Neutron-Producing Reactions by Deuteron Bombardment of B^{11}†

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The neutrons produced by deuteron bombardment of a thin, enriched B^{11} target have been studied for nine different deuteron energies ranging from 1.60 to 2.70 MeV. The absolute differential cross sections for the production of neutrons feeding well-established states in C^{12} were determined. In addition to the monoenergetic neutron groups feeding the states of C^{12}, previously unreported continuum neutrons due to many-body breakup of deuteron plus B^{11} system were observed and analyzed. The breakup mechanism is inferred to be a direct reaction process rather than the compound nucleus process. The angular distributions of neutrons leaving C^{12} in 15.11 MeV (1^+), $Q=-1.37$ MeV and 12.73 MeV (1^+), $Q=+1.00$ MeV states were studied in detail. The effect of compound resonance at $E_d=2.18$ MeV on the angular distributions of the above neutron groups was studied. The investigations were performed employing time-of-flight technique utilizing pre-acceleration pulsed, post-acceleration bunched deuteron beam from a 3-MeV Van de Graaff accelerator.

I. INTRODUCTION

The angular distribution of the outgoing particle in (d,p) or (d,n) reaction, in terms of the orbital angular momentum carried into the target nucleus by the captured particle, has been interpreted by Butler[1] and Bhatia *et al.*[2] Despite the extreme approximations used in the original theory of the deuteron stripping reaction, the theory has been very successful in explaining many observed angular distributions of (d,p) and (d,n) reactions. A more detailed and improved stripping theory that takes account of the Coulomb and nuclear interactions of the relevant particles has produced good agreement for some cases where the original theory was quite unsuccessful.[3] Although the original Butler theory is a very useful means in extracting nuclear spectroscopic data, it faces many difficulties. In particular, the Butler theory is totally incapable of explaining many observed cases of backward angle peaking of the outgoing nucleon. Transitions to the ground state and the first excited state of the reaction $B^{11}(d,n)C^{12}$ are representative cases where the above difficulty is well illustrated. In order to fit these cases Owen and Madansky[4] have proposed the mechanism of heavy-particle stripping by considering the stripping processes to be a coherent process of deuteron and heavy-particle stripping. A combination of the deuteron and the heavy-particle stripping has been found which fits the observed nucleon angular distributions.[5,6] It seems that the heavy-particle stripping does compete with the deuteron stripping to some degree, and makes nonignorable contributions to the (d,n) and (d,p) reactions on light nuclei.

Wilkinson[7] pointed out that the deuteron stripping approximations made in the Butler theory should be well fulfilled when the reaction Q value is low ($\sim\pm1$ MeV) and E_d is also low (<3 MeV). Wilkinson's argument is based on the consideration of the nucleon separation distances within the deuteron for the required conservation of linear momentum and energy of the stripping reaction under these criteria. Neutron groups from the reaction $B^{11}(d,n)C^{12}$ at deuteron energies between 2 and 3 MeV leaving C^{12} in states of high excitation would satisfy the Wilkinson criteria for observing Butler stripping distributions. Johnson[8] has observed neutron groups from the above reaction for essentially all the excited states of C^{12}. Of particular interest are the states of excitation $E_x=15.11$ MeV ($Q=-1.37$ MeV) and $E_x=12.73$ MeV ($Q=+1.00$ MeV). The Wilkinson argument is particularly applicable to the first case for $E_d=2$ to 3 MeV ($\cong -2Q$).

In addition to the above considerations, the single-particle width of the 15.11-MeV state of C^{12} is estimated to be very close to the stripping width expected, indicating that the $B^{11}(d,n)C_{15.11\,\mathrm{MeV}}^{12*}$ may be predominantly due to stripping reaction.[9] Good stripping is expected even near the threshold energy of the reaction for the excitation of the 15.11-MeV state.

Various attempts[10,11] have been made to determine the relative contribution to the reaction mechanism of the compound nucleus process and the direct reaction in (d,p) or (d,n) reactions by observing the effect on the angular distribution of the stripped nucleon. At the present time there is no completely consistent and satisfactory way of determining the contribution from the compound nucleus process. There are indications that the compound nucleus contribution may be a

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[1] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1952).

[2] A. B. Bhatia, K. Huang, R. Huby, and H. C. Newns, Phil. Mag. **43**, 485 (1952).

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

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

[5] R. Zdanis, G. E. Owen, and L. Madansky, Phys. Rev. **121**, 854 (1961).

[6] A. J. Elwyn, J. W. Kane, S. Ofer, and R. Pixley, Phys. Rev. **120**, 2207 (1960).

