$B^{11}(d,n)C^{12*}{}_{4.43}$ (γ-n) Angular Correlations at 0.94 and 0.62 MeV†

W. F. HUANG* AND R. C. RITTER
Department of Physics, University of Virginia, Charlottesville, Virginia
(Received 26 December 1962)

(γ-n) angular correlations are reported for the $B^{11}(d,n)C^{12*}{}_{4.43}$ reaction at incident deuteron energies of 1 MeV and 0.7 MeV. Correlations were measured with the γ detector perpendicular to the reaction plane and with the detector in the reaction plane. The latter were taken with the neutron detector at 0°, 10°, 45°, 90°, 135°, and 150°. Strong P_4 terms appear in the reaction plane corrections. This suggests either (1) the presence of compound nuclear effects in the reaction, or (2) a more complicated stripping situation than has previously been assumed for this reaction.

I. INTRODUCTION

MEDIUM- and low-energy (d,n) and (d,p) reactions, as well as other ones, often have substantial cross sections at backward angles for the outgoing particles, even when stripping conditions seem to be well satisfied. For some of these cases, both the distorted-wave Born-approximation theory (DWBA) for ordinary stripping and the mixed mode (heavy particle plus ordinary) plane wave stripping theory predict such angular distributions. The $B^{11}(d,n)C^{12}$ reaction is one for which there has been considerable experimental[1–4] and theoretical[2–8] effort to find the mechanism which better accounts for this effect.

Additional experimentally furnished requirements, such as those from angular correlation and polarization measurements, provide the possibility of deciding between alternate explanations for the backward peaking. With this object, $B^{11}(d,n)C^{12*}{}_{4.43}$ (γ-n) angular correlations were previously measured for 2.65 and 5.35 MeV bombarding energies.[1] The analyses[1,3] of these data have not settled the question for this reaction. In this paper, we report the same type measurements at 0.7 and 1.0 MeV incident deuteron energies. The likelihood that heavy particle (h.p.) stripping should be relatively more important at lower energies in this case[5,7] suggested that this data might be more definitive between the two stripping mechanisms, providing compound nucleus effects did not become important.

† Sponsored by the U. S. Army Research Office (Durham) and the National Science Foundation.

* Now at the Research Laboratories for the Engineering Sciences, Charlottesville, Virginia.

[1] J. B. Garg, N. H. Gale, and J. M. Calvert, Nucl. Phys. **23**, 630 (1961).

[2] J. B. Garg, N. H. Gale, and J. M. Calvert, in *Proceedings of the Rutherford Jubilee International Conference*, edited by J. B. Birks (Heywood and Company, Ltd., Manchester, 1962), p. 573.

[3] R. A. Zdanis, C. A. Bruns, G. E. Owen, L. Madansky, and S. Edwards, Nucl. Phys. **28**, 550 (1961).

[4] O. Ames and G. E. Owen, Phys. Rev. **109**, 1639 (1958); O. Ames, G. E. Owen, and C. D. Swartz, *ibid.* **106**, 775 (1957).

[5] M. A. Nagarajan, University of Maryland Physics Department Technical Report No. 242, 1962 (unpublished).

[6] Steve Edwards, Jr., Phys. Rev. **113**, 1277 (1959).

[7] T. Honda and H. Ui, Progr. Theoret. Phys. (Kyoto) **25**, 635 (1961).

[8] D. Robson, Nucl. Phys. **33**, 594 (1962).

II. EXPERIMENTAL DETAIL[9]

Deuterons of 1 MeV and 0.7 MeV (nominal energies) were obtained from the University of Virginia 1 MV Van de Graaff accelerator (High Voltage Engineering Type J, Model N). A 25 deg bending magnet provided the energy analysis, in conjunction with a conventional slit arrangement. Energy spread in the beam is estimated at less than 1%.

