Gamma-Ray Correlations from the Reaction $B^{10}(d,p)B^{11}$†

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The $B^{10}(d,p)B^{11}$ reaction was studied at a deuteron bombarding energy of 1.2 Mev. Angular distributions and proton-gamma correlations associated with transitions to the first and second excited states of B^{11} were obtained.

An analysis including the effects of heavy-particle stripping has been performed for the first excited state transition and is consistent with the observed distribution and correlation.

I. INTRODUCTION

THE reaction $B^{10}(d,p)B^{11}$ has been the subject of many experimental and theoretical studies.[1,2] Over a wide range of energies, the angular distributions of the proton groups resulting from transitions to the excited states of B^{11} are not adequately explained by compound nucleus or deuteron stripping theories. This paper is concerned with the proposal that the heavy-particle or exchange stripping mode may be a contributing factor in the angular distributions and correlations in this reaction.[3–5]

An analysis of this reaction using one exchange term was performed by French and Evans[2]; however, the primary heavy-particle stripping term was not included in the final analysis, and agreement was obtained by incorporating an arbitrary isotropic term (see Fig. 5 of the second paper).

To review briefly, the deuteron stripping mode is evidenced, in cases of small capture angular momentum, by a peaking of the proton angular distribution in the forward direction relative to the deuteron beam direction. In Born approximation the p-γ correlation function maintains the same form for the excited state transitions as the proton direction is varied. Peaking of the proton angular distribution in the backward direction relative to the deuteron beam axis may be taken as evidence of the heavy-particle stripping mode. Because each mode has a different orientation of preferred axes of quantization and different relative contributions to the reaction, the p-γ correlation function for the excited state transition can be shown to change characteristics for different outgoing nucleon directions.[5]

Angular correlations for the first and second excited states were measured at a deuteron bombarding energy of 1.2 Mev with the proton counter set at angles of 30, 90, and 150 degrees relative to the deuteron beam axis.

Experimental procedure, deuteron-heavy particle stripping theory, experimental results, and conclusions will be discussed in following sections.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

The B^{10} targets consisted of a mixture containing 92.1% B^{10} which was evaporated onto 0.05-mil nickel foil. These target foils were mounted on copper frames which were then placed in an evacuated target chamber. Targets were located at 45 degrees relative to the deuteron beam axis. These had to be rotated through 90 degrees to cover all proton angles. Proton distribution runs were made on both sides of the deuteron beam axis to check the centering of the target after rotation. Foil-covered windows provided exit ports for the outgoing protons.

For the p-γ correlation measurements, limited anode pulses from both the proton and gamma-ray photomultiplier tubes (RCA 6342A) were amplified in distributed amplifiers and passed into a standard, biased diode fast coincidence circuit. Resulting coincidence pulses were amplified and a pulse-height discriminator was used to select coincidence pulses above a certain height. The discriminator output then passed into one side of a slow coincidence circuit.

The output of the tenth dynode of the gamma-ray photomultiplier was used as a sidegate. The dynode output was amplified and an integral discriminator selected pulses of an appropriate height. The discriminator output was fed into the other side of the slow coincidence circuit, and the output of the slow coincidence circuit was used to gate a forty-channel pulse-height analyzer. When gated the analyzer accepted the appropriate proton pulse from the tenth dynode of the proton photomultiplier tube. Figure 1 shows the electronic arrangement.

The proton monitor, which supplemented a Faraday cup-current integrator system, consisted of a NaI crystal mounted on a photomultiplier tube. The tube assembly was fixed to a port in the target chamber cover. The output of this circuit was amplified and fed into an integral discriminator, the level of which was

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[1] J. Thirion, Ann. phys. 8, 489 (1953); S. A. Cox and R. M. Williamson, Phys. Rev. **105**, 1799 (1957); **105**, 1801 (1957); B. Zeidman and J. M. Fowler, Phys. Rev. **112**, 2020 (1958).
[2] A. P. French, Phys. Rev. **107**, 1655 (1957); A. P. French and N. T. S. Evans, Phys. Rev. **109**, 1272 (1958). Because this analysis utilized an expansion in terms of deuteron stripping amplitudes the heavy-particle stripping term was not readily calculated. The calculation presented incorporated the effects of distortion at the forward angles caused by proton "knock-on."
[3] G. E. Owen and L. Madansky, Phys. Rev. **105**, 1766 (1957).
[4] T. Fulton and G. E. Owen, Phys. Rev. **108**, 789 (1957).
[5] S. Edwards, Phys. Rev. **113**, 1277 (1959).