[7] D. H. Wilkinson, Phil. Mag. **3**, 1185 (1958).

[8] V. R. Johnson, Phys. Rev. **86**, 302 (1952).

[9] E. K. Warburton and L. F. Chase, Phys. Rev. **120**, 2095 (1960).

[10] J. B. Marion and G. Weber, Phys. Rev. **102**, 1355 (1956).

[11] M. T. McEllistrem, Phys. Rev. **111**, 596 (1958).

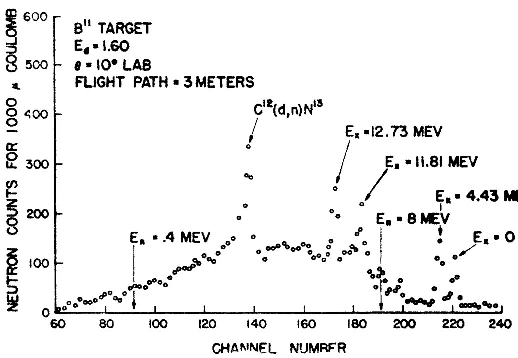

FIG. 1. Neutron time-of-flight spectrum from the reaction $B^{11}(d,n)C^{12}$ for $E_d=1.60$ MeV. Time increases from right to left. Dispersion is 1.3 nsec per channel.

significant contribution to the observed angular distribution of the outgoing nucleon for the low incident deuteron energy.

Kavanagh and Barnes[12] report a small resonance-like behavior in their zero-degree yield curve of 15.11-MeV de-excitation gamma ray from $B^{11}(d,n\gamma_{15.11})C^{12}$ at 2.18 MeV incident deuteron energy. This small resonance offers the possibility of studying the effect of a compound process on the angular distributions of neutrons produced in this reaction.

It is also suggested by Johnson[8] that the B^{11} plus deuteron system might break up into a neutron plus three alpha particles or a neutron plus alpha plus Be^8 system giving rise to a continuum of neutron energies. He, however, was not able to state that his observed "background" had this origin. No subsequent studies to explore this point have been reported.

The present investigation of $B^{11}(d,n)C^{12}$ reaction in which the angular distributions of the outgoing neutrons are studied over a range of incident deuteron energies (1.6 MeV $<E_d<$ 2.8 MeV) is performed with the following objectives: examination of the merit of Wilkinson's argument concerning the effect of Q values on this stripping reaction, determination of absolute cross sections, a study of the compound nucleus process as it affects the stripping pattern at a resonance, and an observation and study of the possible continuum neutrons due to many-body breakup of the B^{11} plus d system.

II. EXPERIMENTAL CONSIDERATIONS

The Case 3-MeV Van de Graaff is operated as a pulsed source of deuterons employing pulsing in the high-voltage terminal at a 1-Mc/sec repetition frequency. The accelerated, pulsed beam is further bunched by a time compression, doubly focusing Mobley magnet. The pulsed beam accelerator system has been described by Cranberg *et al.*[13] Under the optimum operating condition the accelerator produces deuteron pulses of less than 2-nsec pulse width with a time average current of 7 μA. The neutrons are detected by a plastic proton recoil scintillator and the time spectrum recorded on a 256-channel pulse-height analyzer using a time-to-pulse-height converter very similar to that used by Weber *et al.*[14] Under the average operating condition the overall system provided a time resolution of 2.5 to 3 nsec.

The targets used are B_2O_3 and elemental boron evaporated onto thin, clean Ta backings. The isotopic enrichment of B^{11} used for both forms of targets is 98.6%. The thickness of one of the targets used was

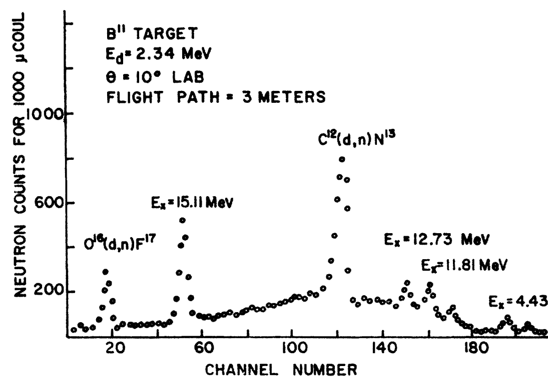

FIG. 2. Neutron time-of-flight spectrum from the reaction $B^{11}(d,n)$-C^{12} for $E_d=2.34$ MeV. Dispersion is 1.3 nsec per channel.

determined by measuring the shift in energy of one of the many $Al^{27}(p,\gamma)Si^{28}$ resonances due to proton energy loss in the thin layer of B_2O_3 vacuum deposited onto an Al sheet at the same time the B_2O_3 deposited on a Ta sheet was prepared as the target for this investigation. The layers of B_2O_3 thus prepared exhibited the same optical interference patterns and were therefore considered to be equal thickness. The typical target thickness used is 30 keV for a 1.30-MeV proton.

