Nuclear Spectroscopic Studies with High-Energy Boron Ions*†

M. W. SACHS,‡ C. CHASMAN,§ AND D. A. BROMLEY
Yale University, New Haven, Connecticut

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High-energy boron beams have been used in studies of proton and deuteron transfer reactions involving a carbon target. These studies, involving examination of reactions leading to isolated states in the residual nuclei, were undertaken to obtain information on the transfer mechanism at high energies, and to ascertain the extent to which such reactions might serve as probes for certain one- and two-nucleon states in the residual nuclei involved. The proton transfer reactions $C^{12}(B^{11},Be^{10})N^{13}$ and $C^{12}(B^{10},Be^{9})N^{13}$, at bombarding energies of 115.5 and 105 MeV, respectively, are observed to populate only a few levels in N^{13}. The first excited state, which is known to have a large proton width, is not one of these levels. It is suggested that this reflects an angular-momentum mismatch which acts to inhibit the S-wave proton transfer which would populate this state. The deuteron transfer reaction $C^{12}(B^{11},Be^{9})N^{14}$, at 115.5 MeV bombarding energy, is also observed to populate only a few levels in the residual nucleus N^{14}. Arguments are presented favoring direct population of N^{14} levels having $C^{12}+(d_{5/2})^2$ and $C^{12}+(d_{3/2},d_{5/2})$ two-particle configurations. In particular, the observed strongly populated levels at approximately 9- and 13-MeV excitation have been tentatively identified as the $J=5$, $T=0$ and $J=4$, $T=0$ members of the above multiplets, respectively. The existing intermediate-coupling calculations pertaining to N^{14} are in excellent accord with such a description but suggest significant $(p_{1/2}, f_{7/2})$ admixtures in the latter state. The angular distributions of the strong groups in all reactions are smoothly varying, exponential functions of angle. These have been fitted, in terms of a surface-diffuseness parameter, using a simple diffraction model. The diffuseness obtained is in excellent accord with other results in the same mass and energy range. By comparing the present data with those on other reactions involving the same incident systems, qualitative conclusions are drawn regarding fractional parentage in the incident systems. In both single- and two-nucleon situations, the experimental results are compared in detail with corresponding data from He^3- and He^4-induced reactions.

I. INTRODUCTION

THE recent successful use of low-energy heavy ions in nuclear spectroscopic studies[1,2] has suggested the possibility that higher energy heavy ions might also show unique characteristics as probes for nuclear behavior. The present paper reports on a series of studies carried out using the 10.5 MeV/nucleon boron beams from the Yale heavy ion accelerator.

The $C^{12}(B^{11},Be^{10})N^{13}$, $C^{12}(B^{10},Be^{9})N^{13}$, and $C^{12}(B^{11},Be^{9})N^{14}$ reactions, at B^{10} and B^{11} bombarding energies of 105 and 115.5 MeV, respectively, were chosen for initial study; those may be considered, respectively, as proton, proton, and deuteron transfer reactions. Several considerations prompted this choice. The fact that below 14 MeV of excitation (where the first $T=\frac{3}{2}$ states have recently been established[3]), only the ground state of Be^9 is stable against decay by particle emission, and the availability of B^{10} and B^{11} beams made possible the observation of proton and deuteron transfer reactions with no ambiguity as to whether the final-state excitation (below 14 MeV) is to be attributed to the observed particle or the residual nucleus (since all the detected Be^9 nuclei corresponding to excitation below 14 MeV must be in their ground states). A detector and associated data-acquisition system, capable of identifying and measuring the energy of Be^9 (as well as isotopes of heavier elements), had already been developed at this laboratory[4]; the C^{12} target was convenient to produce and handle.

Considerable experimental and theoretical work has already been reported on N^{13} and N^{14}, the residual nuclei in these reactions. In particular, data exist for the reactions $C^{12}(He^3,d)N^{13}$ and $C^{12}(\alpha,d)N^{14}$, at roughly corresponding incident energies, which are particularly relevant since these reactions may also be considered as proton- and deuteron-transfer situations. It was anticipated that comparison of equivalent transfer reactions induced by light and heavy ions would highlight specific aspects of the reaction mechanisms involved. It may be argued, for example, that the (α,d) reactions may proceed via both direct and compound mechanisms; in the (B^{11},Be^{9}) case, particularly in view of the low Be^9 binding energy, it is clear that only a direct mechanism can contribute. Of interest was the work of Harvey and his associates[5] on the "giant excitations" observed in

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‡ Present address: Department of Nuclear Physics, The Weizmann Institute of Science, Rehovoth, Israel.

§ Present address: Physics Department, Brookhaven National Laboratory, Upton, Long Island, New York.

[1] G. C. Morrison, Phys. Rev. Letters **5**, 565 (1960).

[2] D. A. Bromley, A. R. Quinton, L. C. Northcliffe, R. W. Ollerhead, and K. Nagatani, *Proceedings of Rutherford Jubilee International Conference*, edited by J. B. Birks (Heywood and Company, Ltd., London, 1962), p. 597.

[3] T. Lauritsen, B. Lynch, and G. Griffiths, Bull. Am. Phys. Soc. **8**, 597 (1963); G. Griffiths, *ibid.*; W. L. Imhof, L. F. Chase, and D. B. Fossan, *ibid.* **9**, 391 (1964).

[4] C. E. Anderson, D. A. Bromley, and M. Sachs, Nucl. Instr. Methods **13**, 238 (1961); D. A. Bromley, M. W. Sachs, and C. E. Anderson, *Symposium on Nuclear Instruments, Harwell, England*, edited by J. B. Birks (Heywood and Company, Ltd., London, 1962), p. 67.

[5] B. G. Harvey and J. Cerny, Phys. Rev. **120**, 2162 (1960); J. Cerny, B. G. Harvey, R. H. Pehl, Nucl. Phys. **29**, 120 (1962); B. G. Harvey, J. Cerny, R. H. Pehl, and E. Rivet, *ibid.* **39**, 160 (1962); B. G. Harvey, J. Cerny, and R. H. Pehl, Bull. Am. Phys. Soc. **5**, 493 (1960).

the $C^{12}(\alpha,d)N^{14}$ reaction which, these authors have suggested, correspond to population of particularly pure, two-nucleon states at high excitation in N^{14}. While the (α,d) reaction is restricted by isospin considerations to population of $T=0$ states (ignoring for the present isospin contamination and mixing), the (B^{11},Be^{9}) reaction involves no such restriction. It was hoped that the latter reaction might therefore permit identification of $T=1$ members of the two-nucleon configuration multiplets predicted by the intermediate-coupling shell-model calculations.

Since Be^{10} has several excited states which are stable against decay by particle emission, the reaction $C^{12}(B^{11},Be^{10})N^{13}$ presents an inherent ambiguity regarding which of the final nuclei is excited, since several combinations of excitation in the two final nuclei can produce total Q values which are too similar to be resolved by the detector system. As will be demonstrated these ambiguities can be largely resolved, for low residual excitations, by comparison of the Be^{10} energy spectrum with that of Be^{9} from the reaction $C^{12}(B^{10},Be^{9})N^{13}$.

Although extensive experimental and theoretical work has been reported on transfer reactions induced by heavy ions, all such work has involved reactions having high (9 or higher) values of the Sommerfeld parameter, η. A detailed review of work in this field through early 1960 has been published recently.[6] Such reactions, involving low energies or high values of nuclear charge or both, have been quite successfully described by invoking a mechanism in which the heavy nuclei undergo a classical scattering, with only the associated transfer process itself being considered as an effective perturbation and described quantum mechanically.[7] More recently, theories which also describe the scattering of the heavy nuclei quantum mechanically have been successfully applied to the low-energy transfer-reaction data.[8–10]

It has considered of interest to examine reactions involving lower values of η to determine, for example, to what extent such reactions are describable by more conventional direct-interaction or stripping formalisms.[11,12] Since the high incident energy implies that the equivalent classical impact parameters (assuming Coulomb trajectories) are sufficiently small to ensure intimate contact (hence nuclear interaction) of the colliding nuclei, it is not meaningful to discuss these reactions in terms of simple tunneling of the transferred nucleon between the potential wells of the colliding cores.

TABLE I. A listing of possible reactions in the boron-carbon systems. Beryllium-producing transfer reactions induced by high-energy boron-ion bombardment of carbon. In each of the three cases the "forward" and "backward" stripping reaction mechanism is indicated.

(*A*)		$B^{11}+C^{12}\rightarrow Be^{9}+N^{14}$	5.56 MeV
	(1)	$C^{12}+d\rightarrow N^{14}$	
	(2)	$B^{11}+He^{3}\rightarrow N^{14}$	
(*B*)		$B^{11}+C^{12}\rightarrow Be^{10}+N^{13}$	9.296 MeV
	(1)	$C^{12}+p\rightarrow N^{13}$	
	(2)	$B^{11}+2p\rightarrow N^{13}$	
(*C*)		$B^{10}+C^{12}\rightarrow Be^{9}+N^{13}$	4.65 MeV
	(1)	$C^{12}+p\rightarrow N^{13}$	
	(2)	$B^{10}+He^{3}\rightarrow N^{13}$	

One of the major experimental difficulties in heavy-ion reaction studies is the problem of distinguishing between excitations in the two reaction products. For this reason, much work in the past has been done with reactions leading to N^{13} since its excited states are unstable against particle emission (and thus to break-up in times short compared to transit time from target to detector). Furthermore the ground state has a 10-min half-life for positron emission which makes it accessible to standard radiochemical techniques.[13,14]

The first excited state of Be^{9} is at 1.75 MeV, while its threshold for breakup into $Be^{8}+n$ is at 1.665 MeV.[15] Hence Be^{9} shares the above-mentioned advantage of N^{13}.

It should be emphasized that the recent identification of sharp, gamma-emitting $T=\frac{3}{2}$ states in Be^{9} at excitations[3] in excess of 14 MeV does not reduce this advantage in the range of excitations under study although it could certainly reduce the utility of this experimental approach for higher final-state excitations.

States thus far reported are those at 14.392 ± 0.005 MeV as studied in the $Li^{7}(He^{3},p)Be^{9}$ reaction and at 16.980 ± 0.005 MeV as studied in the $Li^{7}(d,\gamma)Be^{9}$ reaction. Since such $T=\frac{3}{2}$ states could only contribute to reactions leading to $T=1$ states in the conjugate nucleus, in N^{14} for example no ambiguity is introduced for total excitations below 16.7 MeV. Since its ground state is stable, Be^{9} is inaccessible to radiochemical methods but provides the possibility of comparison between reactions leading to stable and unstable products. Earlier studies[16] have suggested marked enhancement of the former. Since B^{10} and B^{11} are both available as beam projectiles, reactions involving trans-

[6] A. Zucker, Ann. Rev. Nucl. Sci. **10**, 27 (1960).
[7] G. Breit and M. Ebel, Phys. Rev. **103**, 679 (1956); **104**, 1030 (1956).
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[16] C. Chasman and D. A. Bromley, Bull. Am. Phys. Soc. **7**, 36 (1962); C. E. Anderson, W. J. Knox, A. R. Quinton, and G. R. Bach, Phys. Rev. Letters **3**, 557 (1959).

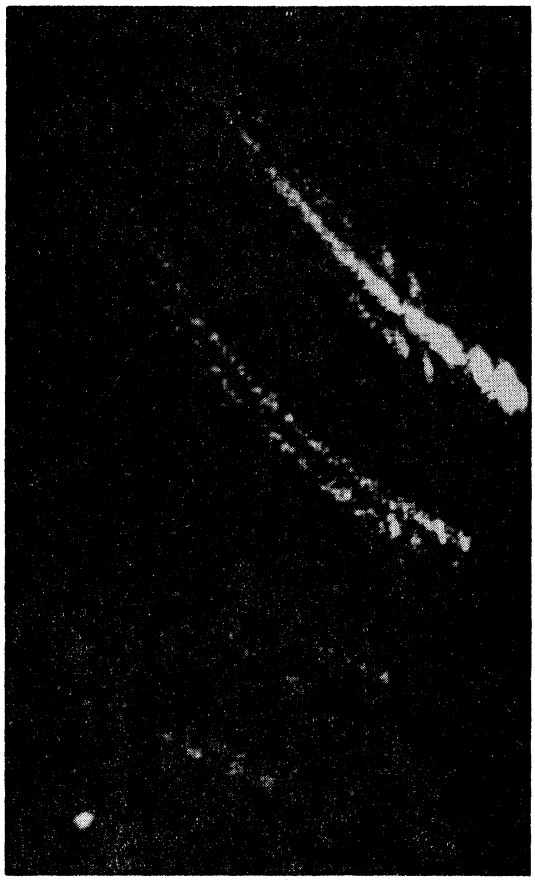

FIG. 1. Direct oscillographic plot of dE/dx against E for the bombardment of carbon by 126-MeV C^{12}.

fer of a proton or deuteron to known final states in the residual nucleus may be studied conveniently through detection of the product Be^9.

