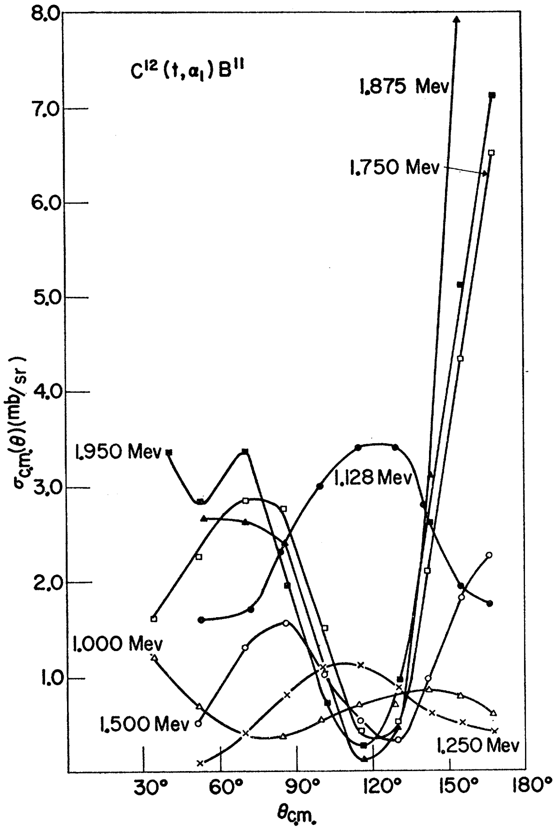

FIG. 10. The differential cross sections for the first-excited-state alpha-particle group from the $C^{12}(t,\alpha)B^{11}$ reaction as functions of the angle at various bombarding energies.

Because of the complexity of the angular distributions and the manner in which their structures are observed to shift with energy, it is difficult to obtain definitive information about this anomaly from the observation of the yields as functions of the bombarding energy at individual angles. All these yields exhibit complex behaviors; on the other hand, the total cross sections, obtained from the integration of the differential cross sections over angle, show relatively simple behaviors. The total cross sections of all groups increase between 1.5 and 1.8 Mev; however, the observations do not extend to sufficiently high energy to determine whether the total cross sections decrease above this energy. The Coulomb barrier for this reaction is about 1.6 Mev; thus, the increasing total cross section with increasing energy in this region may be associated with the increasing penetrability of the Coulomb barrier by the tritons, and effects of the 1.8-Mev broad anomaly may be exhibited primarily in the yields at high angles. The observation must be extended beyond 2 Mev in order to determine whether the observed increases in the total cross sections between 1.5 and 1.8 Mev are associated primarily with the effect of the Coulomb barrier or a resonance. The deviation of the shifts of the angular positions of the central minimum for the $C^{12}(t,\alpha_0)B^{11}$ reaction from a smooth curve (see Fig. 13) is a further indication of the existence of an anomaly in the region of 1.8 Mev.

Since this anomaly is exhibited in all channels, it may be associated with the entrance channel, the $C^{12}+t$ configuration. If the increase in the yields between 1.5 and 1.8 Mev is mainly a result of the effects of the Coulomb barrier, the large width may suggest that this anomaly arises from an interference of the distortion effects in the entrance channel.

The failure of the 1.13-Mev resonance, observed in the first-excited-state alpha-particle group, to appear in other channels, especially the entrance channel, and the persistence of the characteristic angular distribution of the first-excited-state alpha-particle group on the resonance suggest that this resonance is associated with the exit channel,[12] the $B^{11*}+\alpha_1$ configuration. Even the shift of the structure of the angular distribution appears to be unaffected by the resonance (Fig. 13). It is interesting to note that the anomalies in the $B^{11}(\alpha,n)N^{14}$ reaction, which were mentioned previously do not appear significantly in these reactions, particularly the $C^{12}(t,\alpha_0)B^{11}$ reaction. The entrance channel configuration for the $B^{11}(\alpha,n)N^{14}$ reaction should be the same as the exit channel configuration for the $C^{12}(t,\alpha_0)B^{11}$ reaction; thus some of the same anomalies might have been expected to appear in both reactions.