The deuteron beam is focused on the B^{11} target through a rectangular aperture 1.5 mm×3.0 mm and the beam current incident on the target was integrated to monitor and normalize the experimental runs. The angular divergence of the focused beam from the compression magnet is 5 deg while the uncertainty of the mean incident deuteron direction is of the order of one deg.

The incident deuteron energies quoted were determined by observing nuclear magnetic resonance frequencies of proton and lithium nuclei in the magnetic field of the 90-deg doubly focusing beam analyzing magnet previously calibrated using the $Li^7(p,n)$ threshold. The deuteron energy was determined within ±1.5 keV.

The neutron detector used is a $\frac{1}{2}$ in. thick, 2-in. diam-

[12] R. W. Kavanagh and C. A. Barnes, Phys. Rev. **112**, 503 (1958).

[13] L. Cranberg, R. A. Fernald, F. S. Hahn, and E. F. Shrader, Nucl. Instr. Methods **12**, 335 (1961).

[14] W. Weber, C. Johnston, and L. Cranberg, Rev. Sci. Instr. **27**, 166 (1956).

eter cylindrical Nuclear Enterprise 102 plastic scintillator mounted on an RCA 7264 photomultiplier.

The pulses from the PM anode after amplification by two Model 460 B Hewlett Packard wide-band amplifiers were used to trigger the time-to-pulse height converter. Fiducial timing or "stop" pulses are derived from a beam pickup electrode[13] located near the target. A dynode signal was used in a separate side channel to gate a 256-channel pulse-height analyzer in which the time-of-flight spectrum was stored. The level of the side channel discriminator was set to correspond to a 0.3-MeV recoil proton in the plastic scintillator. At this setting the photomultiplier noise makes only a small contribution to the background.

The experimental arrangement permitted one to locate the neutron detector at all angles from -130 to $+130$ deg relative to the incident deuteron direction for the neutron flight path of 1 to 3 m. A time-of-flight neutron spectrum at a deuteron energy of 1.60 MeV is shown in Fig. 1. The flight path of 3 m used was sufficient to resolve neutron groups corresponding to C^{12} excitation of 4.43, 7.66, 11.81, and 12.73 MeV in addition to the ground-state group. There is, in addition, suggestions of a group corresponding to the 10.8-MeV level of C^{12}. The neutron group due to $C^{12}(d,n)N^{13}{}_{g.s.}$ shown in the figure is due to the carbon buildup during the course of experiment. Since the carbon buildup did not interfere with this investigation, no attempts were

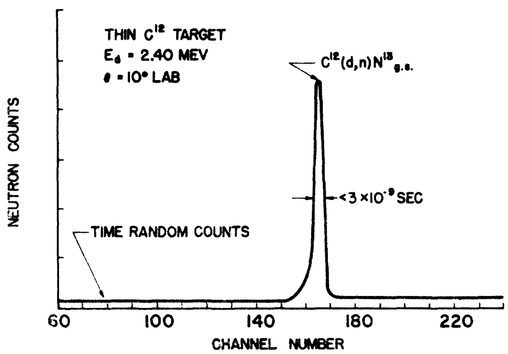

FIG. 3. Neutron time-of-flight spectrum from the reaction $C^{12}(d,n)N^{13}$ for $E_d=2.40$ MeV. Only one monoenergetic neutron group is expected and the flat time-random background displays no spurious structure over the time interval of interest. Dispersion is 1.3 nsec per channel.

made to reduce or eliminate the buildup. Figure 2 shows another neutron time-of-flight spectrum at a incident deuteron energy sufficiently above the threshold energy for the excitation of 15.11-MeV state of C^{12}. Seven groups of neutrons from the $B^{11}(d,n)C^{12}$ reaction are well resolved and the continuum neutrons from the many-body breakup are clearly shown. That the continuum neutrons are associated with the boron target is shown by comparison with the spectrum shown in Fig. 3 of neutrons from the reaction $C^{12}(d,n)N^{13}{}_{g.s.}$ using a C^{12} target. The uniformly distributed time random background shown in the $C^{12}(d,n)N^{13}{}_{g.s.}$ spectrum was shown to be independent of the location of the neutron detector hence structure in the time-of-flight spectrum is target associated.