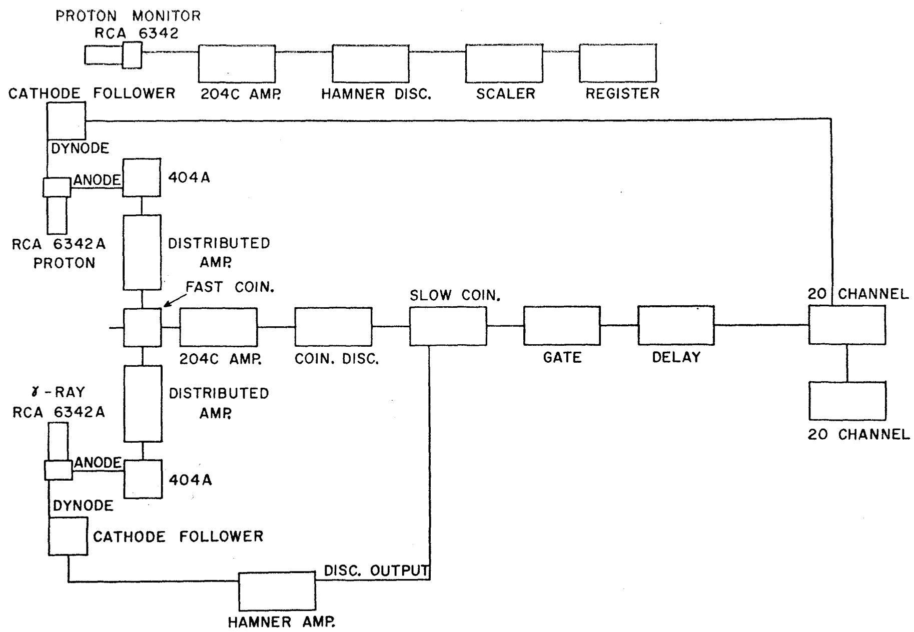

FIG. 1. A block diagram of the electronic arrangement.

set to accept only those pulses from protons which resulted from transitions to the ground state of B^{11}.

Experimental p-γ corrections were taken with the proton counter set at angles of 30, 90, and 150 degrees relative to the deuteron beam axis. The gamma-ray detector was rotated through 30 degree angles relative to the fixed proton angle. By requiring the p-γ coincidence pulse to be in coincidence with the side gate gamma-ray pulse in the slow coincidence circuit, a gate pulse was formed which then opened the 40-channel analyzer to accept proton pulses, and the appropriate proton pulse appeared in the proper channel range. The number of proton pulses appearing in each peak was considered as the number of proton-gamma ray coincidences. The gated and ungated proton spectra are shown in Figs. 2 and 3.