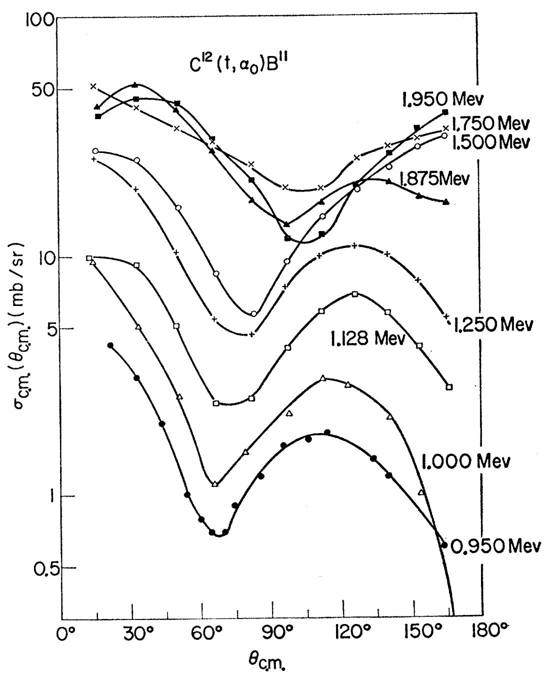

FIG. 11. Semilog plot of the differential cross sections for the ground-state alpha-particle group from the $C^{12}(t,\alpha)B^{11}$ reaction as functions of the angle at various bombarding energies.

[12] G. C. Phillips and T. A. Tombrello, Nuclear Phys. **19**, 555 (1960); T. A. Tombrello and G. C. Phillips, Nuclear Phys. **20**, 648 (1960).

The observations indicate that the angular distributions of all groups are complex and that none of them exhibits symmetry about 90°. The basic features of the angular distributions for each reaction group persist throughout most of the energy region studied, except that they shift in angle with bombarding energy (see Fig. 13). However, the rates of shift are observed to decrease with energy. These behaviors are indicative of reactions which may be best described in terms of the direct interaction approximation; that is, ones in which the characteristic time of the interaction is sufficiently short so that much of the information about the kinematics of the initial system is retained.[13] The persistence of the foward and/or backward peaking in the angular distributions seems to suggest that the $C^{12}(t,\alpha)B^{11}$ reaction proceeds by the exchange type of direct interaction proposed by Owen and Madansky.[14] However, the observed difference in the direction of the angular shifts for the two alpha-particle groups suggests that the nature of the direct process, which predominates in each case, is different. The forward shift for the first-excited-state group could be associated with either a dominant pickup or a knockout process. In this case the knockout process may be preferred; however, the forward shift in the ground-state proton group is probably related to a double-stripping process.[15–18] Also, the forward shift would be further enhanced by the decreasing effect of the Coulomb distortions with increasing energy. The dashed line in Fig. 13 indicates the shift expected on the basis of a plane-wave pickup process for the $C^{12}(t,\alpha_1)B^{11*}$ reaction. (The calculated and observed curves have been adjusted to coincide at 1.95 Mev.) The difference between the behaviors of the calculated and observed curves is consistent with the expected effects of distortions at low energies.[19] The shift of the structure of the angular distributions of the ground-state alpha-particle group to larger angles with increasing energy may indicate that heavy-particle stripping components of the exchange interaction are the dominant amplitudes for this reaction. However, the significance of this process in nuclear reactions has been questioned.[20] Thus, in view of the extremely large observed cross sections for this reaction, the heavy-particle stripping interpretation may be questionable. On the other hand, the behavior of the backward shift of the angular structure is somewhat difficult to account for without such a mechanism. One other possible means of accounting for this backward shift would be either an increasing nuclear distortion or an interference effect produced by a large nuclear distortion, which just happens to have the observed energy variation. The pickup component of the Owen-Madansky exchange interaction model[14] would be expected to be small in the $C^{12}(t,\alpha)B^{11}$ reactions due to the relatively poor overlap between the triton-proton wave function and the alpha-particle wave function. The contribution of the knockout process, in which the incident triton is assumed first to collide with an alpha particle in the target nucleus, may be far more important in this reaction.

The validity of the above interpretation depends strongly upon the usefulness of Wildermuth's cluster model expansion[21] of the wave functions of the nuclei involved in the reaction and on Phillips'[12] concept of cluster interactions. From this point of view both the heavy-particle stripping and the knockout processes are "cluster exchange interactions."[13] In general a "cluster exchange interaction" is one in which the outgoing particle is one of the clusters in the dominant cluster configuration of the target nucleus, and the incoming particle simply replaces this cluster in forming the residual nucleus. The exact nature of the replace-

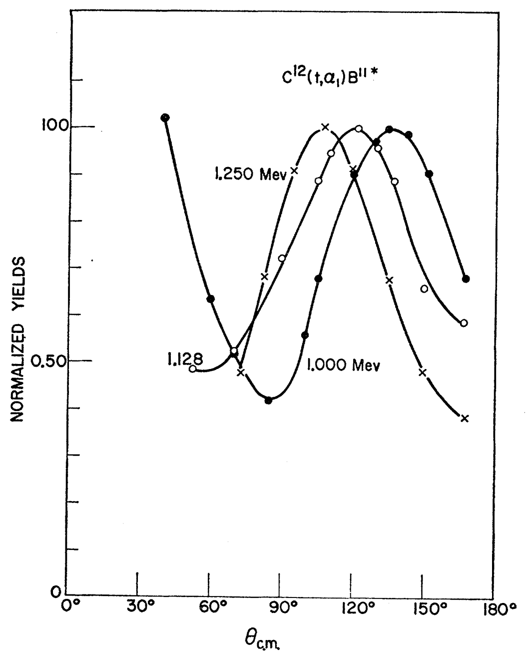

FIG. 12. Angular distributions for the first-excited-state alpha-particle groups from the $C^{12}(t,\alpha)B^{11}$ reaction in the region of the 1.13-Mev resonance. All angular distributions have been normalized to the same peak height.