In order to obtain the intensities of the monoenergetic neutron groups, the time-random background and the continuum neutrons must be taken into consideration. The time resolution was felt to be good enough that a smooth curve drawn through the spectrum points between peaks would suffice (when interpolated under the peaks) to take into account detector counts from these two sources. The angular distribution of the various groups have been transformed to the center of mass system and corrected for detector solid angle and the energy dependence of the neutron detection efficiency. This latter correction for the low-energy neutron group was appreciable due to the kinematic shift of energy with angle.

For absolute cross-section determinations the absolute efficiency of the detector was calculated.

III. RESULTS

$Q=-1.37$ MeV, $E_x=15.11$ MeV (1^+) State of C^{12}

An absolute yield at 10 deg of the neutron group feeding the 15.11 MeV (1^+) state as a function of deuteron energy is shown in Fig. 4. The error bars shown are based on counting statistics only. The relative yield curve is in good agreement with the 15.11-MeV de-excitation gamma-ray yield curve obtained by Kavanagh and Barnes[12]; however, the absolute cross section does not agree with their value. Kavanagh and Barnes report the gamma-ray cross section of the $B^{11}(d,n\gamma_{15.1\text{ MeV}})C^{12}$ reaction at $E_d=2.20$ MeV to be 29 ± 7 mb and this value is 2 to 3 times greater than the cross section feeding the same state determined by the present investigation. The yield curve in the region of $E_d=2.18$ MeV indicates a small compound nucleus resonance. The fact that the anisotropy in the gamma-ray angular distribution changes abruptly at[9] $E_d=2.18$ MeV is an

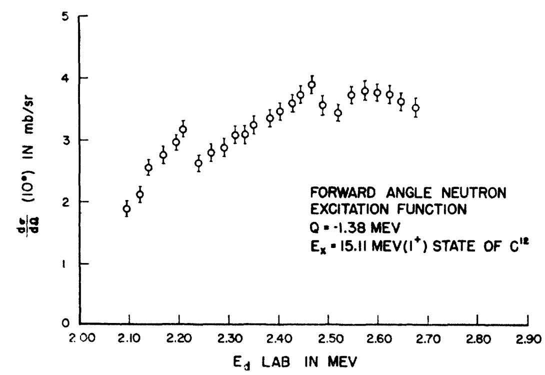

FIG. 4. Excitation function for $B^{11}(d,n)C^{12*}$ ($E_x=15.11$ MeV) neutrons observed at an angle of 10° relative to the incident deuteron direction.

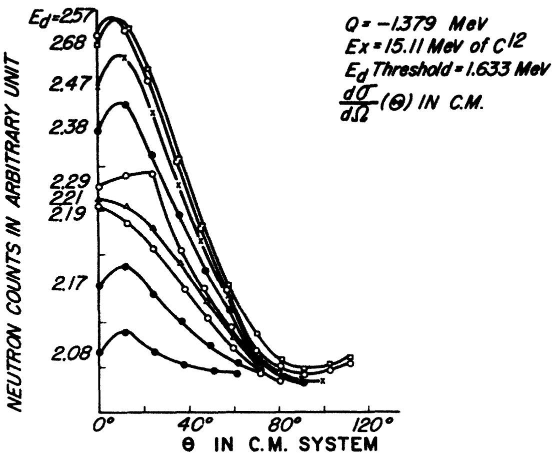

FIG. 5. Angular distributions of neutrons from the $B^{11}(d,n)C^{12*}$ reaction leaving the C^{12} nucleus with 15.11 MeV of excitation energy. Deuteron energy in MeV is indicated for each distribution.

indication of the presence of a resonance. Figure 5 shows a set of nine angular distributions of the neutron feeding the 15.11-MeV state. The experimental points lie on curves which are quite smooth and show characteristic strong forward peaking of the deuteron stripping reaction. The effect of the 2.18-MeV resonance is very prominently shown. A trend of increasing intensity for angles greater than 90 deg is indicated by the curves; however, it was not feasible to take statistically significant data beyond the angle shown. This difficulty arose due to two considerations: low counting rate for the backward angles and the kinematic loss of neutron energy. The kinematic loss of neutron energy was such that for backward angles the neutron energies were near the detector bias value. The absolute differential cross sections for three values of incident energy are shown in Fig. 6. The solid lines are the theoretical fits taking the interaction radius or cutoff radius, R as an adjustable parameter. The above curves are calculated using a table computed by Lubitz.[15] The agreement between the theory and the experiments are remarkable. That the proton captured by B^{11} carries a unity orbital angular momentum is in agreement with the 1^{+} assignment for the 15.11-MeV state of C^{12}. It is interesting to note the variation in radius R as the incident energy varies. Ferguson *et al.*[16] fitted the 8-MeV data with $R=3.2$ F. It is regrettable that the present experimental conditions did not allow one to obtain the angular distribution barely above the threshold energy. As Warburton and Chase point out,[9] the neutron angular distribution near the threshold would yield very useful, additional information. The reduced width of the state is computed for the three different deuteron energies indicated in Fig. 6. The absolute reduced widths so computed are: 0.014 at $E_d=2.68$ MeV, 0.013 at $E_d=2.47$ MeV, and 0.007 at $E_d=2.17$ MeV.