The reactions to be discussed herein are listed in Table I. In each case, the energy spectrum of the detected Be^9 or Be^{10} particle shows group structure characteristic of the excitation of particular energy levels in a two-body exit channel. For each reaction listed, the second and third entries in Table I give the two possible direct transfer-reaction mechanisms. The listed, ground state, Q values were calculated from the published mass excesses.[15]

Of the two parallel transfer mechanisms possible for each reaction, the available evidence suggests that the first (as listed in Table I) is dominant, although the low values of η, and thus the above-mentioned intimate collisions, do not permit exclusion of the second possibility on Coulomb-barrier grounds. In studies on the Be^9+N^{14} system at lower energies Bock *et al.*[17] have adduced evidence for significant amplitudes for all four of proton, deuteron, He^3, and alpha transfer reactions. It was found however, that at forward angles the contribution from the so-called heavy-particle stripping reactions[18] was negligible, providing further support for neglect of the equivalent amplitudes in the boron-induced transfer reactions to be considered herein.

II. EXPERIMENTAL METHOD

The basis of the experimental method is the Bethe-Bloch[19,20] expression for the rate of loss of energy of a charged particle traveling through an absorber

$$-\frac{dE}{dx_1}=\frac{4\pi e^4 Z_1^2}{mv^2}\times N_2 Z_2\left[\ln\frac{2mv^2}{I}-\ln(1-\beta^2)-\beta^2\right], \quad (1)$$

where the subscript 1 denotes the moving ion, and 2, the absorber. Z_1 is the ionic charge in units of the electron charge, N_2Z_2 is the electron density of the absorber, v is the velocity of the moving ion, β is the ion velocity in units of that of light, I is an average ionization potential for the absorber, and m is the electron mass. If the numerators and denominators are multiplied by M_1, the mass of the moving ion, and the nonrelativistic limit is taken, the equation becomes

$$\frac{dE_1}{dx_1}=k\frac{M_1Z_1^2}{E_1}\ln\left\{\frac{4(E_1/M_1)}{mI}\right\}, \quad (2)$$

where k includes only physical constants. Since the logarithm varies slowly with energy, in many practical situations it may be considered constant; hence the equation finally becomes

$$E(dE/dx)\cong KMZ^2, \quad (3)$$

where E, M, and Z refer to the moving ion. Since no two nuclides have the same value of MZ^2 (assuming Z to be the atomic number), this product provides an absolute identification of the particle under study, provided that the average charge of the ion during the dE/dx measurement is close to the nuclear charge, as it is at the energies of interest in this work.

The detector and electronic system developed for the present work is capable of identifying and measuring the energy spectra of isotopes of elements at least as heavy as oxygen, and has adequate resolution to study production of isolated low-lying states in the final nuclei. Since this system has already been described in detail,[4,21,22] only a brief summary will be included here.

The dE/dx detector[4] was a special, parallel-plate, gridded ionization chamber, 17.4 mg/cm² (aluminum

[17] R. Bock, H. H. Duhm, G. Hartig, and R. Rudel, Proceedings of the 1964 International Conference on Nuclear Structure, Paris, 1964 (unpublished); R. Bock, R. Rudel, H. H. Duhm, and M. Grosse (private communication), and Nucl. Phys. (to be published).

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[21] M. W. Sachs, doctoral dissertation, Yale University, 1964.

[22] M. W. Sachs, J. P. Allen, J. Poth, R. Ollerhead, C. Chasman, and D. A. Bromley, Nucl. Instr. Methods (to be published).

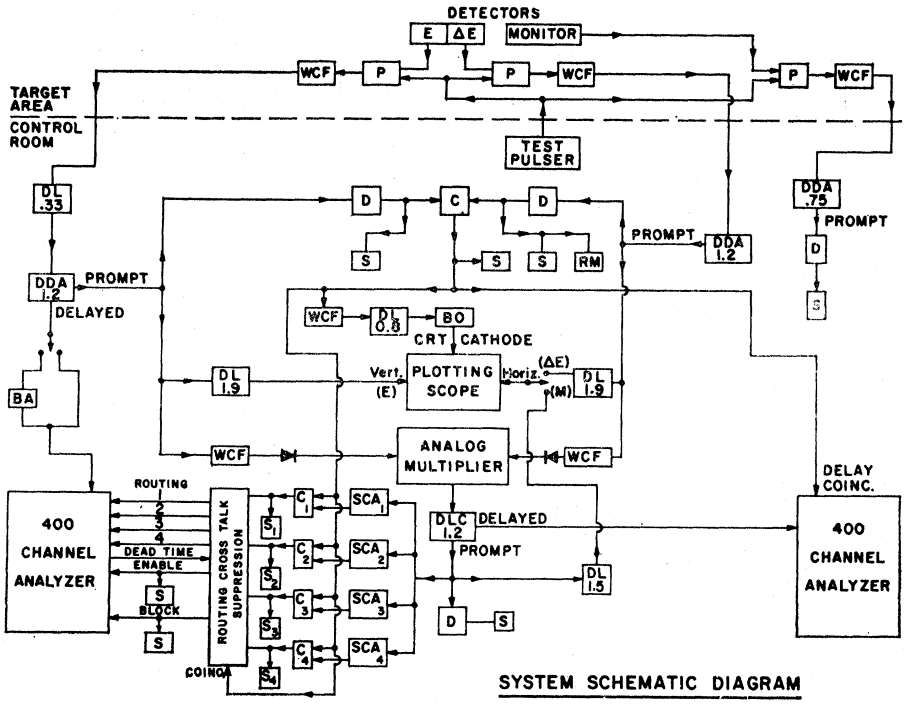

FIG. 2. Block diagram of the electronic system. The symbols are as follows: BA—biased amplifier; BO—blocking oscillator; C—coincidence circuit (6BN6 tube); D—"medium-fast" discriminator; DDA—double delay line clipped amplifier (clipping time shown in microseconds); DL—delay line (delay time shown in microseconds); DLC—single delay line clipped amplifier (clipping time shown in microseconds); P—preamplifier; RM—ratemeter (accelerator operators' counting rate monitor); S–scaler; SCA—single channel analyzer; WCF—White cathode follower.

equivalent) thick, including its 0.00025 in. Mylar entrance and exit windows. The design was selected for its fast output pulse rise time and its high-resolution properties. Its pulse-height output was adequate for all nuclides except the hydrogen isotopes, which have too low specific ionization. For the species and energies of interest in this work, its resolution was typically 3.5% and it typically was adjusted to absorb 10% of the incident energy.

The residual energy (E) detector was an Au-Si surface barrier unit placed directly beyond the ionization chamber. Its measured resolution in use was 600 keV, which largely reflected the energy resolution of the accelerator beam and lesser energy straggling introduced by traversal of the ionization chamber by the reaction products. Its angular resolution was 0.4°.

The performance of the detector system is illustrated in Fig. 1, which is a direct spectrum corresponding to the bombardment of carbon by 126-MeV C^{12}. Each spot represents the passage of a reaction product through the detector system; its coordinates are proportional to dE/dx and E. The figure is a time exposure including 5464 such events. Since Eq. (3) is that of a rectangular hyperbola asymptotic to the E and dE/dx axes, the spots fall along a series of such hyperbolas, whose relative positions are characterized by the approximate values of MZ^2. The prominent hyperbolas are identified as (from top to bottom) C^{13}, C^{12}, C^{11}, B^{11}, B^{10}, Be^9, Be^7, Li^7, and Li^6. The bright spot at the lower left corner is artificially introduced to mark the origin of coordinates.

Energy spectra of individual product species were recorded with a conventional multichannel analyzer gated by identification pulses provided by an analog multiplier, a highly modified version[21,22] of the Los Alamos circuit[23]; the E and dE/dx pulses were multiplied to obtain an output pulse proportional to MZ^2. Electronic correction was made for the fact that the E pulse corresponds to the residual energy after passage through the ionization chamber, rather than the instantaneous energy in Eq. (1).

Initial amplification of the detector signals was by conventional thermionic voltage amplifiers mounted

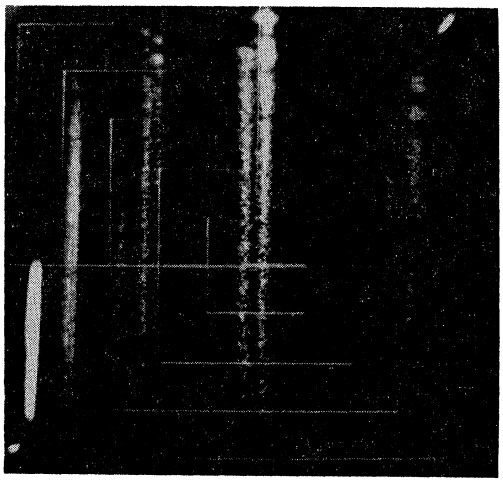

FIG. 3. Direct oscillographic plot of E against the multiplier output for the bombardment of oxygen by 112.9-MeV B^{11}.

[23] R. H. Stokes, Rev. Sci. Instr. **31**, 768 (1960).

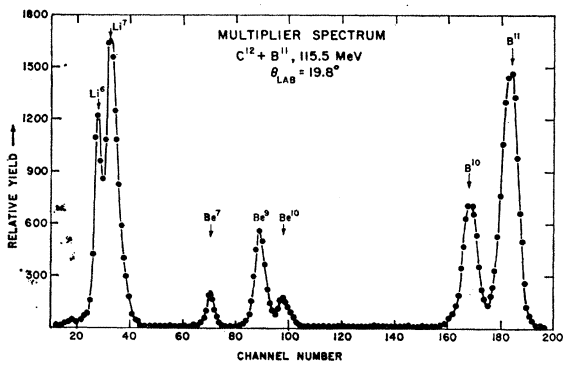

FIG. 4. Multiplier pulse-height spectra for the bombardment of carbon by 115.5-MeV B^{11}.

immediately adjacent to the detectors. Further amplification and pulse height analysis were accomplished by conventional transistorized instrumentation.[24,25] Analysis of an event was accomplished in response to a slow (1 μsec) coincidence between the E and dE/dx signals.

The electronic system is shown in some detail in Fig. 2. As illustrated, the system provides for the simultaneous recording of energy spectra of four different species. The biased amplifier shown in the figure was used to expand the high-energy parts of the energy spectra, and thus to allow more precise determinations of the excitation energies associated with the observed peaks.

The performance of the multiplier is illustrated in Figs. 3, 4, and 5. Figure 3 is an oscillographic plot of E against the multiplier output for the bombardment of oxygen by 115.5 MeV B^{11}. The loci are, from left to right, He^4, Li^6, Li^7, Be^9, Be^{10}, B^{10}, B^{11}, C^{11}, C^{12}, and C^{13}. Good data can be obtained simultaneously on the beryllium, boron, and carbon isotopes in the case shown since these loci are parallel to the E axis as is required if the output of the multiplier is a function of MZ^2 only. Figure 4 is a conventional pulse-height spectrum of the multiplier output made under the same conditions as Fig. 3, except with a carbon target. Figure 5 is a plot of MZ^2 against pulse height, derived from the data in Figs. 3 and 4. The small deviations from linearity are ascribed to the fact that the average ionic charge states during passage through the dE/dx detector are slightly less than the nuclear charge, and lower for the heavier isotopes of a given element than for the lighter isotopes of the same element.[21,22]

The scattering chamber has been described previously,[26] apart from extensive modifications[21] for this work. It had an angular resolution of 1°, and allowed the dE/dx detector telescope to be placed at any angle from 8.5° to 171.5°. Provision was also made for insertion of other detectors, including an elastic scattering monitor counter, at arbitrary angles.

Measurement of cross sections was accomplished by integration of total delivered beam charge, using a Faraday cage and a commercial electrometer circuit, and was checked by means of elastic scattering measurements made with a monitor counter held at a fixed angle.

Cross sections were calculated directly from the measured detector solid angle, target thickness, beam flux, and counting rate (corrected for analyzer dead time). The beam flux was obtained directly from the integrated beam charge, assuming that the ions entering the Faraday cage had the full nuclear charge. This assumption is in agreement with all available data.[27] Experimental studies indicated that electron collection or loss by the Faraday cage used was negligible under the prevailing experimental conditions.