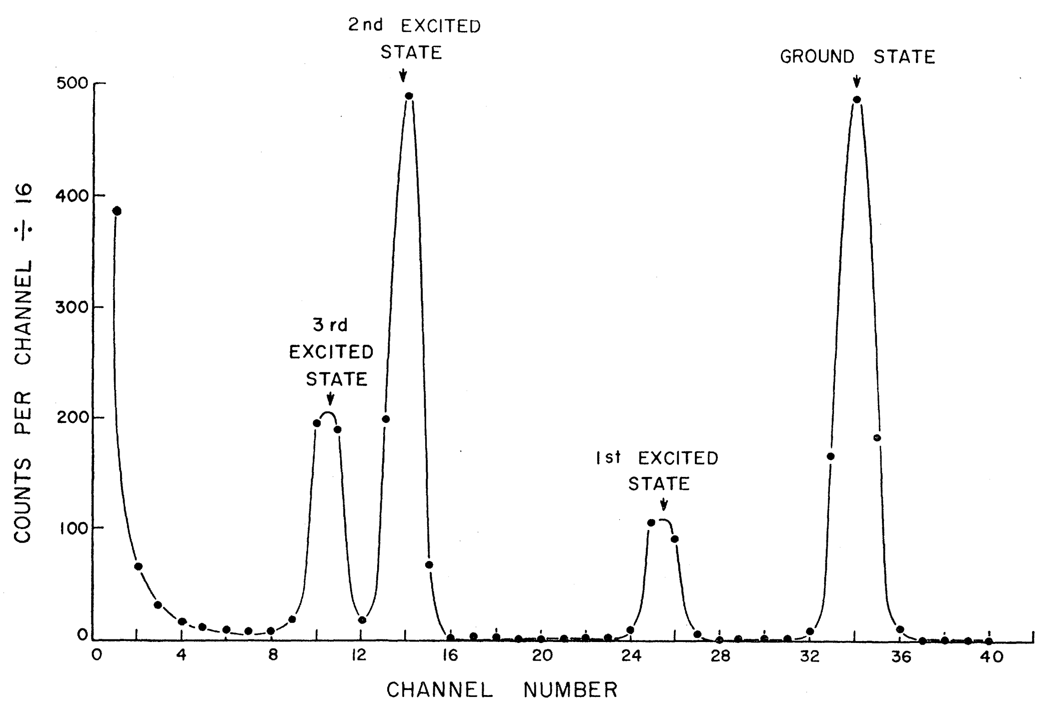

FIG. 2. Proton pulse-height spectra taken at a scattering angle of 90° with an incident deuteron energy of 1.2 Mev. This is an ungated spectrum.

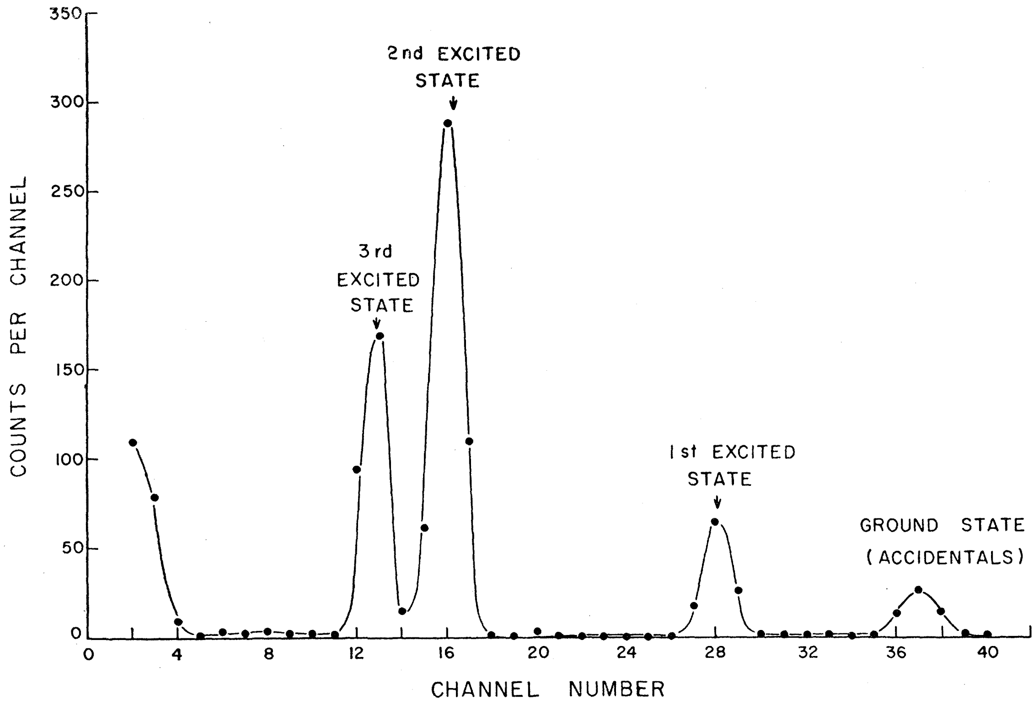

FIG. 3. Proton pulse-height spectra in coincidence with the 2.13-Mev gamma ray.

A measure of the accidental coincidences occurring during a run was made by use of the coincidence pulses appearing in the ground-state peak. There is no gamma ray associated with the reaction leading to the ground state of B^{11}. Consequently, any coincidence pulse appearing in the ground-state channel during a proton-gamma ray correlation run represents an accidental coincidence. If σ_e and σ_g are the respective cross sections