$Q=+1.00$ MeV, $E_x=12.73$ MeV (1^+) State of C^{12}

As was the case with the 15.11 MeV, this is a reaction which satisfies Wilkinson's conditions for good stripping. Some work has been reported on this reaction by Marion and Weber[10] and McEllistrem.[8] Parity and spin of the above state is known to be 1^+.[17] Neutron angular distributions for nine different incident energies are shown in Fig. 7. The smooth curves joining the experimental points are drawn for the purpose of visual aid. The drastic change in shape of these curves as the incident energy passes through 2.18-MeV resonance is very striking. Using reasonable extrapolation to 180 deg the total cross section so estimated is fairly constant over the range of deuteron energies investigated. The strong forward-angle peaking, the definite maximum and minimum, and the gradual rise for the backward angle of the neutron counts are consistently shown for the whole incident energy range. Elwyn *et al.*[18] devised a method of treating a set of data such as the ones shown in the Fig. 7 to isolate, in a crude way, the contributions due to direct interaction from the compound process, and the validity of the above method is well illustrated in their treatment of $C^{12}(d,n)N^{13}$ data. With

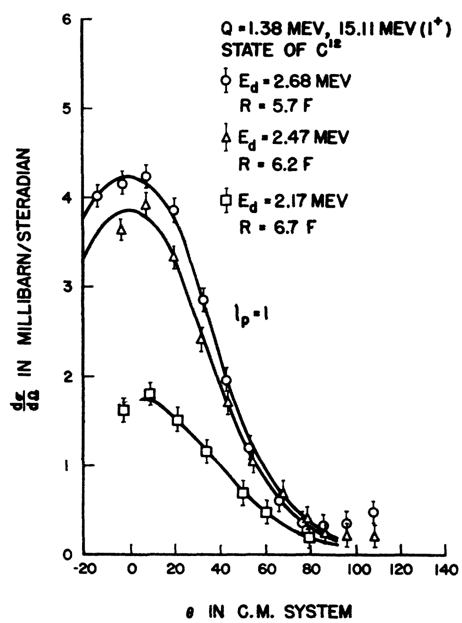

FIG. 6. Butler theory fits to the observed $B^{11}(d,n)C^{12*}$ ($E_x=15.11$ MeV) neutron angular distributions for $E_d=2.17$, 2.47, and 2.68 MeV. Cutoff radii of 6.7, 6.2, and 5.7 F, respectively, were used with $l_p=1$.

[15] C. R. Lubitz, U. S. Atomic Energy Commission Report AECU-3990, 1959 (unpublished).

[16] A. J. Ferguson, H. E. Gove, A. E. Litherland, and R. Batchelor, Bull. Am. Phys. Soc. **5**, 45 (1960). The authors are grateful to A. J. Ferguson for providing us with the details of this work.

[17] F. Ajzenberg and L. Lauritsen, Nucl. Phys. **11**, 117 (1959).

[18] A. J. Elwyn, J. W. Kane, S. Ofer, and D. H. Wilkinson, Phys. Rev. **116**, 1490 (1959).

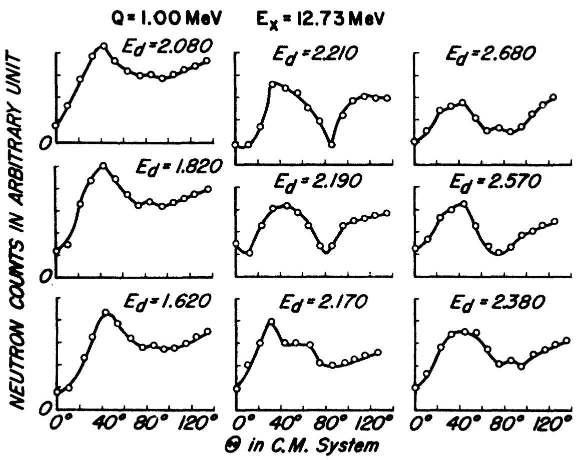

FIG. 7. Angular distribution of neutrons from $B^{11}(d,n)C^{12*}$ leaving the C^{12} nucleus with 12.73 MeV of excitation energy. Deuteron energy in MeV is indicated for each distribution.