On the basis of the constancy of the monitor counting rate, it was demonstrated that the major uncertainty in the relative differential cross sections is statistical. The absolute values of the cross sections, in contrast, were found to be reproduceable only to within 30% reflecting uncertainties in the determination of effective target thicknesses and integrator constants.

The carbon target used for this work was a 0.21 ± 0.02

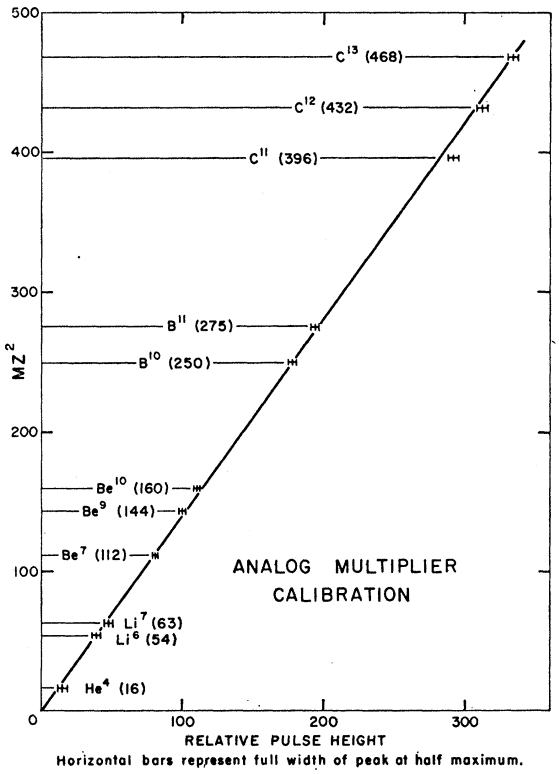

FIG. 5. Multiplier calibration: MZ^2 plotted against multiplier pulse height.

[24] C. E. L. Gingell, IEEE Trans. Nucl. Science, **NS10**, 32 (1963).
[25] R. L. Chase, Rev. Sci. Instr. **31**, 945 (1960).
[26] C. E. Anderson, A. R. Quinton, W. J. Knox, and R. Long, Nucl. Instr. Methods **7**, 1 (1960).
[27] L. C. Northcliffe, Ann. Rev. Nucl. Sci. **13**, 67 (1963).

mg/cm², self-supporting film of natural isotopic carbon, made by vacuum evaporation from a carbon arc. Its thickness was determined by measurement of target weight and area. The major impurities, hydrogen and oxygen, cannot affect the measurement in this work as a consequence of energy and kinematic restrictions.

As part of the study of the reaction $C^{12}(B^{11},Be^{9})N^{14}$, the reaction $O^{16}(B^{11},Be^{9})F^{18}$ was also investigated briefly. For this purpose, a gaseous oxygen target was employed.[28] The stated purity of the gas used was 99.5%. The thickness of the active gas target volume was approximately 0.2 mg/cm² (aluminum equivalent).

The beam energies were 105.0 and 115.5 MeV for B^{10} and B^{11}, respectively. These values were obtained from the calibration of the magnetic-analysis system associated with the accelerator and were in turn used to calibrate the detector pulse height. Energy losses of the reaction products in the ionization chamber were obtained from the available range-energy data[29–31] and the measured aluminum equivalent of the ionization chamber thickness.[21,22]

The differences in the Q values for two groups in the same spectrum are known to an accuracy of 0.2 MeV for most of the data. Although the measurement of the absolute Q values has a larger uncertainty (reflecting 1% and 7% uncertainties in beam energy and ionization chamber thickness, respectively), all groups can be identified with specific energy levels with an accuracy of ±0.2 MeV by normalizing to levels which can be identified within the larger uncertainty.

III. EXPERIMENTAL RESULTS

A. Proton Transfer Reactions

The energy spectrum of Be^{10} from the bombardment of carbon by 115.5-MeV B^{11} ions is shown in Fig. 6.

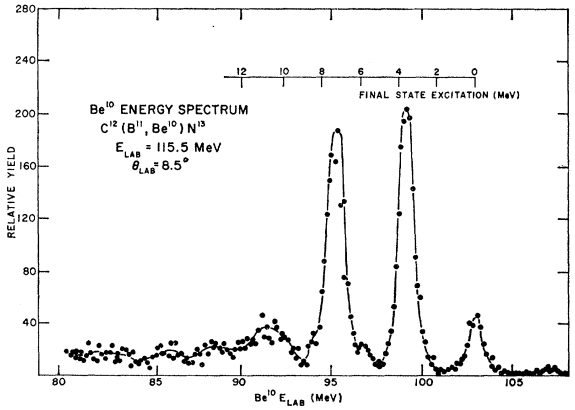

FIG. 6. High-energy part of the energy spectrum of Be^{10} from the bombardment of carbon by 115.5-MeV B^{11}.

[28] P. G. Roll and F. E. Steigert, Nucl. Phys. **29**, 595 (1962).
[29] L. C. Northcliffe, Phys. Rev. **120**, 1744 (1960).
[30] L. C. Northcliffe, calculated range-energy curves interpolated from data in Ref. 29 (private communication).
[31] P. E. Schambra, A. M. Rauth, and L. C. Northcliffe, Phys. Rev. **120**, 1758 (1960).

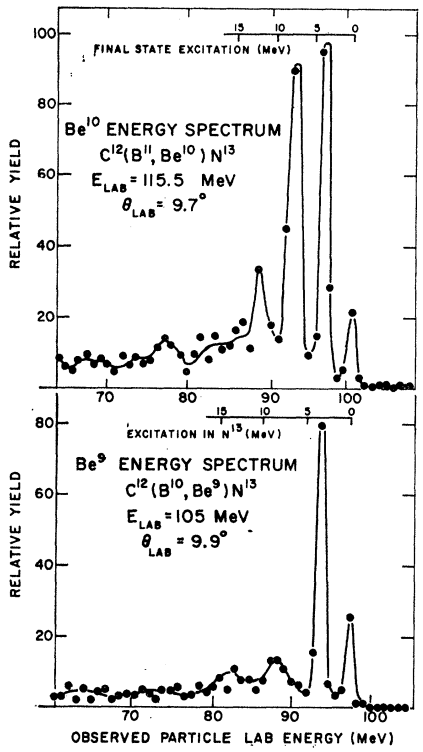

FIG. 7. Energy spectra of Be^{10} and Be^{9} from the reactions $C^{12}(B^{11},Be^{10})N^{13}$ and $C^{12}(B^{10},Be^{9})N^{13}$ plotted on approximately the same scale of final-state excitation.

This spectrum, recorded simultaneously with that of Be^{9} to be discussed subsequently, was obtained with a biased amplifier which expanded the high-energy portion of the entire spectrum. No prominent groups were seen at lower energies (corresponding to higher final system excitations). Within the stated uncertainty, the group at the right (E_{lab} = 103 MeV) can only correspond to both final nuclei being in their ground states. Thus the other groups correspond to excitations of 3.6±0.2 and 7.2±0.2 MeV above the ground state. Because the first four excited states of Be^{10} are stable against decay by nucleon emission, the sharing of this excitation energy between Be^{10} and N^{13} cannot be directly deduced from this spectrum. Arguments will, however, be advanced below for the conclusion that the group corresponding to 3.6 MeV of excitation corresponds mostly to events in which Be^{10} is left in its ground state, and N^{13} in its second or third state (3.51 or 3.56 MeV). Similarly, the group corresponding to 7.2 MeV of excitation corresponds primarily to events in which N^{13} is excited to its second or third excited state, and Be^{10} to its first excited state (3.368 MeV). It should be noted in particular that there is no evidence for a group corresponding to population of the first excited state of N^{13} (2.365 MeV).

One method of determining which N^{13} and Be^{10} levels are excited involves comparing the data on $C^{12}(B^{11},Be^{10})N^{13}$ with data on a reaction, with an

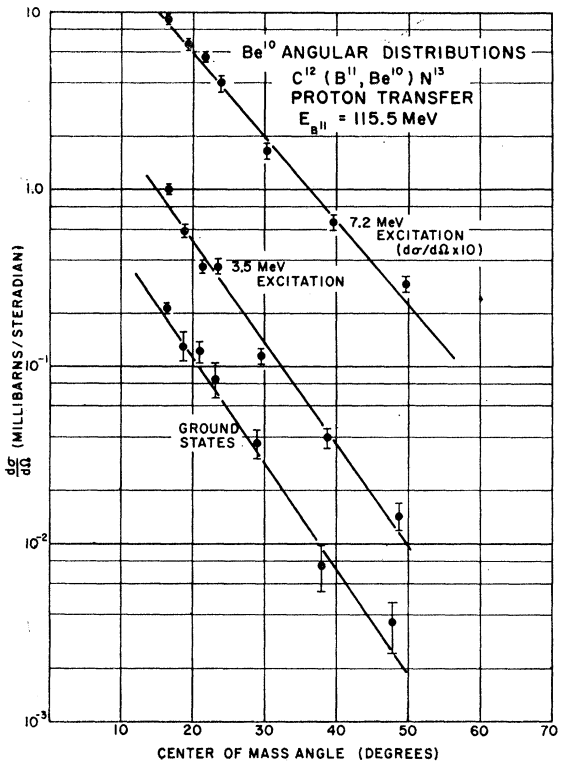

FIG. 8. Angular distributions of the Be^{10} groups from the reaction $C^{12}(B^{11},Be^{10})N^{13}$.

assumed equivalent mechanism, leading to either N^{13} or Be^{10}, in which the final states produced can be identified without ambiguity. Such is the reaction $C^{12}(Be^{10},Be^{9})N^{13}$, at 105-MeV bombarding energy. It is reasonable, in view of the Be^{9} characteristics already discussed, to assume that this reaction will populate the same levels in N^{13} as the reaction $C^{12}(B^{11},Be^{10})N^{13}$ at 115.5-MeV bombarding energy, since both are assumed to be dominated by the transfer interaction $C^{12}+p \rightarrow N^{13}$.

To facilitate comparison of the $C^{12}(B^{11},Be^{10})N^{13}$ and $C^{12}(B^{10},Be^{9})N^{13}$ reactions, the respective Be^{10} and Be^{9} energy spectra were taken at approximately the same center of mass angle, and are shown in Fig. 7, plotted on approximately the same scale of final state excitation.

The relative intensities of the ground state and 3.5 MeV excitation groups in the two spectra implies that the 3.5 MeV group in the Be^{10} spectrum corresponds to events having Be^{10} in its ground state and N^{13} in one of the two states at 3.5 MeV.

The fact that there is a strong group at 7.2 MeV in the Be^{10} spectrum and only a very weak one in the Be^{9} spectrum indicates that a level near 7.2 MeV in N^{13} does not contribute strongly. Since Be^{10}, excited to levels above 6.812 MeV (the neutron threshold) would decay by neutron emission before reaching the detector, the only remaining possibility is a mutual excitation of both Be^{10} and N^{13} to levels having a total excitation of 7.2 MeV. The only possible combination is that of the 3.368 MeV first excited state in Be^{10}, together with one or both of the two levels in the vicinity of 3.5 MeV in N^{13}.

Angular distributions have been measured for the two ground-state groups and three excited-state groups in the two proton-transfer reactions. The results, transformed to the center of mass system, are shown in Figs. 8 and 9. The most striking features of these angular distributions are their close similarity of shape and the lack of any strong oscillatory character. Within the accuracy of the measurements, all are exponential in character. Furthermore, within the accuracy of the measurements, the slopes on these semilogarithmic plots are identical, except for the 7.2 MeV excitation group from $C^{12}(B^{11},Be^{10})N^{13}$, which is slightly less steep. The close similarity of the slopes of the angular distribution on plots for all groups in both reactions lends additional support to the hypothesis that the same mechanism is responsible for both.

B. Deuteron Transfer Reactions

The high-energy portion of the energy spectrum of Be^{9} from the reaction $C^{12}(B^{11},Be^{9})N^{14}$ is shown in Fig. 10. No prominent groups were observed at lower kinetic energy (higher final state excitation) than shown here.