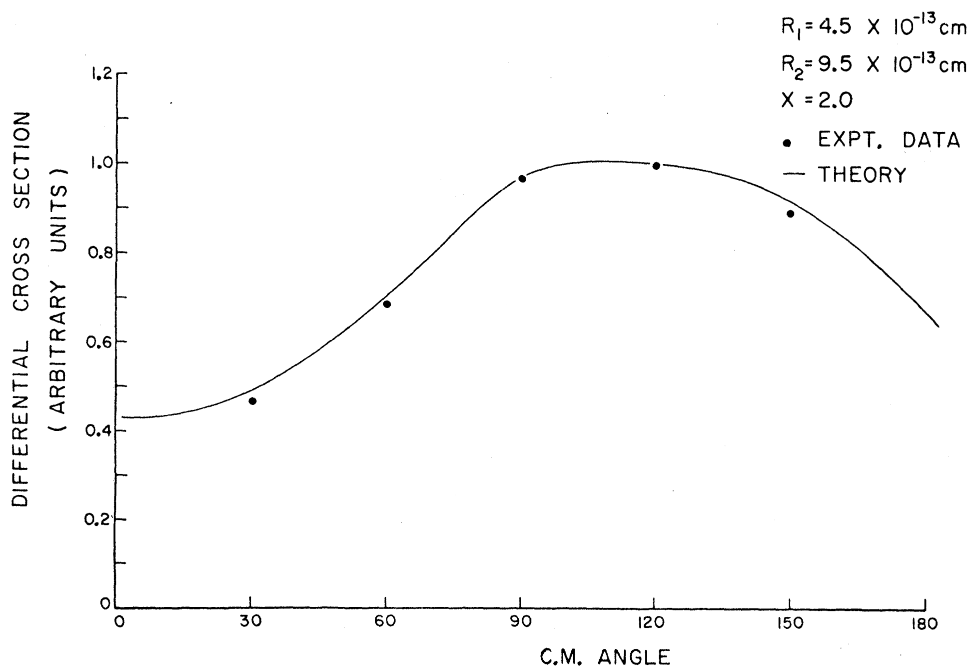

FIG. 4. Angular distribution of the protons from the reaction $B^{10}(d,p)B^{11}$ to the first excited state of B^{11} corresponding to an incident energy of 1.2 Mev. The solid curve represents the theoretical fit incorporating both deuteron and heavy-particle stripping according to Eq. (24).

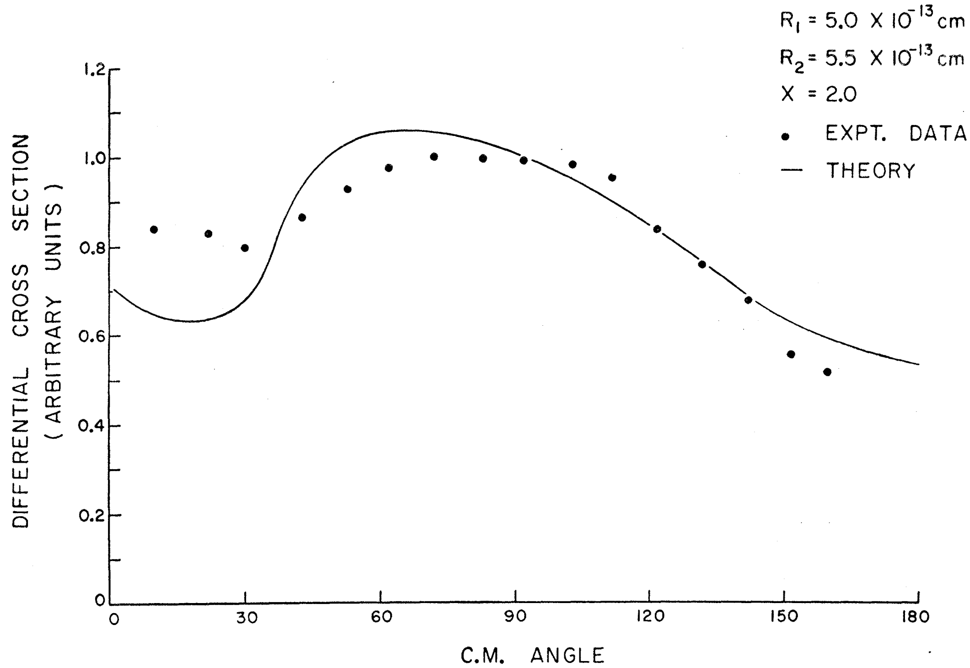

FIG. 5. Theoretical angular distribution for the angular distribution of the first excited state transition for a bombarding energy of 2.5 Mev. The data shown are those of reference 4.

for the excited and ground-state proton groups, and N_e is the number of coincidence pulses appearing in the excited state peak, then $N_e \times \sigma_e/\sigma_g$ is taken to be the number of accidentals for the excited state. This method for determining the accidentals was checked at the three proton detector angles by inserting approximately 45 feet of additional cable between either distributed amplifier and the fast coincidence circuit. Under these conditions, all coincidence pulses were accidental and the number so recorded was in agreement with those determined above.