the assumption that the experimental angular distributions are a coherent sum of the direct and compound processes and that the contribution from the compound process is small compared to the direct process even at a compound state resonance one may cancel the interference term between the two processes present in the angular distribution by taking suitable average of many angular distributions taken across the small resonance. Figure 8 shows the result of the averaging method applied to the angular distributions shown in Fig. 7. Five of nine curves shown in Fig. 7 (E_d=2.08, 2.17, 2.19, 2.21, and 2.38 MeV) are added point by point and their average absolute value is presented in Fig. 8. The arithmetic average of the five angular distributions are taken since, as stated earlier, total cross sections are fairly constant for the energy range of interest. The solid curve appearing in Fig. 8 is a Butler fit with the values of the relevant parameters shown in the figure. The fit is surprisingly good for forward angles up to 70 deg. The choice of R=3.5 F for the best fit is a reasonable one. The proton capture by B^{11} with unity angular momentum is consistent with 1^+ assignment for the 12.73-MeV state of C^{12}. The smooth and monotonic increase of differential cross section for the backward angle could be accounted for by a heavy-particle stripping mode in a manner very similar to that of the $B^{11}(d,n)C^{12}{}_{g.s.}$ shown in reference 4. The absolute reduced width extracted in the same manner indicated earlier for the above averaged data is 0.029.

Q=9.30 MeV, E_x=4.43 MeV (2^+) State of C^{12}

The neutron angular distribution for four different incident energies are shown in Fig. 9. The neutron group leaving C^{12} in the above state has been investigated and reported by many investigators.[17] The present results are in good agreement with the previous ones. This reaction also shows the effect of the resonance at 2.18 MeV. The absolute differential cross section determined for E_d=2.21 MeV at zero degree in the c.m. system is 5±1 mb/sr.

The Continuum Neutrons

The many-body breakup of the B^{11} plus d system has been inferred from the determination of alpha-particle energy spectrum of the $B^{11}(d,\alpha)Be^{9*}$ reaction.[12,19] The observation of the continuum neutrons from the above breakup has not been reported to present. The maximum energy and the rough distribution of the continuum neutrons are indicated in the Figs. 1 and 2. (Note: The abscissas of Figs. 1 and 2 are proportional to the neutron flight time.) The maximum neutron energy is about 8 MeV for the incident energy shown, and this value is within the experimental error the maximum neutron energy kinematically available if the B^{11} plus d system breaks up to $n+\alpha+Be^8{}_{g.s.}$ or $n+3\alpha$. The low alpha binding energy of Be^8 makes it difficult to distinguish kinematically between the unbound pair of alphas and the bound pair.

On the other hand, the maximum neutron energy from the decay of Be^{9*} formed by the well-established reaction $B^{11}(d,\alpha)Be^{9*}$ 2.42 MeV is about 3 MeV and the neutron energy would have a kinematic energy spread of about 1 MeV. Undoubtedly there is some contribution from the neutrons emitted by Be^{9*} superimposed on the continuum neutrons. In order to obtain the information concerning the mechanism for the continuum neutrons, angular distributions of the continuum are plotted in Fig. 10. If the neutrons are due to decay of a compound state, then the angular distribution should be symmetric about 90 deg. On the other hand, if the neutrons are produced by a direct breakup of the B^{11} plus d system, then one would expect the neutrons to be peaked about a certain angle that depends on the nature of the direct process involved.

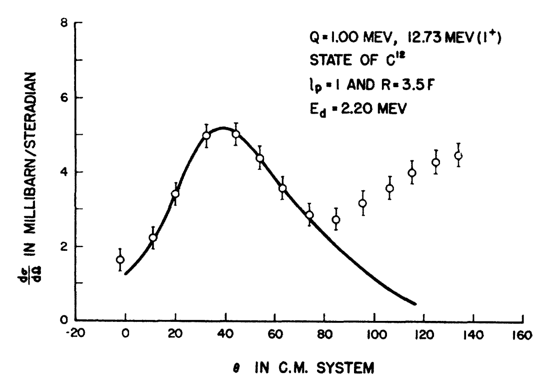

FIG. 8. Butler theory fit to the observed $B^{11}(d,n)C^{12*}$ (E_x=12.73 MeV) neutron angular distribution averaged over deuteron energy range from 2.08 to 2.38 MeV (see text). A cutoff radius of 3.5 F was used with l_p=1.