Since, as has already been stated, all the detected Be^{9}

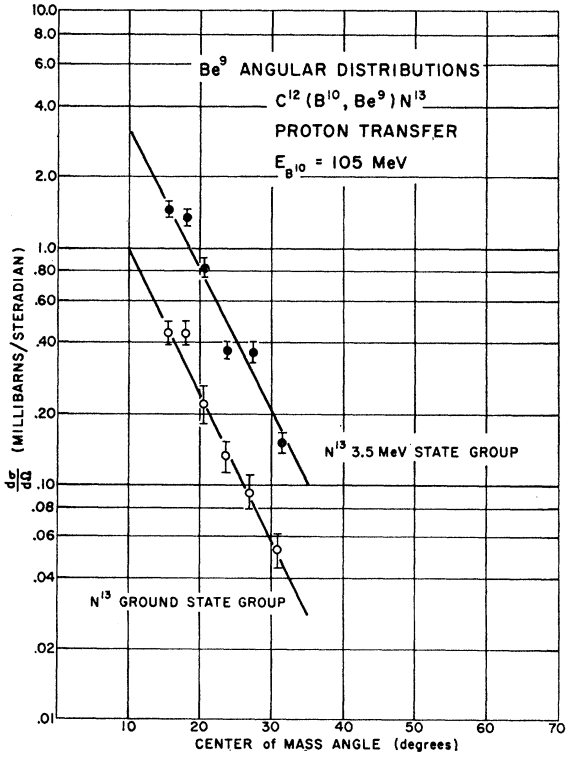

FIG. 9. Angular distributions of the Be^{9} group from the reaction $C^{12}(B^{10},Be^{9})N^{13}$.

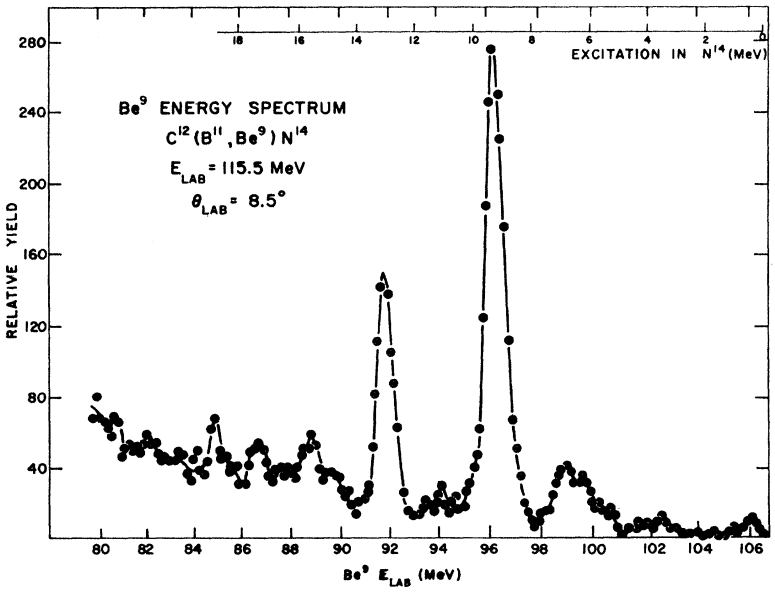

FIG. 10. High-energy part of the energy spectrum of Be^9 from the bombardment of carbon by 115.5-MeV B^{11}.

nuclei, below 14 MeV of excitation, were formed in their ground states, the groups correspond to specific levels in N^{14}, and a scale of excitation in N^{14} has been included in the figure. Since this spectrum was recorded simultaneously with that of Be^{10} (Fig. 6), in which one of the groups can be identified unambiguously with the ground-state transition of $C^{12}(B^{11},Be^{10})N^{13}$, the Be^9 groups can be identified with specific levels in N^{14} with an accuracy comparable to that from the Be^{10} spectrum. The dominant feature in this spectrum is a strong group, corresponding to $\sim$9.0 MeV of excitation in N^{14}. Another group, approximately one-half as intense, is also observed, corresponding to a level at $\sim$13 MeV. Since the level spacing in this excitation region is smaller than the width, and uncertainty in position, of these peaks, they cannot be conclusively identified with particular levels although, as will be discussed later, the group at 9 MeV of excitation undoubtedly corresponds to the same level as the intense deuteron group observed in the $C^{12}(\alpha,d)N^{14}$ reaction.[5]

The structure extending from 5 to 8 MeV of excitation is significantly wider than the resolution of the system, and can include contributions from any of at least 12 known levels. There are also suggestions of groups corresponding to excitations 15.7, 17.4, and 19.0 MeV.

No other strong excitations are visible, although there is no *a priori* reason for not expecting them. There is almost complete absence of groups corresponding to the ground and first two excited states (2.312 and 3.945 MeV) of N^{14}; furthermore, there is little evidence of excitation of levels between 9 and 13 MeV. While it is tempting to assign the small peak at $E_{lab}=106$ MeV to the ground state, such an assignment would be inconsistent with the position of both the ground state in the accompanying Be^{10} spectrum and the locations of other low-lying levels in N^{14}; its intensity is not inconsistent with its resulting from a contaminant reaction.

Angular distributions for the two intense groups ("giant excitations") have been measured, and are shown, transformed to the center of mass system, in

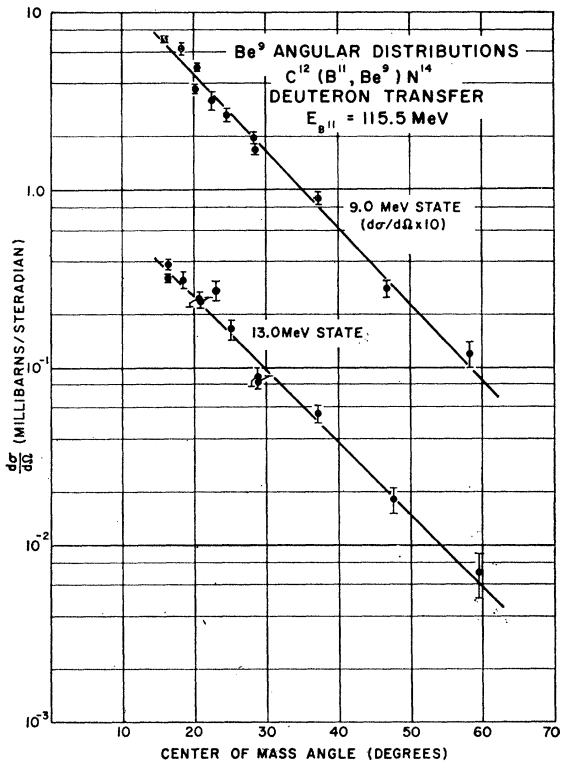

FIG. 11. Angular distributions of the Be^9 groups from the reaction $C^{12}(B^{11},Be^9)N^{14}$.

TABLE II. Summary of the cross-section data obtained in boron-ion bombardment of carbon.

Reaction	$C^{12}(B^{11},Be^{9})N^{14}$		$C^{12}(B^{10},Be^{9})N^{13}$		$C^{12}(B^{11},Be^{10})N^{13}$		
Transferred particle	Deuteron		Proton		Proton		
Final-state excitation	9 MeV in N^{14}	13 MeV in N^{14}	Ground states	3.5 MeV in N^{13}	Ground states	3.5 MeV	7.2 MeV
σ_G, geometric cross section[a]	1330 mb	1330 mb	1290 mb	1290 mb	1290 mb	1290 mb	1290 mb
σ_T, total cross section[b]	0.67 mb	0.33 mb	0.33 mb	1.3 mb	0.20 mb	0.78 mb	0.94 mb
α[b]	0.099	0.099	0.139	0.139	0.139	0.139	0.107
σ_T/σ_G	5.0×10^{-4}	2.5×10^{-4}	2.6×10^{-4}	1.0×10^{-3}	1.6×10^{-4}	6.0×10^{-4}	7.3×10^{-4}
Incident energy (c.m. system)	60.3 MeV	60.3 MeV	57.3 MeV	57.3 MeV	60.3 MeV	60.3 MeV	60.3 MeV

[a] $\sigma_G=\pi r_0^2(A_1^{1/3}+A_2^{1/3})^2$ cm², with $r_0=1.45\times10^{-13}$ cm.
[b] Differential cross sections taken as $d\sigma/d\Omega=\sigma_0 e^{-\alpha\theta}$; the value of α is given for center-of-mass angles in degrees.

Fig. 11. Like those of the proton transfer reactions, these angular distributions show no oscillatory character. Within the accuracy of the measurement, both have the same shape, an exponential fall off with an increasing angle. The slopes are the same within the accuracy of the measurements, and are not as steep as those of the proton transfer reactions.

C. Summary of Cross-Section Data

The data on cross sections for the reactions studied are summarized in Table II, together with the incident energy and geometric cross section. The radius parameter r_0 was taken as 1.45 F, in accordance with the data on elastic scattering of protons by C^{12}.[32]

For purposes of consistently estimating total cross sections, an exponential dependence was fitted to the angular distribution data. This is given by

$$d\sigma/d\Omega=\sigma_0 e^{-\alpha\theta} \quad (4)$$

with the tabulated values of α given for θ in degrees (center of mass system). The total cross sections, also also given in Table II, were then obtained analytically by integrating this function from 0 to 180 deg. Although this extrapolation cannot be entirely justified on the basis of the data presented here, it can be readily shown that unless a sharp rise occurs at larger angles, no significant error is introduced in the total cross section; survey experiments at large angle have shown no evidence for any such increase and the counting rates were so low that collection of differential-cross-section data with any statistical accuracy was precluded. In any case, the cross sections calculated in this way are good measures of the "forward-stripping" process (alternatives 1 in Table I) whereas any significant cross section at backward angles is to be attributed to the "heavy-particle stripping" processes (alternatives 2 in Table I), as demonstrated by the results of Bock *et al.*[17] As previously noted, the value of α is substantially the same for all the proton-transfer reactions, and greater for the proton transfers than for the deuteron transfers, both of which again have the same value of α.

All the incident geometric cross sections are approximately 1300 mb whereas the total cross sections determined for the various groups range between 0.20 and 1.3 mb. The fact that the total cross sections are such small fractions of the geometric cross section is in part indicative of the large number of open exit channels in these high-energy heavy-ion reactions. This fact is seen quite vividly in Fig. 3, which shows eleven different nuclides from He^4 to C^{13}, produced in the bombardment of O^{16} by B^{11}, and does not include the heavier and lighter fragments produced, nor does it include the energy below the cutoff energy of the dE/dx detector.

IV. DISCUSSION

A. Proton-Transfer Energy Spectra

Since the characteristics of the reactions $C^{12}(B^{11},Be^{10})N^{13}$ and $C^{12}(B^{10},Be^{9})N^{13}$ are identical, except for the additional presence in the former of a group corresponding to the mutual excitation of the Be^{10} first excited state (3.368 MeV) and one of the N^{13} states at 3.5 MeV, many of the remarks below will apply in general to both reactions.

It was earlier hoped that the relative populations of the levels excited in these reactions would provide a measure of the relative reduced widths for the transferred particle in these levels. If so, it would be expected that on the basis of the available reduced width information[33] the first excited state of N^{13}, which has a proton reduced width of 0.54 relative to the Wigner limit, would be quite strongly excited. No such excitation was found.

Inhibition of the reaction populating this state has also been observed by Wegner and Hall[34] in studies of the $C^{12}(He^3,d)N^{13}$ reaction carried out at comparable

[32] C. W. Reich, G. C. Phillips, and J. L. Russell, Jr., Phys. Rev. **104**, 143 (1956).

[33] G. C. Phillips and T. A. Tombrello, Nucl. Phys. **19**, 555 (1960).

[34] H. E. Wegner and W. S. Hall, Phys. Rev. **119**, 1654 (1960).

energies per nucleon in the entrance channel. Figure 12 compares the spectra from the (B^{10},Be^9) and (He^3,d) reactions. Wegner and Hall[34] also report that no significant population of higher states in N^{13}, corresponding to deuteron groups of lower energy, was observed in agreement with the Be^9 spectrum shown.

The general similarity of these spectra indeed suggests that direct proton transfer represents the dominant mechanism. In each case the one or both members of the doublet[15] at 3.5 MeV in N^{13} receives strong population and Wegner and Hall[34] have presented evidence suggesting that the transferred angular momentum is predominantly 2^+ corresponding to population of the $\frac{5}{2}^+$ (3.56 MeV) state. The only apparent difference between these spectra is the appearance of a deuteron group leading to the $\frac{1}{2}^+$ first excited state via an S wave proton transfer.

The appearance of such a group and the absence of a corresponding one in the Be^9 spectrum suggests that the latter inhibition may be explained on angular momentum grounds analogous to those advanced by Pehl[35] to explain similar phenomena in the (d,α) reaction. On the basis of an extremely simplified classical model it follows that for a pure surface reaction the angular momentum transferred to the target core is given by

$$\mathbf{L}=\mathbf{L}_{\text{inc}}-\mathbf{L}_{\text{out}}, \tag{5}$$

where

$$\mathbf{L}_{\text{inc}}\cong\mathbf{k}_{\text{inc}}\times\mathbf{R}; \quad \mathbf{L}_{\text{out}}\cong\mathbf{k}_{\text{out}}\times\mathbf{R}. \tag{6}$$

In situations where the reaction Q is such that $|\mathbf{k}_{\text{inc}}|$ and $|\mathbf{k}_{\text{out}}|$ are quite different, the lowest L permitted is significantly larger than the l_p value appropriate to the shell-model configuration of the transferred proton in the residual state. This extreme model has been placed in a much more realistic basis through detailed consideration of the form of the direct transition matrix elements. Greider[36] has recently demonstrated that such an approach reproduces the inhibition suggested by the simple model and for purposes of the present discussion the latter will suffice.