III. THEORY

The angular correlation and distribution functions are developed according to Edwards.[5]

For the purposes of analysis it is assumed that the J–J coupling scheme and shell model are valid for the $B^{10}(d,p)B^{11}$ reaction. The choice of coupling scheme is arbitrary, and the L–S or channel spin coupling could have been used. In this reaction under study the B^{10} target nucleus is considered as a Be^9 core plus a $p_{\frac{3}{2}}$ proton. Although there is a possible choice between the three protons in the outer shell of B^{10}, Edwards has shown[5] that the same contribution for the exchange process is expected from any one of the three. Consequently, including the three protons only introduces a constant factor.

The final-state nucleus for deuteron stripping mode will consist of a B^{10} nucleus plus a neutron, while that for the heavy-particle mode will consist of a Be^9 core plus a proton and a neutron. The coupling of the angular momenta for the two modes must be such that the correct final-state angular momenta result.

The angular correlation for the first excited state is isotropic if one assumes the following quantum numbers:

$$J_B=3;\quad J_f=\tfrac{3}{2};\quad J_e=\tfrac{1}{2};\quad l_n=3;\quad J_n=\tfrac{5}{2};\quad l_c=2;$$
$$J_c=\tfrac{1}{2};\quad j_e=\tfrac{3}{2};\quad J_p=\tfrac{3}{2};\quad j_n=\tfrac{1}{2};\quad j_p=\tfrac{1}{2};\quad j_d=1.$$

The subscript B refers to B^{10}; f refers to the ground state of B^{11}; e to the first excited state of B^{11}; n to the captured neutron; c to the Be^9 core for the proton in B^{10}; and p to the outgoing proton. The J_k's are total angular momenta, and the j_m's are spin angular momenta.

Using the development of Edwards the correlation is of course isotropic and the angular distribution is of the form

$$\begin{aligned}\frac{d\sigma}{d\Omega}\propto &\,|G(K_1)F_{l(n)}(k_1R_1)|^2\\ &+(0.325\sin^4\alpha+0.917\sin^2\alpha\cos^2\alpha\\ &+0.376\cos^4\alpha)\left|\frac{\Lambda_1}{\Lambda_2}G(K_2)F_{l(d)}(k_2R_2)\right|^2\\ &-\{1.32(10)^{-2}(5.77-7.01\cos^2\beta)\cos\beta\sin^2\alpha\\ &+1.56(\cos2\beta)\sin\beta\sin2\alpha+(6.22\cos^2\beta\\ &-3.73)\cos\beta\cos^2\alpha\}\frac{\Lambda_1}{\Lambda_2}G(K_1)G(K_2)F_{l(n)}F_{l(d)}.\end{aligned}$$

α is the angle between the vectors $\mathbf{k}_2$ and $\mathbf{K}_2$; while β

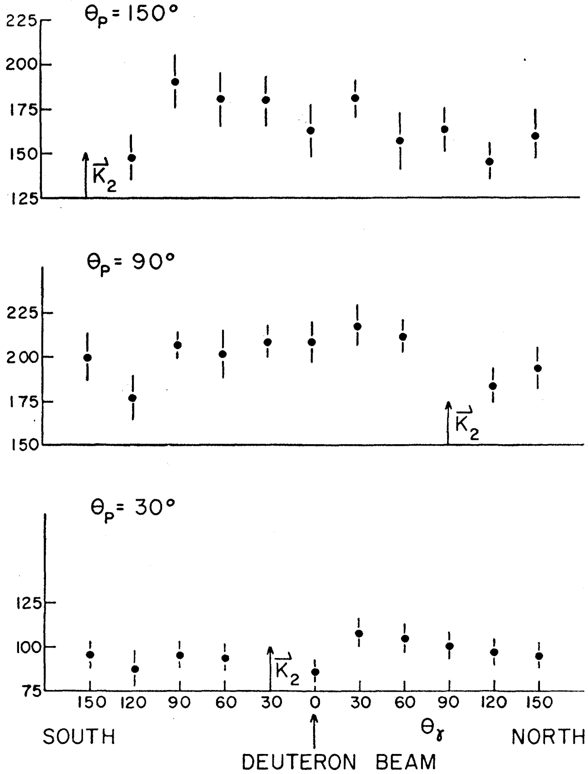

FIG. 6. Proton-gamma ray correlations for the first excited state transition at a bombarding energy of 1.2 Mev.