Two different targets of enriched B^{11} (98.6%), deposited on 0.5 mm thick tantalum backings, were obtained from the Oak Ridge National Laboratory. One, 190 μg/cm^2 thick, was used with $E_d = 1$ MeV; the other, 293 μg/cm^2 thick, was used with $E_d = 0.7$ MeV. The estimated thicknesses to these deuterons were about 70 and 140 keV, respectively. The mean deuteron

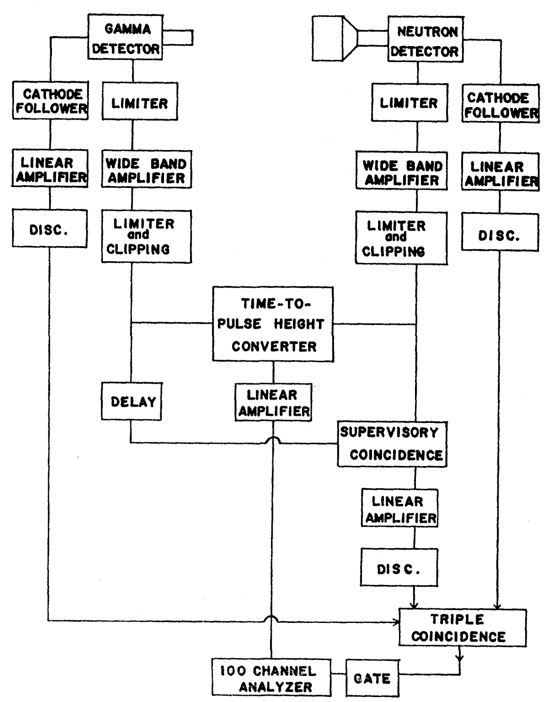

FIG. 1. Block diagram of electronic equipment for (n-γ) correlation measurements.

[9] W. F. Huang, Ph.D. thesis, University of Virginia (unpublished).

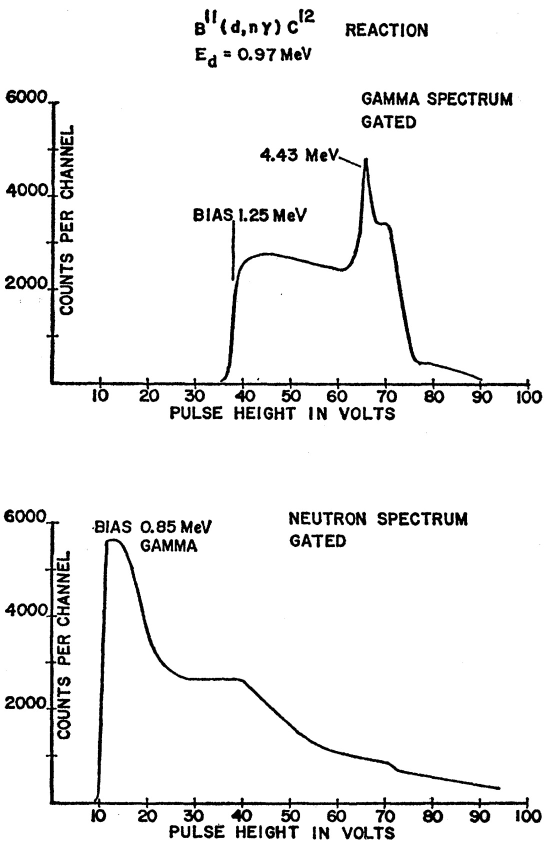

FIG. 2. Typical γ- and neutron-side channels scintillation pulse height spectra. Nonlinearity in the γ spectrum was caused by overvoltage on the photomultiplier.

energies in the targets, weighted by the reaction yield curve,[10] were 0.94 and 0.62 MeV.

A conventional neutron time-of-flight spectrometer, with a Green-Bell time-to-pulse-height converter,[11] was employed. A modified supervisory coincidence circuit[12] provided an unusually flexible arrangement for eliminating the double-valuedness in the overlap spectrum. Figure 1 is a block diagram of the electronics.

The neutron detector used a 5-in.×5-in. cylindrical NE102 plastic scintillator (Nuclear Enterprises, Ltd.) A $1\frac{1}{2}$-in.-diam×1-in. cylindrical NaI(Tl) scintillator detected the γ rays. We were able to get a lower background with NaI(Tl) for the γ detector, than with NE102. Both scintillators were mounted on 6342A photomultipliers which were operated with +1700 V at their anodes. A $4\frac{1}{2}$-in.-long truncated conical light pipe coupled the 5-in.-diam neutron scintillator to the 2-in.-diam face of the phototube. A $\frac{1}{4}$-in.-thick lead shield, inserted between the target and the γ counter, stopped fast electrons from the B^{12} target activity produced from the competing (d,p) reaction. Without the shield, a strong β spectrum was evident on the γ-detector singles spectrum. Figure 2 shows representative singles spectra and biases for each of the side channels.