Table III lists the appropriate quantities for the (B^{11},Be^{10}) and (He^3,d) reactions. Although only the ground-state Q is shown, the values of $|\mathbf{L}_{\text{out}}|$ change by much less than an integer over the excitation range of interest, and so the values of $|\mathbf{L}_{\text{min}}|$ are the same for all these final states. For the first four excited states, the transition l values are $l_p=1$, 0, 1, and 2, respectively. For the (He^3,d) reaction, the intensities of the various groups vary inversely with the difference $|\mathbf{L}_{\text{min}}|-l_p$, the strongest excitation being the third excited state ($l_p=2$), and the weakest being the first excited state. In the (B^{11},Be^{10}) reaction the same order of intensities occurs, except that the differences are even greater, which agrees with the larger value of $|\mathbf{L}_{\text{min}}|$, hence the greater mismatch in the angular momenta. The intensity of the first excited state, if present at all, is sufficiently low to be completely obscured by the tail of the pulse-height distribution from the second and third states.

TABLE III. Angular-momentum listing for single-proton-transfer reactions leading to N^{13}.

Reaction	E_{inc} (MeV)	Q_0 (MeV)	$\lvert\mathbf{L}_{\text{inc}}\rvert$	$\lvert\mathbf{L}_{\text{out}}\rvert$	$\lvert\mathbf{L}_{\text{min}}\rvert$
$C^{12}(B^{11},Be^{10})N^{13}$	115	−9.3	28	25	3
$C^{12}(He^3,d)N^{13}$	25	−3.6	8	6	2

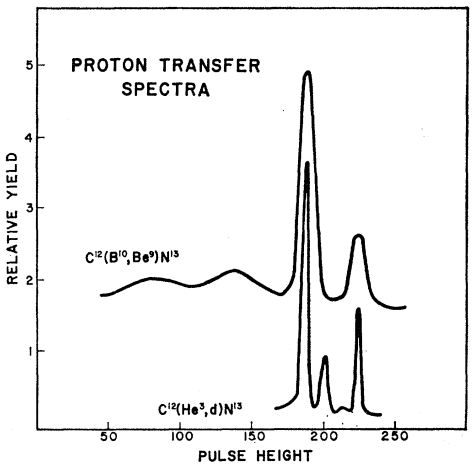

FIG. 12. Comparison of the proton-transfer spectra from the $C^{12}(B^{10},Be^9)N^{13}$ and $C^{12}(He^3,d)N^{13}$ reactions at 105 and 21.6 MeV, respectively. It has been shown that neither spectrum changes significantly with incident energy over many megaelectron volts. Although not published, it is reported that no strong excitations are observed at lower pulse heights in the $C^{12}(He^3,d)N^{13}$ reaction.

Based on the above interpretation, it is expected that the relative contribution of the second excited state ($l_p=1$) to the $E_{\text{exc}}=3.5$-MeV group in the (B^{11},Be^{10}) reaction is even less than in the (He^3,d) reaction, being more strongly suppressed by the angular-momentum mismatch.

It is interesting to note that neither reaction shows population of states with parentage other than C^{12}(g.s.)+p and in particular that none of the states with parentage $C^{12*}(4.43)+p$, (3.51, 6.38, 6.91, and 7.42 MeV), are populated.

The conclusion would appear to be that the existence of a large proton reduced width is a necessary, but not sufficient, condition for a large proton transfer cross section. It is clear that before any more detailed conclusions can be drawn, detailed calculations of the cross sections for production of all these levels, including all the relevant factors, must be carried out.

B. Deuteron Transfer Energy Spectrum

Figure 13 presents the energy spectrum from the $C^{12}(B^{11},Be^9)N^{14}$ reaction together with those from the

[35] R. H. Pehl, doctoral dissertation, University of California Lawrence Radiation Laboratory Report UCRL 10993, 1963 (unpublished).

[36] K. R. Greider (private communication; to be published).

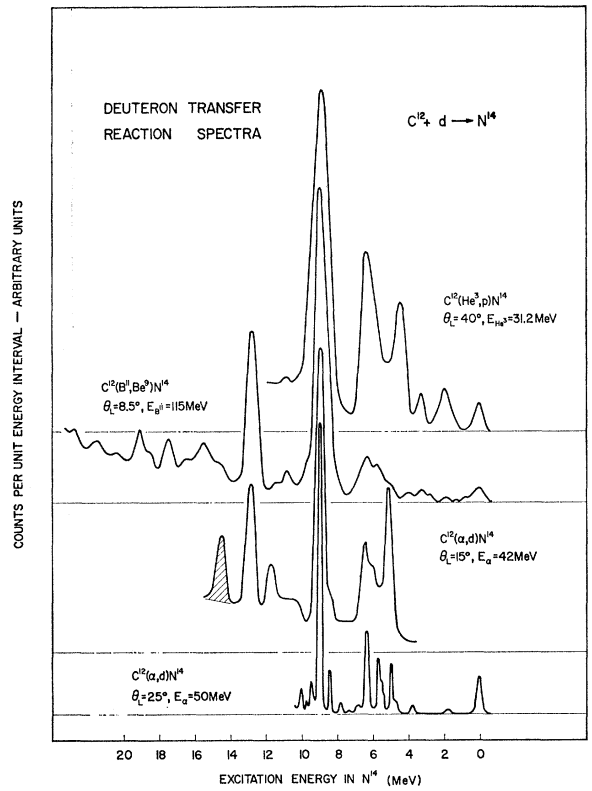

FIG. 13. Comparison of the deuteron-transfer spectra leading to formation of N^{14}. Only in the lower spectra is the experimental resolution adequate to resolve individual states. The (He^3,p) data show characteristic population of the 2.31 MeV, 0^+, $T=1$ first excited state of N^{14} which is not inhibited by T selection rules as in the (α,d) reaction. The weak population of this state evident in the lower spectrum presumably reflects T mixing in the F^{18} compound states involved.

$C^{12}(\alpha,d)N^{14}$ and $C^{12}(He^3,p)N^{14}$ reactions[5,37] studied at incident energies of 115.5, 50, and 31 MeV, respectively (i.e., under approximately equal conditions of energy per nucleon). These spectra have been converted to a common abscissa for presentation here. Also shown is a more recent measurement of the (α,d) spectrum[38] carried to higher residual excitation in N^{14}.

The striking feature of all these spectra in the "giant excitation" corresponding to $\sim$9 MeV of excitation in N^{14} and the lesser excitation corresponding to $\sim$13 MeV. The general similarity of all these spectra provides striking evidence for a common direct mechanism where in a neutron-proton pair carrying some 20 MeV of energy in the laboratory system is capture by the C^{12} target core.

Since the binding energy of the last neutron is anomalously low in both "carrier nuclei" [Be^9 and d in the (B^{11},Be^9) and (α,d) reactions, respectively], being 1.665 MeV for Be^9, and 2.225 MeV for the deuteron,[39] it might be anticipated that the probability of Be^9 or a deuteron emerging from a projectile-target collision involving significant interaction is extremely small, i.e., that the yield of reactions involving a knockout mechanism is negligible.

In analogy with the arguments presented in the case of single nucleon transfer situations just considered, it is probable that angular-momentum considerations also play an important role in these two nucleon transfer reactions. For convenience herein, the two transferred nucleons will be labeled as a "deuteron"; this does not imply that the two-nucleon wave function is identical to that of a free deuteron nor does it necessarily imply a $T=0$ configuration of the nucleon pair.

At the incident energies involved in these reactions, of some 10 MeV/nucleon, it may readily be shown that each nucleon delivers roughly two units of angular momentum to the target surface so that preferential capture of d wave nucleons might be anticipated. Such capture would thus favor population of N^{14} states having configurations given by $C^{12}{}_{g.s.}+d^2$. From known spin-orbit strengths in the sd shell (i.e., 5.08-MeV splitting in O^{17}) it would be anticipated that the $(d_{5/2})^2$, $(d_{3/2},d_{5/2})$ and $(d_{3/2})^2$ configurations would occur at roughly 5 MeV intervals with increasing excitation and further that residual interactions would remove the energy degeneracy characterizing the members of the J multiplet obtained from each of these configurations by recoupling the available angular momentum.

Such arguments were originally advanced by Harvey *et al.*[5] to explain their observation of "giant excitations" in the (α,d) reactions. They further noted that certain J values in these multiplets would be favored since it might be anticipated that the capture nucleons with parallel angular momentum favoring states with $L=l_p+l_n=4$.

Table IV presents a decomposition of these three j-j configurations into the J multiplets, the corresponding L, S representation of each,[40] the isotopic spin required by symmetry considerations, and the excitation energies calculated by True[41,42] utilizing a realistic intermediate coupling shell-model calculation. In these cases, the True wave function selected for inclusion is that having its dominant j-j component listed and no attempt has been made to take account of the weaker components in the j-j representations.

Glendenning[43,44] has carried out a detailed study of the

[37] We are indebted to Dr. E. Rivet of the Lawrence Radiation Laboratory, Berkeley, for these unpublished spectra from the $C^{12}(He^3,p)N^{14}$ reaction.

[38] K. Nagatani and D. A. Bromley, Bull. Am. Phys. Soc. (to be published); Proceedings of Symposium on Direct Interactions (an American Physical Society Topical Conference), Chicago, March, 1964 (unpublished).

[39] V. A. Kravtsov, Usp. Fiz. Nauk **78**, 65 (1962) [English transl.: Soviet Phys.—Usp. **5**, 761 (1963)].

[40] J. M. Kennedy and M. J. Cliff, Chalk River Report CRT-609, 1955 (unpublished).

[41] W. W. True, Phys. Rev. **130**, 1530 (1963).

[42] W. W. True (private communication 1964); (to be published).

[43] N. K. Glendenning, Symposium on Nuclear Spectroscopy with Direct Reactions, edited by F. E. Throw, Argonne National Laboratory Report ANL-6848, 1964 (unpublished), p. 188.

[44] N. K. Glendenning, University of California, Lawrence Radiation Laboratory Report UCRL-11353, 21 May 1962; Phys. Rev. (to be published).

TABLE IV. *LS* representations of $(d)^2jj$ configurations.[a] Decomposition of pure two-particle d^2 configurations in N^{14} into corresponding *LS* coupling representations. The isobaric spin *T* and excitation energies of the levels predicted by True with these dominant configurations are included for comparison.

Configuration	*J*	*LS* representation	*T*	$E_x(N^{14})$[b]	
				(*a*)[c]	(*b*)[c]
$(d_{5/2})^2$	5	1.00^3G	0	9.32	8.54
	4	$0.447^1G+0.894^3F$	1	12.33	11.66
	3	$-0.151^3G+0.600^1F+0.786^3D$	0	11.60	10.98
	2	$-0.268^3F+0.693^1D+0.669^3P$	1	12.31	12.03
	1	$-0.400^3D+0.748^1P+0.526^3S$	0	9.92	9.27
	0	$-0.632^3P+0.775^1S$	1	10.93	10.44
$(d_{5/2},d_{3/2})$	4	$0.632^1G+0.707^3G-0.316^3F$	0	13.82	10.83
			1	15.95	16.70
	3	$-0.278^3G+0.707^3F+0.490^1F-0.428^3D$	0	15.76	15.90
			1	17.55	17.41
	2	$-0.358^3F+0.707^3D+0.346^1D-0.502^3P$	0	14.28	13.92
			1	17.22	17.02
	1	$-0.374^3D+0.707^3P+0.200^1P-0.566^3S$	0	14.75	14.37
			1	17.55	17.41
$(d_{3/2})^2$	3	$0.907^3G+0.400^1F-0.313^3D$	0	19.46	19.02
	2	$0.820^3F+0.529^1D-0.219^3P$	1	21.65	21.43
	1	$0.748^3D+0.600^1P-0.283^3S$	0	20.57	20.10
	0	$-0.632^3P+0.632^1S$	1	20.86	20.42

[a] From J. M. Kennedy and M. J. Cliff, Chalk River Report, CRT-609, 1955 (unpublished).
[b] From W. W. True, Phys. Rev. 130, 1530 (1963) and private communication.
[c] Column (*a*) including only $s_{1/2}$, $d_{5/2}$, and $d_{3/2}$ configurations. Column (*b*) including, in addition, $p_{1/2}$ and $f_{7/2}$ configurations.

two-nucleon transfer reaction in the $C^{12}(\alpha,d)N^{14}$ case and utilizing the True wave functions[41,42] for N^{14} and the known alpha-particle and deuteron wave functions has demonstrated that these simple arguments have considerable validity, namely, that both parentage and angular-momentum considerations must be satisfied simultaneously. Lacking, as yet, any adequate wave functions for either B^{11}, or Be^9, it is not possible to apply Glendenning's calculations directly to the heavy ion reactions and so only qualitative conclusions may be drawn.