[13] H. D. Holmgren and E. A. Wolicki, paper submitted to the Rutherford Jubilee International Conference 1961 (unpublished) and unpublished lecture notes 1961.

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

[15] H. C. Newns, Proc. Phys. Soc. (London) **76**, 489 (1960).

[16] M. el Nadi, Proc. Phys. Soc. (London) **70**, 62 (1957); Phys. Rev. **119**, 242 (1960).

[17] W. Tobocman (private communication).

[18] I. Manning and A. H. Aitken, NRL Quar. on Nuclear Sci. and Tech., January 1961, p. 21.

[19] W. Tobocman, Phys. Rev. **115**, 98 (1959).

[20] L. Rodberg, T. B. Day, G. A. Snow, and J. Sucher (to be published).

[21] K. Wildermuth and T. Kanellopoulos, Nuclear Phys. **7**, 150 (1958); R. K. Sheline and K. Wildermuth, Nuclear Phys. **21**, 196 (1960).

ment mechanism will depend upon both the target and residual nuclei, as well as the bombarding energy.

In terms of the cluster model of nuclear structure, the dominant cluster configuration of C^{12} maybe $\{Be^8+\alpha\}$ and that of B^{11}, $\{Be^8+t\}$; thus, the "cluster exchange interaction" can proceed by simply replacing the alpha-particle cluster in C^{12} with a triton cluster. The large total cross section for this reaction may be indicative of the stability of the cluster configurations during a nuclear reaction. A similar large total cross section noted by Bromley *et al.*[22] for the $C^{12}(He^3,\alpha)C^{11}$ reaction may be amenable to the same type of "cluster exchange interaction" interpretation. Also, studies by Gooding and Igo[23] of the $C^{12}(\alpha,2\alpha)Be^8$ reaction at high energies have indicated an alpha-particle structure of C^{12}.

The comparison of the present results with those for the $C^{13}(He^3,\alpha)C^{12}$ reaction[2,3] is illuminating. The cluster configurations for the C^{13} could be considered as either $\{(Be^8+n)+\alpha\}$ or as $\{(Be^8+\alpha)+n\}$. In either case, the bombardment with He^3 followed by the emission of an alpha particle could not be considered as a simple interchange of clusters, but would necessarily involve the fusion of $\{He^3+n\}$ to form an alpha-particle cluster, if the final nucleus C^{12} is described as $\{Be^8+\alpha\}$. The observed cross sections for this reaction at 4.5 Mev are almost two orders of magnitude smaller than those for the (t,α) reaction on C^{12} at 2 Mev. This comparison is one of the bases for the development of the "cluster exchange interaction" model, and may indicate the possible usefulness of the cluster model of nuclear structure in interpreting nuclear reactions. Further experimental comparisons may lead to better insight into the basic mechanism of the interaction; however, a real test of the validity of the "cluster exchange interaction" model must await theoretical calculations based on the model.

[22] D. A. Bromley, E. Almqvist, H. E. Gove, A. E. Litherland, E. B. Paul, and A. J. Ferguson, Phys. Rev. **105**, 957 (1957).

[23] T. J. Gooding and G. Igo, Phys. Rev. Letters **7**, 28 (1961).

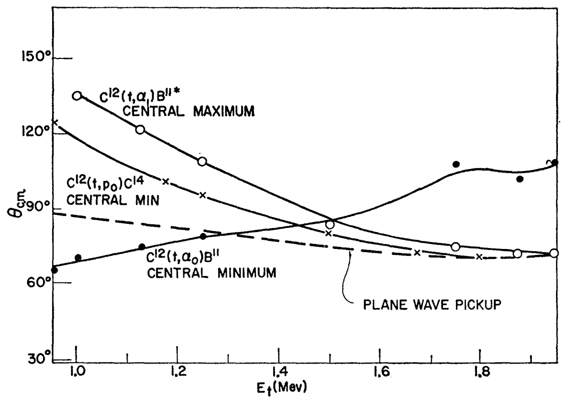

FIG. 13. The positions of characteristic features of the angular distributions from the $C^{12}(t,\alpha)B^{11}$ and $C^{12}(t,p)C^{14}$ reactions as functions of the bombarding energy.

ACKNOWLEDGMENTS

The authors wish to thank Dr. E. A. Wolicki and Dr. J. W. Butler for many helpful suggestions concerning the experimental work and the interpretation of the results.