A flight path of 0.9 m was used for the neutrons. Two different distances were used for the γ detectors. For the reaction plane correlations, the face of the γ detector was 8.7 cm from the target. For correlations with the γ detector perpendicular to the reaction plane, the γ detector distance was 10.3 cm.

The deuteron beam was collimated to approximately a $2\frac{1}{2}$-mm circular spot; the current ranged from 0.5 to 2 μA on the target. A current integrator measured the charge which was collected on the target. This was the primary monitor. A special Faraday cup arrangement was inserted inside the target holder. A 2-in.×2-in. plastic scintillator, with output biased to 3 MeV (γ rays), provided additional monitoring. The ratio of these monitor readings was used to check the condition of the target surface and of the electronics. Although a liquid nitrogen cold trap was installed 8 in. from the target, there were observable quantities of carbon deposited on the target from time to time. At such occasions, the target was shifted to a new spot, and the immediately preceding measurements were repeated. Suspect data were thrown out.

Counting rates in the individual channels varied with angular position. In the γ side channel after the discriminator, an upper limit of about 10 000 counts/sec

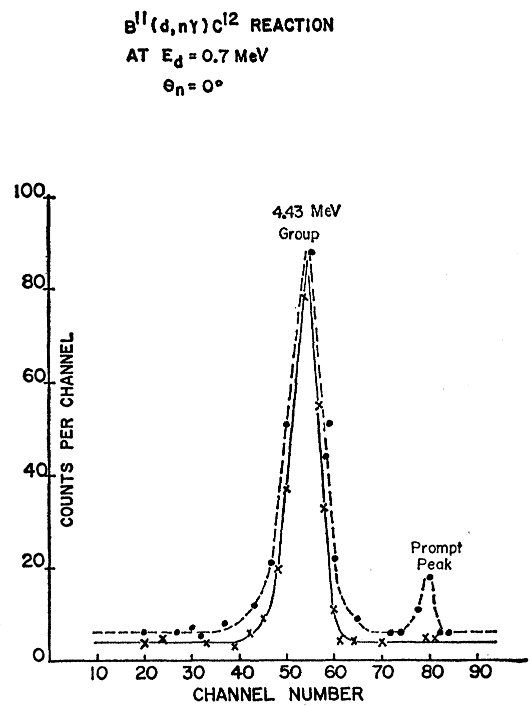

FIG. 3. Typical time-of-flight spectrum. The circles show the spectrum for incorrect adjustment of the supervisory circuit and the crosses show a spectrum for correct adjustment.

[10] W. H. Burke, J. R. Risser, and G. C. Phillips, Phys. Rev. **93**, 188 (1954).
[11] R. E. Green and R. E. Bell, Nucl. Instr. **3**, 127 (1958).
[12] W. F. Huang and R. C. Ritter, Bull. Am. Phys. Soc. **7**, 262 (1962).

was encountered; in the neutron channel this was about 3000 counts/sec.

Figure 3 shows a typical time-of-flight spectrum. (For clarity, only part of the channels are plotted.) The circles show a characteristic effect of having the supervisory coincident circuit bias incorrectly adjusted. Correct adjustment removes the prompt peak and lowers the background. The spectrum peak width (full width at half-maximum) was usually 4 to 5 nsec. This was small enough for observing the isolated level in this reaction.

The centering of the γ detector rotation system was tested experimentally and maintained to within $\pm 2\%$. For this, a Cs^{137} source of about 8 μC on a separate target backing was placed precisely at the reaction point. Attenuation corrections for the target backing and tubing were applied at the various angular test positions.