[19] C. K. Bockelman, A. Leveque, and W. W. Buechner, Phys. Rev. **104**, 456 (1956).

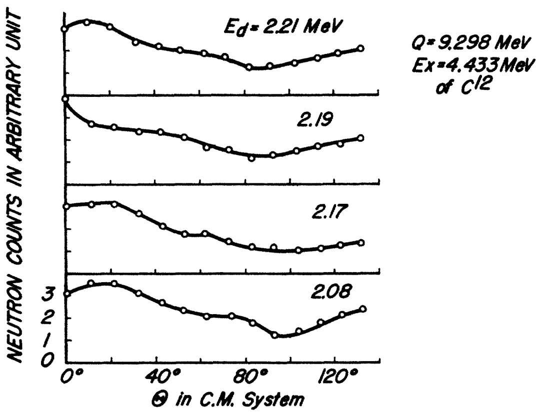

FIG. 9. Angular distributions of neutrons from $B^{11}(d,n)C^{12*}$ leaving the C^{12} nucleus with 4.43 MeV of excitation energy. Deuteron energy in MeV is indicated for each distribution.

Furthermore, the neutrons produced by direct process would have more or less the same angular dependence for all neutron energy range under consideration at a given incident E_d. The above general properties stated for the continuum neutrons are inferred from the following considerations: For the direct process the angular dependence of the cross section is entirely contained in the matrix element connecting the final state to the initial state[20] and this matrix element should be fairly insensitive to the neutron energy variation of the magnitude shown in Fig. 10, while the compound process would require angular dependence symmetric about 90 deg in order to conserve parity.[21] Figure 10 shows very strong and pronounced forward-angle peaking for each of the four different arbitrarily chosen neutron energy intervals.

IV. DISCUSSION AND CONCLUSION

Wilkinson's argument pertaining to the conditions on the Q value of a reaction and the incident deuteron energy for a good stripping reaction is consistent with the demonstrated results of the present work. The experimental angular distributions of neutrons with $Q=-1.37$ and $+1.00$ MeV are in excellent agreement with simple theory while the neutrons associated with high Q values show rather poor theoretical fits. The fact that the above comparison is made for the neutron producing reactions involving the same initial state makes the comparison very meaningful since the approximations made in the theory are common to all neutron producing reactions by the deuteron bombardment of B^{11} as far as the initial state is concerned. Therefore, the deviations of the Butler theory from the experimental results for high-Q reactions may be mainly due to invalid final-state approximations. Distorted-wave deuteron stripping cross sections are being calculated for the reactions discussed thus far. The results should be very interesting since Gibbs and Tobocman[22] upon making distorted-wave Born approximation computations as a function of Q for the reaction $C^{12}(d,p)C^{13}$ were not able to confirm Wilkinson's hypothesis. Instead they suggest that the Coulomb distortion effects on the angular distribution tend to cancel the nuclear distortion effects. Also they point out that at low Q values and low deuteron energies the distorted-wave angular distribution and the Butler distribution, while not identical, are similar enough in shape that they can be brought into agreement by suitable choices of cutoff radii.

The existence of a compound state at $E_d=2.18$ MeV for B^{11} plus d system is substantiated by present work supporting the 15.11-MeV gamma-ray work of reference 8. The method of eliminating the interference effect between the compound nucleus and the deuteron stripping reactions devised by investigators cited in reference 20 is shown to be applicable in this instance.

It is very puzzling to note that the heavy-particle stripping mode makes sizable contributions to all the observed stripping reactions $B^{11}(d,n)C^{12}{}_{g.s.}$ and $B^{11}(d,n)C^{12*}$ except the reaction leading to 15.11 MeV (1^+) state of C^{12}. It is also interesting to note that the maximum value of differential cross sections for $l_p=1$ capture reactions of $B^{11}(d,n)C^{12*}$ is about 5 ± 1 mb/sr.

The major contribution to the continuum neutrons are from the many-body breakup of the B^{11} plus d system into $n+\alpha+Be^8$, $n+3\alpha$, or both, and the mechanism for the breakup seems to be a direct process of a kind yielding very strongly forward-angle peaked angular dependence.