is the angle between $\mathbf{k}_1$ and $\mathbf{K}_2$. The remaining quantities are defined elsewhere.[3–5]

IV. RESULTS AND CONCLUSIONS

A. Transitions Leading to the First Excited State

The theoretical curve shown in Figs. 4 and 5 for the angular distributions of protons suggests that heavy-particle stripping is a consistent picture of the formation of the state at low bombarding energies. The measure of the relative contributions of the heavy-particle and deuteron stripping modes given by $\Lambda_1/\Lambda_2=2$ indicates a large contribution from heavy-particle stripping. This view is further supported by the necessary use of $l_n=3$ for deuteron stripping, which means that there is a low probability for the occurrence of this mode.

In the heavy-particle stripping mode, the core of the target nucleus and the deuteron must approach close enough for capture to occur. In the case for 1.2-Mev deuterons, the bombarding energy is approximately 0.7 Mev below the Coulomb barrier. Consequently the plane wave distortions are rather large, since both core and deuteron are positively charged. To account for these distortions in the theory, a large radius R_2 is required to fit the data.

At bombarding energies greater than 3 Mev, a forward peak[1] starts to develop in the angular distributions. This could possibly be explained by assuming

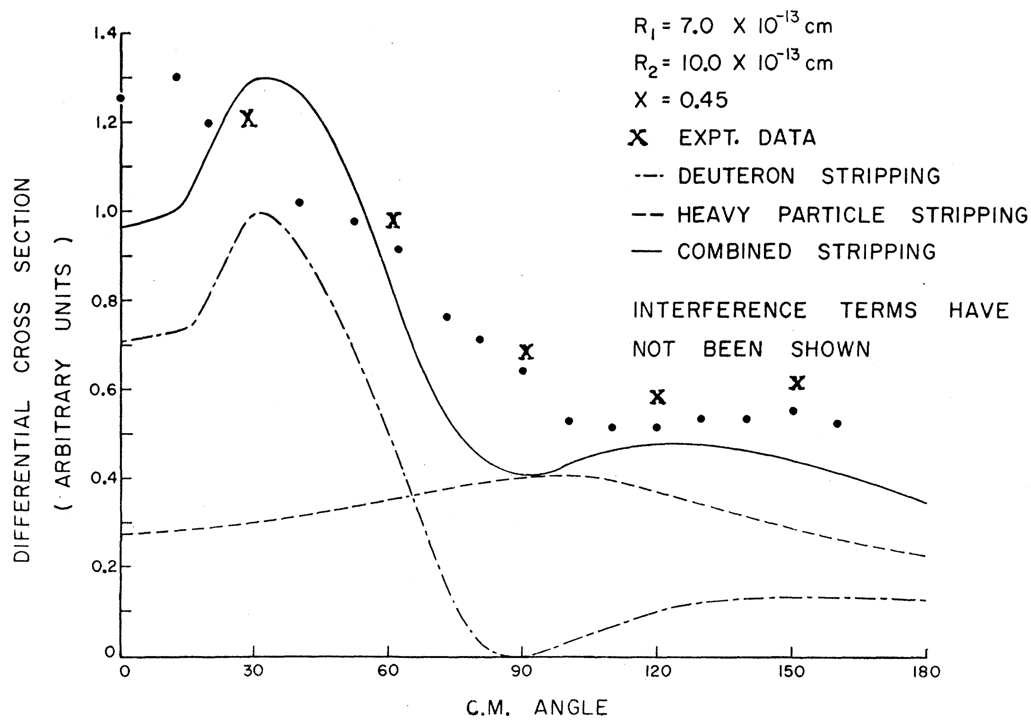

FIG. 7. Angular distribution of the neutrons corresponding to the second excited state transition at $E_d=1.2$ Mev. The data of Gorodetzky *et al.* [S. Gorodetzky, M. Crossiaux, A. Gallman, P. Fintz, J. Samuel, and G. Frich, Compt. rend. **248**, 550 (1959)] have been included as the filled circles.