The two columns listed under excitation energy from the True calculations correspond to calculations ignoring[41] and including[42] $f_{7/2}$ configurations, respectively. Since the single particle $f_{7/2}$ states in N^{13} and C^{13} have not been identified with certainty, the latter energy scale may require significant revision; the tabulated values are those corresponding to the assumption that the 11.92- and 10.36-MeV levels in N^{13} and C^{13} are the single-particle states in question.[45]

Inspection of Table IV shows that the $J=5$ member of the $(d_{5/2})^2$ multiplet with pure $L=4$ character, is predicted to have an excitation of $\sim$9.0 MeV, in gratifying accord with the observed giant excitation. When these measurements were reported in preliminary fashion,[46] no (α,d) data were available corresponding to excitations in excess of $\sim$9 MeV and in consequence it was suggested that the "giant excitation" at $\sim$13 MeV might correspond to the $J=4$, $T=1$ member of this same multiplet, at a predicted excitation of 12.33 MeV. Such an assignment is precluded by the subsequent observation of this same excitation in the (α,d) reaction[38] leading to the suggestion that this strong group may correspond to population of a 4^+, $T=0$ level having a dominant $(d_{3/2},d_{5/2})$ configuration as indicated in this energy region.[47] The True[41,42] calculations predict that such a state should be one member of a strongly mixed $J=4$, $T=0$ pair of states with mixed $(d_{3/2},d_{5/2})$ and $(p_{1/2},f_{7/2})$ parentage.

Examination of the 42 MeV (α,d) data[38] of Fig. 13 shows a further strong excitation corresponding to an excitation of $\sim$15 MeV in N^{14}. Examination of the True calculations suggests that this might correspond to the negative parity, $J=6$, $T=0$ state of $(d_{5/2},f_{7/2})$ parentage predicted at $\sim$14 MeV since this state would have a dominant $L=5$ component in its *LS* wave function minimizing any angular-momentum mismatch.

Further peaks are observed in the (B^{11},Be^9) spectrum corresponding to excitations $\sim$19 MeV. While the $T=\frac{3}{2}$ state in Be^9 may contribute to these, the fact that they also appear in the (α,d) reaction (to which the $T=\frac{3}{2}$ state cannot contribute) makes this unlikely.

As indicated in Table IV, it would be possible to identify one of these with the 3^+, $T=0$ state of dominant $(d_{3/2})^2$ parentage. However, additional states having 3^-, 4^-, and 5^-, $T=0$ character with dominant $(d_{5/2},f_{7/2})$ parentage are also predicted in this energy region[42] and currently available information does not permit identification of these states.

The True calculations indicate that the $(f_{7/2})^2$ mul-

[45] We are indebted to Professor True for making these latter calculations, including the $f_{7/2}$ configurations, available to us prior to their publication.

[46] M. W. Sachs, C. Chasman, and D. A. Bromley, *Proceedings of the Third Conference on Reactions Between Complex Nuclei, Asilomar, California, April 1963*, edited by A. Ghiorso, R. M. Diamond and H. E. Conzett (University of California Press, Berkeley, 1963), p. 90.

[47] D. A. Bromley, Symposium on Nuclear Spectroscopy with Direct Reactions, edited by F. E. Throw, Argonne National Laboratory, Report ANL-6848, 1964 (unpublished).

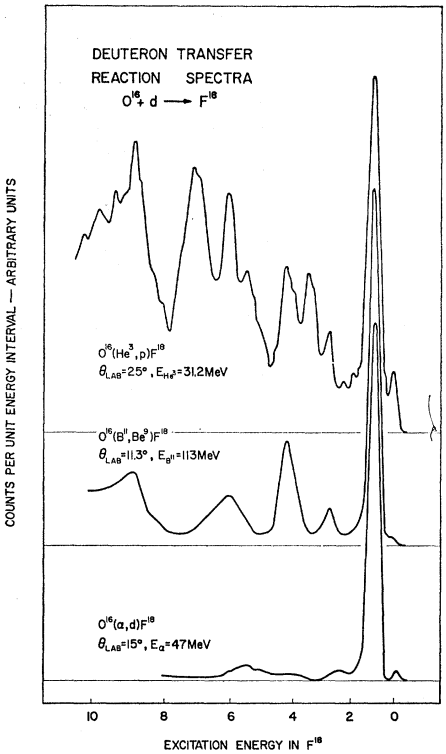

FIG. 14. Comparison of deuteron-transfer spectra leading to formation of F^{18}. The (He^3,p) and (α,d) results were obtained by E. Rivet *et al.* at Berkeley; we are indebted to Dr. Rivet for providing us with unpublished (He^3,p) results.

tiplet members should all have excitation energies ≥ 25 MeV in N^{14} and thus precludes the possibility that the shaded peak in Fig. 13 could correspond to such a configuration as had been suggested lacking such calculations, on the basis of extrapolation of the location of presumed $(f_{7/2})^2$ excitations in the (sd) shell.[47]

From Fig. 13 it may be inferred that the (B^{11},Be^9) reactions are somewhat more selective in populating the giant excitations than is the (α,d) or (He^3,p) reactions. This would be entirely consistent with the assumption that the requirement of a very lightly bound, heavy product such as Be^9 forces an extreme surface interaction mechanism which most strongly favors the population of pure two nucleon configurations.

Figure 14 shows corresponding lspectra eading ot population of F^{18} states via the (B^{11},Be^9), (α,d), and (He^3,p) reactions on O^{16}. The giant excitation here may be[15] identified with the known $(d_{5/2})^2$, 5^+ state at 1.1 MeV in F^{18} adding further support to the assumption of the preferential population of such states in these reactions.

There is as yet, no evidence which suggests that in the (B^{11}, Be^9) reactions, the transferred "deuteron" is ever in the singlet, $T=1$, rather than in the triplet, $T=0$, configuration of the free deuteron. There is no obvious reason why this should be so.

C. Fractional Parentage in the Incident Systems

It has already been noted that the total cross sections for the final states being considered here are quite small fractions of the incident geometric cross sections. It has been suggested that in part, this is a consequence of the large number of open reaction channels, and that further, some levels, which might *a priori* be expected to be populated with large yield are suppressed because of an angular-momentum mismatch. While a quantitative calculation of the effect of the angular-momentum mismatch is not yet complete, it is probable that another important effect is also involved.

In a direct-, as in a compound-system interaction, the reaction yield is proportional to the combined probabilities of formation of the final system and of the breakup of the initial system in an appropriate way. The cross section thus depends partly on the "availability" of the particle or cluster to be transferred (i.e., on the appropriate reduced width in the entrance channel participant). In the case of deuteron stripping, the deuteron wave function is relatively well established; hence nuclear information (i.e., reduced widths) relevant to the final system may be extracted from the reaction data. In the case of heavy-ion induced reactions, there is not yet available adequate information concerning the incident-system wave functions. Hence reaction theories must be formulated in terms of a product of the reduced widths in the incident and final systems. Once enough data are available, it will be possible to extract information by comparing several reactions, thus effectively factoring out the unknown reduced widths. It is only possible, however, to make qualitative comparisons using the present data.

It has been observed by Phillips and Tombrello[33] that their cluster model predicts large reaction cross sections when the incident and final parentages are the same. If one of the two parentages is known the other can, in principle, be estimated from the magnitude of the cross sections, provided all angular-momentum, statistical, and other factors are know. Many of these factors (such as the number of available exit channels, the energy and statistics of the incident systems) are the same for all reactions having the same incident system and incident energy, and it is thus possible to extract reduced-width information by comparing the reaction yields.

Since the states of N^{13}, at least up to 8 MeV, have already been demonstrated to be well represented by parentage $C^{12}+p$ or $C^{12*}(4.43\ \text{MeV})+p$, this cluster model[33] would predict large cross sections for the formation of these states. Reasons have already been advanced for the absence of the first excited state and suppression of other low spin states in the (B^{11},Be^{10}) and (B^{10},Be^9) reactions. However, the fact that none of the low-lying states in N^{13} is populated with large yield is significant and may also reflect the "availability" of the proton in the incident boron nucleus.

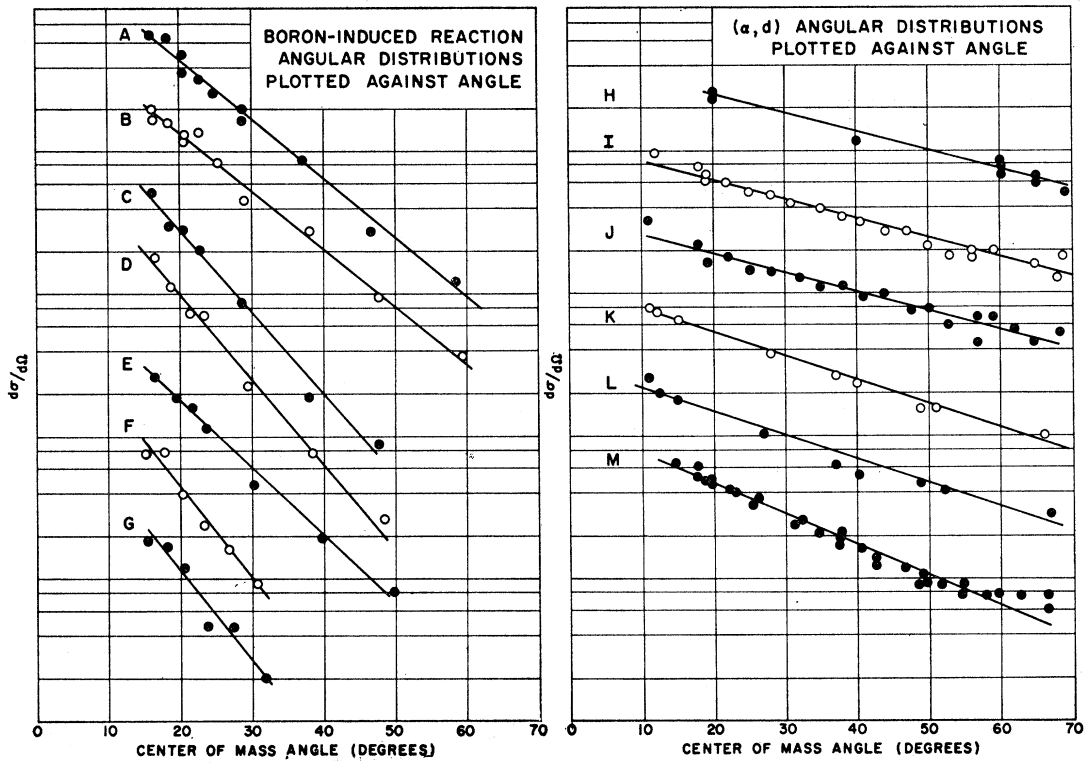

FIG. 15. Product angular distributions of all the proton and deuteron transfer reactions under consideration, plotted on common (arbitrary) scales, as functions of center-of-mass angle. The curves have been displaced for clarity. The reactions are identified as follows, with excitation in the final system given in parenthesis: *A*-$C^{12}(B^{11},Be^{9})N^{14}$ (9); *B*-$C^{12}(B^{11},Be^{9})N^{14}$ (13); *C*-$C^{12}(B^{11},Be^{10})N^{13}$ (ground); *D*-$C^{12}(B^{11},Be^{10})N^{13}$ (3.5); *E*-$C^{12}(B^{11},Be^{10})N^{13}$ (7.2); *F*-$C^{12}(B^{10},Be^{9})N^{13}$ (ground); *G*-$C^{12}(B^{10},Be^{9})N^{13}$ (3.5); *H*-$C^{12}(\alpha,d)N^{14}$ (9.0); *I*-$N^{14}(\alpha,d)O^{16}$ (14.7); *J*-$N^{14}(\alpha,d)O^{16}$ (16.2); *K*-$N^{15}(\alpha,d)O^{17}$ (7.6); *L*-$N^{15}(\alpha,d)O^{17}$ (9.0); *M*-$O^{16}(\alpha,d)F^{18}$ (1.1).