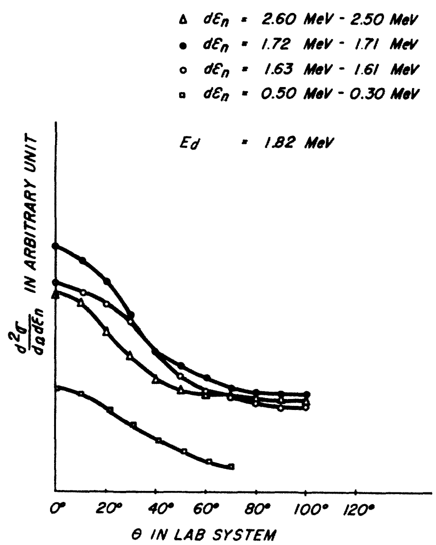

FIG. 10. Angular distributions of the continuum neutrons from the deuteron bombardment of B^{11} with $E_d=1.82$ MeV. Each curve is the average over the neutron energy interval indicated.

[20] S. T. Butler and O. H. Hittmair, *Nuclear Stripping Reactions* (John Wiley & Sons, Inc., New York, 1957), p. 19.
[21] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 532.
[22] R. C. Gibbs and W. Tobocman, Phys. Rev. **124**, 1496 (1961).

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APPENDIX

The reduced width can be regarded as a product of two factors. Of these factors, the first is a measure of the probability that, in the initial nuclear state, all but one of the nucleons find themselves in an arrangement corresponding to the final state; the second factor measures the probability that, when this happens, the remaining nucleon appears as the reaction product.

The following equation gives the stripping reduced width as defined by Macfarlane and French[23] and modified for the present case:

$$\theta^2=\frac{d\sigma}{d\Omega}\left\{61.2\left[\frac{m+1}{m+2}\right]^2\left[\frac{2J_f+1}{2J_i+1}\right]\left(\frac{E_n}{E_d}\right)^{1/2}R^3\sigma_{\rm tab}\right\}^{-1}$$

where m is mass of target nucleus, J_i and J_f are the spins of the target and residual nucleus, respectively, E_d and E_n are the deuteron and neutron energies as determined in the rest frame of the target and residual nucleus, respectively, R is the interaction radius, and $\sigma_{\rm tab}$ is the angular distribution function tabulated in reference 15.

[23] M. H. Macfarlane and J. B. French, Rev. Mod. Phys. **32**, 567 (1960).

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Properties of F^{20}†

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The half-life of F^{20} is 11.36±0.07 sec. The thermal $F^{19}(n,\gamma)F^{20}$ cross section is 10.09±0.70 mb. Limits on the improbable decay modes of F^{20} were obtained.

BECAUSE of astrophysical applications and because of relevance to nuclear models, there has been, lately, interest in the $A=20$ nuclei.[1] We present our results for limits on improbable decay modes of 11-sec F^{20}, for the half-life of F^{20}, and for the thermal neutron capture cross section of F^{19}. In all our experiments, F^{20} was made by neutron capture in Teflon,[2] $(C_2F_4)_n$, in the 10^9/sec cm^2 thermal neutron flux density available at the 4-ft-thick graphite thermal column of the Pennsylvania State University 200-kW "swimming pool" reactor.

LIMITS ON IMPROBABLE DECAY MODES

A strong and constant F^{20} source was made by running with an electric motor a continuous 55-ft-long Teflon belt, 0.02 in. thick, $2\frac{1}{2}$ in. wide, through the slow neutron flux, out of the reactor pool water, past the counters, and back again. The usual decay proceeds[3,4] from the 2+ F^{20} by 5.42-MeV β^- emission to the 2+ 1.63-MeV state of Ne^{20}, and then to the 0+ ground state by 1.63-MeV γ emission.

We searched for the direct 7.05-MeV ground state β^- as follows: The beta spectrum of the belt was observed with a 3-in.-diameter, 2-in.-thick plastic phosphor,[5] a Dumont 6363 photomultiplier, a preamplifier, and a Radiation Counter Laboratories 128-channel analyzer. To reduce the background, a $\frac{1}{16}$-in.-thick sheet of plastic phosphor[5] was placed between the source and the 3 in. × 2 in. phosphor, and the multichannel analyzer was gated by pulses from the sheet. The background was thus reduced appreciably. The probability of γ interactions in the thin sheet was small, and those β rays that traveled in the correct direction were selected. The distance between the source and the $\frac{1}{16}$-in. sheet was 21 in., and the distance between the $\frac{1}{16}$-in.

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[1] J. A. Kuehner, Phys. Rev. **125**, 1650 (1962) and references therein.
[2] Teflon, grade 770M, was obtained from the Polymer Corporation of Pennsylvania, Reading, Pennsylvania.
[3] E. Freiberg and V. Soergel, Z. Physik **162**, 114 (1962).
[4] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).
[5] SC-700 Plastic Phosphor obtained from R.E.A.C., Crystals Division, Lynbrook, New York.