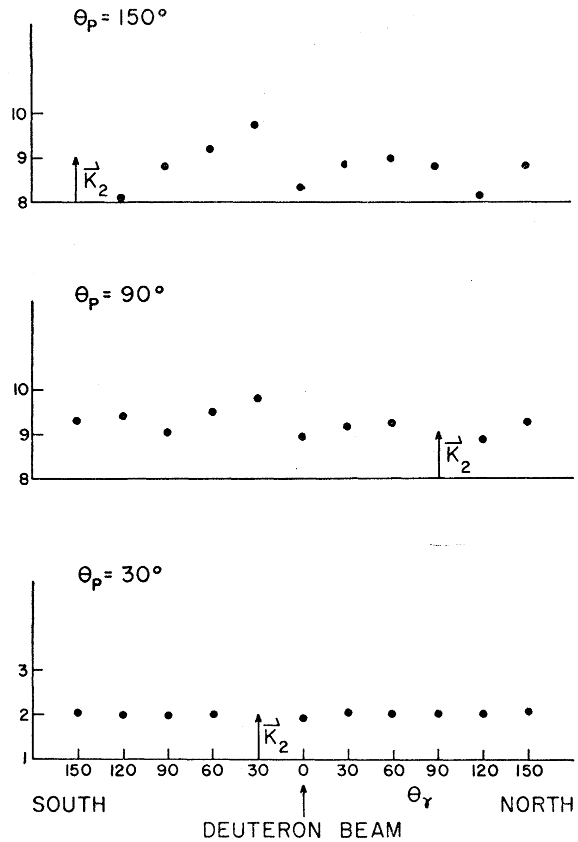

FIG. 8. Proton-gamma ray correlations for the second excited state transition at $E_d = 1.2$ Mev.

that competing reactions at higher energies are forcing the radius of the interaction to larger values in the case of deuteron stripping. This view, however, does not explain the peak centered about 70 degrees. This peak becomes more prominent at higher bombarding energies. The forward peak may be due to a process such as "spin-flip" which could become important at higher energies.[1,2,6] The peak at 70 degrees would then result from the deuteron stripping contribution, while the large fill-in at backward angles would result from heavy-particle stripping contributions.

The experimental correlation was found to be isotropic for three proton angles (Fig. 6). The most significant result is that the angular distribution can be accounted for by such a simple approach. The primary analysis still will require a distorted-wave analysis.

B. Transitions Leading to the Second Excited State

The simple curves in Fig. 7 for the proton distributions imply that heavy-particle stripping might also be important in the formation of this state. Experimental observations of Marion and Weber[7] at a bombarding energy of 2 Mev show a strong peak in the backward direction. This backward peaking of the angular distributions is characteristic of the heavy-particle stripping mode.

It should be noted here that no inference as to the magnitude of the interference term or angular coefficients can be made. The calculations must be carried out in their entirety to determine the sizes. In the case of the first excited state of B^{11}, the interference term was small relative to the deuteron and heavy-particle stripping terms; Edwards has found that for the case of $B^{11}(d,n)C^{12}$ the term is very large. The same statements hold for the angular coefficients also.

Additional evidence for heavy-particle stripping contributions in the formation of the second excited state comes from the experimental correlations at a bombarding energy of 1.2 Mev. As pointed out previously, the introduction of the heavy-particle stripping mode means that the correlation function may be a sensitive function of the proton detector angle. The experimental observations shown in Fig. 8 indicate strong changes when the proton counter is moved.

It should be noted that the preceding interpretations of the angular distributions and correlations in terms of combined deuteron and heavy-particle stripping modes are not unique. Compound nucleus effects which may contribute to the results have been neglected.

The fact that the correlation changes as the setting of the nucleon counter is varied does not uniquely determine the presence of a second mode in the reaction. As has been demonstrated by Satchler and Tobocman,[8] a polarization of the outgoing proton could also cause the form of the correlation function to change, since the coefficients of the correlation expansion are polarization dependent.

[6] J. E. Bowcock, Phys. Rev. **112**, 923 (1958).

[7] Jerry B. Marion and Gustav Weber, Phys. Rev. **103**, 1408 (1956).

[8] G. R. Satchler and W. Tobocman, Bull. Am. Phys. Soc. **5**, 30 (1960).