By comparing these data with others on the $B^{10}+C^{12}$ and $B^{11}+C^{12}$ systems, it is possible to estimate the importance of $Be^{9}+p$ parentage in the ground state of B^{10} and of $Be^{9}+d$ and $Be^{10}+p$ parentages in the ground state of B^{11}.

The comparison data are those on reactions leading to the dissociation of the projectile (in this case the boron). A cross section of 49.4 mb has been reported[48,49] for the dissociation of B^{10} into $Li^{6}+He^{4}$ in collisions with a C^{12} target at a bombarding energy of 105 MeV. This is 0.038 of the incident geometric cross section, and is 38 times larger than the cross section for the production of the 3.5 MeV excitation group in $C^{12}(B^{10},Be^{9})N^{13}$, and 146 times larger than the cross section for the ground state. Similarly data have already been published[50,51] on the dissociation of B^{11} into $Li^{7}+He^{4}$ in collisions with C^{12} at an incident B^{11} energy of 115.5 MeV. While total cross sections were not published, reexamination of the experimental data again leads to the conclusion that this cross section is approximately 0.03 of the incident geometric cross section, and thus 50 to 250 times larger than the cross sections for the formation of the various levels excited in N^{13} and N^{14}.

Since these dissociation reactions are believed to be good measures of the cluster parentage of the dissociated ion,[49] the conclusion is that B^{10} is not well described by wave functions of the form $Be^{9}+p$, nor is B^{11} well described by $Be^{10}+p$ or $Be^{9}+d$; rather, they are much better described by $Li^{6}+\alpha$ and $Li^{7}+\alpha$, respectively.

It might be argued that the comparison is distorted because there are many exit channels involving the transferred proton or deuteron, i.e., all the possible levels in which the N^{13} or N^{14} can be formed. However, the multiplier spectrum for the $B^{11}+C^{12}$ system (Fig. 4) shows that the total Li^{7} yield is four times larger than the total Be^{9} yield, and 12 times larger than the total Be^{10} yield. Since the shape of the dissociation angular distributions[48,49] are similar to those for the transfer reactions, this multiplier spectrum is a good measure of the relative magnitudes of the total cross sections. Thus from either viewpoint, the Li^{7} yield is significantly larger than the beryllium yields, indicating that the

[48] R. Ollerhead, C. Chasman, and D. A. Bromley, *Proceedings of the Conference on Reactions Between Complex Nuclei, Asilomar, California, April 1963*, edited by A. Ghiorso, R. M. Diamond, and H. E. Conzett (University of California Press, Berkeley, 1963), p. 191. Also Bull. Am. Phys. Soc. 8, 397 (1963).

[49] R. W. Ollerhead, C. Chasman, and D. A. Bromley, Phys. Rev. **134**, B74 (1964).

[50] R. W. Ollerhead, M. W. Sachs, C. Chasman, and D. A. Bromley, Bull. Am. Phys. Soc. 8, 141 (1963).

[51] R. W. Ollerhead, C. Chasman, and D. A. Bromley, *International Symposium on Direct Interactions and Nuclear Reaction Mechanisms, Padua, Italy, September 1962*, edited by E. Clementel and C. Villi (Gordon and Breach, Science Publishers, New York, 1963), p. 984.

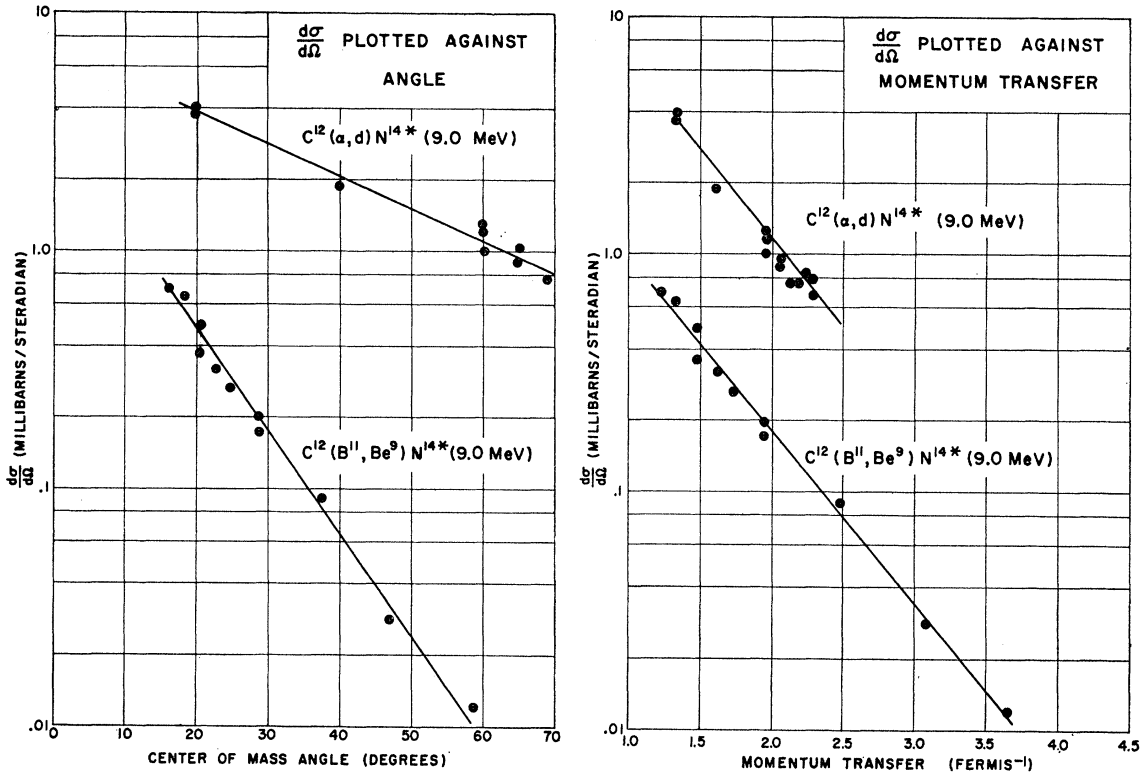

FIG. 16. Angular distributions of deuterons and Be^9 from the reactions $C^{12}(\alpha,d)N^{14}$ and $C^{12}(B^{11},Be^9)N^{14}$, leading to 9 MeV of excitation in N^{14}, as functions of center-of-mass angle (left side) and linear momentum transfer (right side).

mere presence of a large number of exit channels is inadequate to account for the small total cross sections for the formation of N^{13} and N^{14}.

D. Angular Distributions

The angular distributions studied for the (B^{11},Be^9) reactions have been plotted on a common scale, along with those of the relevant (α,d) reactions,[5] and are shown in Fig. 15. The cross-section scale is arbitrary, and the curves have been displaced for clarity. As previously noted, the shapes are remarkably similar.

Since stripping reactions are characterized most directly in terms of the linear momentum transfer $\mathbf{q}$, which contains the dominant angular dependence, additional information may be obtained by transforming the measured differential cross section to functions of this parameter. A typical result of the transformation is shown in Fig. 16. On the left, the angular distributions for $C^{12}(\alpha,d)N^{14}$ and $C^{12}(B^{11},Be^9)N^{14}$, both leading to the same level in N^{14} are plotted against angle. On the right, the same two angular distributions are shown plotted against the linear momentum transferred to the N^{14}, given by

$$|\bar{q}| = |\bar{K}_f - \bar{K}_i| = [K_f^2 + K_i^2 - 2K_f K_i \cos\theta]^{1/2}, \quad (7)$$

where $\bar{K}_i$ and $\bar{K}_f$ are the incident and final relative momentum wave numbers, and θ is the center-of-mass angle of observation. Figure 16 shows that the major difference between the (B^{11},Be^9) and (α,d) reactions completely disappears when the angular distributions are plotted in this way. Figure 17 shows all the data from the boron induced reactions similarly transformed. The similarity of these plots implies that the momentum transferred is a dominant factor in determining the angular distributions, while quantities dependent on the species of projectile and observed particle play relatively minor roles. The flattening of the (α,d) curves may reflect inaccuracies in transcribing these low cross-section points from the published curves.

It should be noted that although the data on the boron-induced reactions cover a smaller range of angles, they cover a larger range of momentum transfers than do the data on the alpha-induced reactions. This illustrates the fact that in a given angular range, much larger momentum transfers are possible with heavier particles.

Any reasonable diffraction model applied to these data, albeit with considerable uncertainty regarding the proper wave functions to be used for the projectile and product nuclei, has always predicted marked oscillatory structure in the angular distributions with an angular period of some 10°. This is not in accord with the experimental observations, nor are any of the distorted wave calculations yet attempted. These do, however,

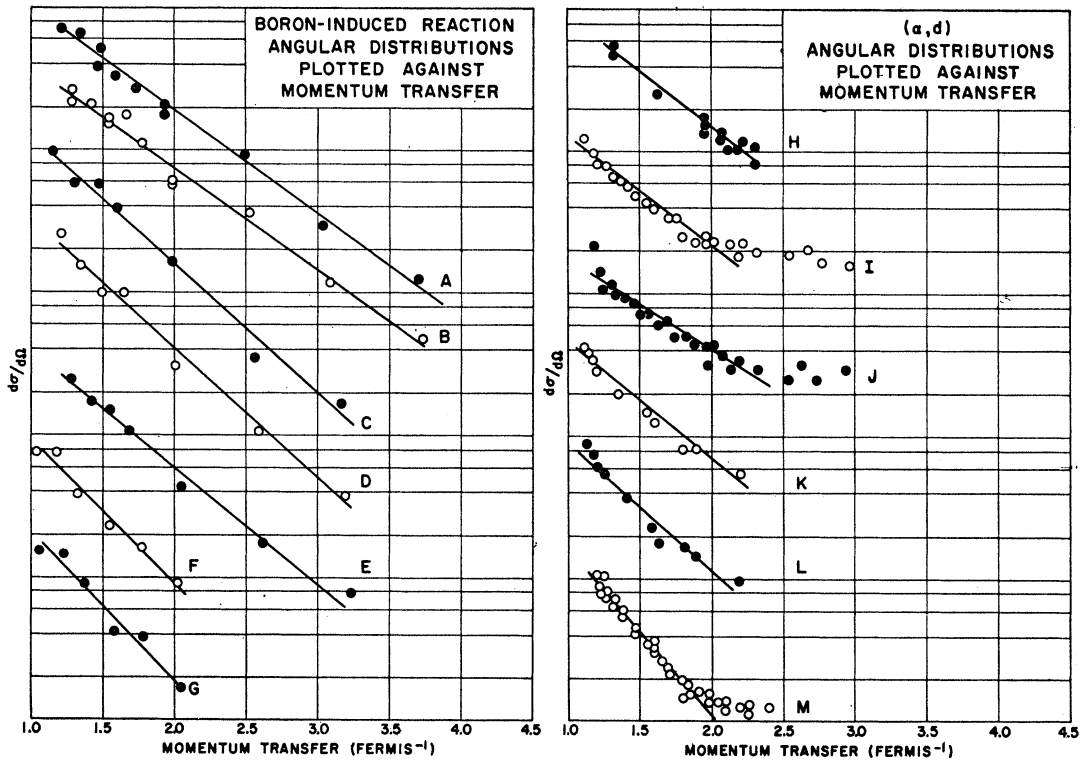

FIG. 17. Product angular distributions of all the proton and deuteron transfer reactions under consideration, plotted on common scale as functions of linear momentum transfer. The curve labels are identical to those in Fig. 16.

succeed in reducing the predicted oscillatory amplitudes.

Dar has recently suggested,[52] however, that in fact the conditions of these reactions may violate some of the specific assumptions of the diffraction models, and that when the assumptions in question are removed, the model can yield agreement with the experimental observations.

Dar's model[10] has been calculated with the following assumptions:

(1) The Q value of the reaction is small compared with the incident energy.

(2) The mass transferred is small compared with the masses of the colliding particles.

(3) The angular momentum transferred is small compared with the dominant contributing l values.

(4) The value of the Coulomb parameter η is large so that the semiclassical condition $2\pi\eta \gg 1$ is well satisfied.

The model calculated with these assumptions has already been shown[10] to describe a large body of experimental data.

Although the boron-induced reactions being discussed here fulfill the first three assumptions quite well, the value of η is approximately 1.5 for all reactions, and so the validity of the last assumption is open to question. A way of removing this assumption has recently been found.[52]

[52] A. Dar (private communication).

In this model, the description of the reaction is in terms of the diffraction of Coulomb waves around the nucleus, using a smooth cutoff of the low partial waves, wherein each partial wave is multiplied by the square root of its reflection coefficient.[53] The dominant interaction is assumed to be that between the transferred nucleon or cluster and the remaining heavy core. That is, if the reaction is represented by

$$A+(B+c) \rightarrow (A+c)+B$$

the dominant interactions are between A and c in the incident system, and between B and c in the final system. After approximations in keeping with the four assumptions above are made, the calculation yields a differential cross section of the form

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{\sin\theta}\left[\frac{1}{\cosh^2[\delta\pi(\theta-\theta_0)]-\cos^2[\delta(\tfrac{1}{2}\Delta)\pi]} + \frac{1}{\cosh^2[\delta\pi(\theta+\theta_0)]-\cos^2[\delta(\tfrac{1}{2}\Delta)\pi]} + I\right] \quad (9)$$

wherein I is an interference term having an analytic expression which is not needed in the present discussion;

[53] N. J. Sopkovitch, Nuovo Cimento **26**, 186 (1962); K. Gottfried and D. Jackson, *ibid.* **34**, 735 (1964); L. Durand, III, and Y. T. Chiu, Boulder Conference on Particle Physics, 1964 (unpublished), and Yale University Report, 1964 (unpublished).

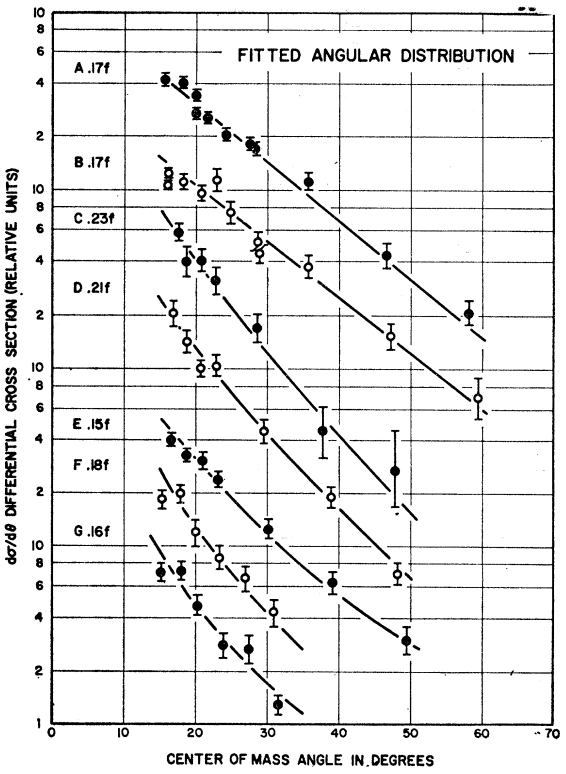

FIG. 18. Product angular distributions ($d\sigma/d\theta$) of all the boron-induced reactions, with the best theoretical curves and resulting values of the diffuseness, d, in fermis. The reactions are identified as follows, with the final-system excitation in parentheses: A-$C^{12}(B^{11},Be^{9})N^{14}$ (9); B-$C^{12}(B^{11},Be^{9})N^{14}$ (13); C-$C^{12}(B^{11},Be^{10})N^{13}$ (ground); D-$C^{12}(B^{11},Be^{10})N^{13}$ (3.5); E-$C^{12}(B^{11},Be^{10})N^{13}$ (7.2); F-$C^{12}(B^{10},Be^{9})N^{13}$ (ground); G-$C^{12}(B^{10},Be^{9})N^{13}$ (3.5).

θ is the scattering angle; δ is the nuclear diffuseness in l space; θ_0 is the Rutherford scattering angle corresponding to a distance of closest approach equal to the interaction radius; and $\frac{1}{2}\Delta$ is the ratio of the wave number for the binding of the transferred cluster and core to the wave number for the momentum of the colliding heavy ions (actually the average Δ for the incident and final systems is used).

The diffuseness δ is related to the usual radial diffuseness d, by

$$\delta=\bar{k}d[1-\bar{\eta}/\bar{k}R][1-2\bar{\eta}/\bar{k}R]^{-1/2}, \qquad (10)$$

where $\bar{k}$, $\bar{\eta}$, and R are, respectively, the average of the incident and final heavy-ion momenta, average of the incident and final coulomb parameters, and the interaction radius of the heavy ions.

Initially, the differential cross section was calculated for the reactions at hand, using the complete expression [Eq. (9)]. The calculation resulted in a prediction of an oscillating angular distribution in agreement with other similar models, but not with the experimental data. It was then realized[52] that the saddle-point approximation used in the calculation of the differential cross-section formula fails for small values of η, such as those encountered here. While the model has not yet been calculated in detail for small η, it can be shown[52] that one of the main effects of removal of the assumption of large η is the introduction, into the calculation of the reaction amplitude, of a summation over the possible contributing values of the transferred angular momentum between the limits $|l_1-l_2|$ and $|l_1+l_2|$ where l_1 and l_2 are the relative angular momenta between B and c, respectively. If both l_1 and l_2 are nonzero, as is true for all the reactions investigated here, the sign of the interference term alternates in successive terms of the summation, whereas the other terms do not change sign. The effect is thus to significantly reduce the magnitude of the interference compared to the other terms in Eq. (9).

Although the detailed calculation for small η is not yet available, an estimate of the validity of the model may be had by assuming the interference to be absent, and calculating the differential cross section as the first two terms in Eq. (9).

It will be noted that the predicted angular distribution depends only on the diffuseness, bombarding energy, and the gross properties of the nuclei involved (masses, interaction radius, binding of cluster to core, etc.). The detailed properties of the wave functions of the nuclear states involved affect the absolute magnitude of the cross sections, and should appear as a reduced width multiplying the predicted angular distribution. In the absence of adequately refined nuclear wave functions for these heavy ions, the reduced widths have been ignored and arbitrary normalization assumed for each reaction.

The ground-state binding energies of cluster to core have been used in calculating Δ. Although this is not entirely correct, it can be shown that the error in neglecting Coulomb barriers and excitation energies is not significant in the angular region in which the data exist. In the case of the reactions $C^{12}(B^{11},Be^{10*})N^{13*}$ (7.2-MeV total excitation) and $C^{12}(B^{11},Be^{9})N^{14}$ (13.1) there is an additional problem since the total excitation in the final state is even higher that the total of binding energy and Coulomb barrier. Since, however, the measured angular distributions for these reactions have the same general shape as the others, it may be assumed that the error is not serious.

In accordance with the convention adopted in comparing this model to other measurements,[10] the predicted angular distribution has been multiplied by $\sin\theta$, and the data plotted as the polar angular distribution

$$(d\sigma/d\theta)\equiv 2\pi \sin\theta(d\sigma/d\Omega). \qquad (11)$$

All the data in Figs. 8, 9, and 11 have been transformed in this manner and are shown in Fig. 18 with the calculated curves, and the values of the diffuseness, d (in fermis) which yielded these fits. Since the absolute magnitudes of the cross sections are of no consequence here, the data have been displaced vertically for clarity,

and the theoretical curves normalized individually and arbitrarily.

In all cases, the values of the diffuseness parameter are quite small, tending to confirm the assumed extreme surface reaction mechanism. These values are also in accord with the range of values found by Frahn and Venter[54] for heavy-ion elastic scattering, and with those found by Dar[10] for the application of this model to other reaction data.

It should also be observed that the size of the uncertainties in the data in Fig. 18 leads to an uncertainty of approximately 30% in the values of d obtained. Thus comparison of the values found for the different cases is probably not significant. However, because of the small values (which correspond to values of δ between 0.5 and 1 unit of angular momentum), the conclusions of an extreme surface-reaction mechanism would not be changed by more accurate values.

Note added in proof. Recently K. Greider and L. Dodd in this laboratory have demonstrated that excellent fits to all the exponential angular distributions including all those presented herein are obtained within the framework of a general direct interaction formalism if nuclear recoil effects are properly included. This work will be submitted for publication shortly.

V. SUMMARY

Boron-induced reactions on C^{12} have been investigated at incident energies of 10.5 MeV per nucleon leading to isolated states in the final nitrogen nuclei. The proton and deuteron transfer-reactions characteristics have been shown to very similar to those of the corresponding (He^3,d) and (α,d) reactions at equivalent incident energies.

In the proton transfer reactions it has been demonstrated that existence of a large proton width for the final state does not necessarily result in a large proton-transfer cross section and that in particular these cross sections may be inhibited by angular-momentum mismatch conditions.

In the deuteron-transfer case evidence has been presented favoring preferential population of relatively pure two nucleon configurations at high excitations in the residual nucleus. The heavy-ion reactions have the advantage that they emphasize this preference, reflecting the strong surface interaction character of the reactions themselves. As such they provide useful probes for the existence and study of such highly excited configurations.

Angular distributions of the emergent heavy particles from the boron-induced transfer reactions are closely exponential functions of angle, and are fitted by a diffraction model, modified to take into account the relatively small values of the coulomb parameter present in these reactions. The values of the nuclear diffuseness obtained in these fits are in agreement with values for other heavy-ion reactions.

On the basis of a comparison of the data reported herein with other relevant data, it is concluded that the Be^9+p, $Be^{10}+p$, and Be^9+d components of the ground-state wave functions of B^{10}, B^{11}, and B^{11}, respectively, are small compared to their $Li^6+\alpha$ and $Li^7+\alpha$ components.

These measurements have demonstrated the utility of Be^9 as a reaction product, in removing the ambiguity in the residual excitations; the full benefits of this will be realized in its use in studies with the better energy resolution anticipated from the newer high-energy tandem accelerators.

ACKNOWLEDGMENTS

We are indebted to R. Ollerhead, J. Poth, J. Allen, K. Nagatani, J. Birnbaum, and G. Seaman for their assistance in developing the techniques utilized herein and in taking the experimental data; to Dr. A. Dar, Dr. K. Greider, and Dr. T. Tombrello for valuable discussions; to Dr. B. G. Harvey, Dr. N. K. Glendenning, Dr. E. Rivet, Dr. W. W. True, and Dr. R. Bock for providing us with results of experiments and calculations prior to their publication; and to C. E. L. Gingell for his assistance with the electronic instrumentation.

[54] W. E. Frahn and R. H. Venter, Ann. Phys. (N. Y.) **27**, 401 (1964).

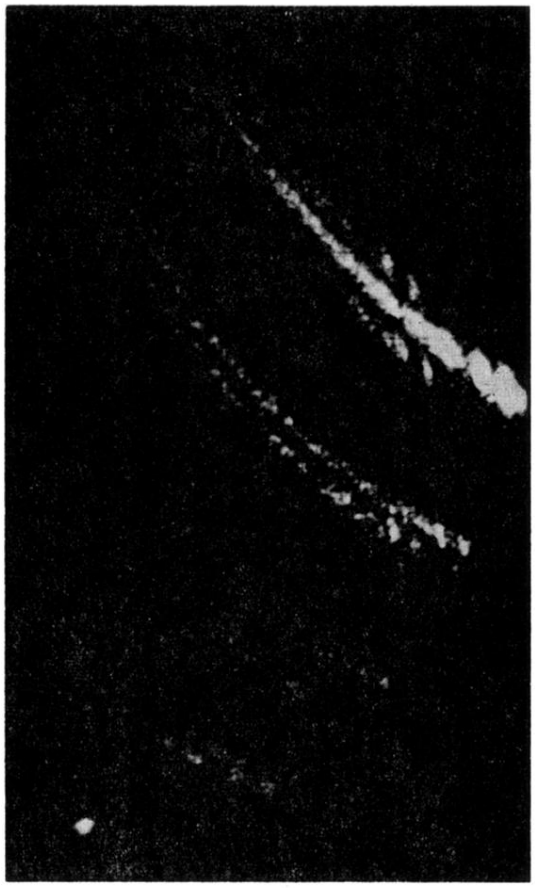

FIG. 1. Direct oscillographic plot of dE/dx against E for the bombardment of carbon by 126-MeV C^{12}.

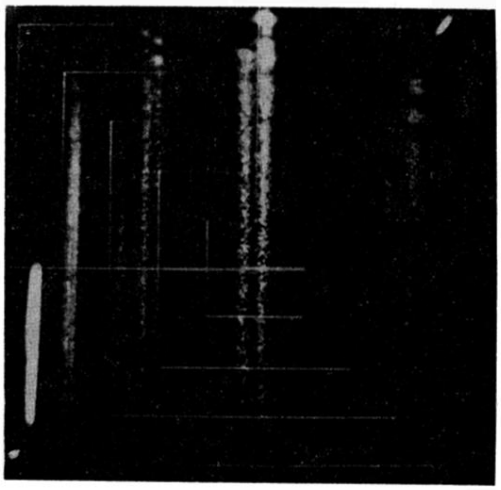

FIG. 3. Direct oscillographic plot of E against the multiplier output for the bombardment of oxygen by 112.9-MeV B^{11}.