The known sources of experimental error have been studied, and we have the following estimates for their standard deviations under average conditions. (The actual values varied with the detector angles) as follows:

Counting statistics	4%
Decentering	2%
Current integrator	2%
Faraday cup imperfections	4%
Total rms	6.4%

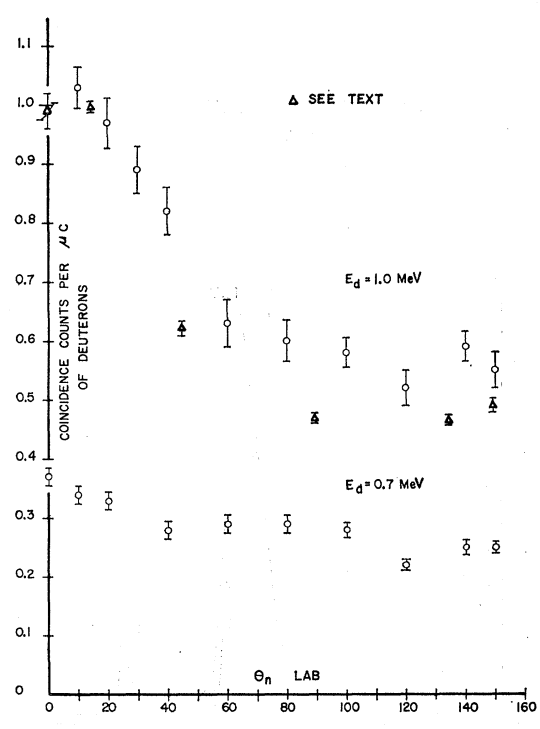

FIG. 4. (n-γ) correlations measured at $E_d = 1$ MeV and 0.7 MeV with the γ detector perpendicular to the reaction plane. The special points, marked with triangles, are the isotropic components of the reaction plane correlations, A_0. They are normalized at $\theta_n = 0°$. The different target thicknesses for data at the two energies have not been accounted for in this figure.

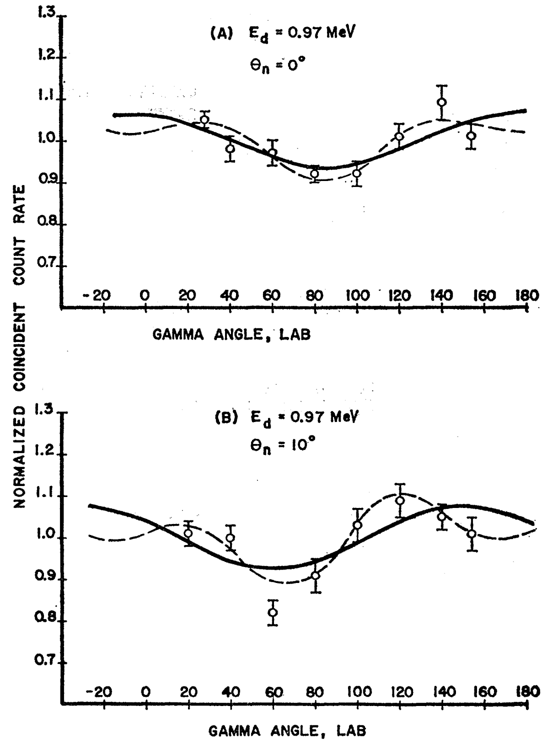

FIG. 5. (n-γ) correlations measured at 1 MeV with the γ detector varied in the reaction plane. The solid curves are: (A) $W = 1 + 0.072 \cos 2(\varphi - 175°)$; (B) $W = 1 + 0.075 \cos 2(\varphi - 150°)$. The dashed curves are: (A) $W = 1 + 0.054 \cos 2(\varphi - 171°) - 0.037 \cos 4(\varphi - 175°)$; (B) $W = 1 + 0.067 \cos 2(\varphi - 143°) + 0.069 \cos 4 \times (\varphi - 159°)$.

III. THE ANGULAR CORRELATION RESULTS

The reaction plane, containing $\mathbf{k}_d$ and $\mathbf{k}_n$, was horizontal in these experiments. The coordinate system and nomenclature used here is essentially that of Satchler and Tobocman.[13] The z axis is taken along $\mathbf{k}_d \times \mathbf{k}_n$ (downward), and the x axis ($\varphi = 0$) is along the deuteron beam direction, $\mathbf{k}_d$. θ and φ are the polar and azimuthal angles to the γ detector. The angle of the neutron detector, θ_n, is taken with respect to the x axis. Viewed along $\hat{z}$, θ_n is clockwise and positive φ is (unconventionally) taken to be counterclockwise.

Correlations with the γ detector perpendicular to the reaction plane (i.e., at $\theta = \pi$) approximate the neutron angular distribution. If the reaction were pure stripping and if $l_p = 1$, as has been found for this reaction by most experimenters in the past, the distorted wave theory[13] predicts that the equivalence would be exact. Figure 4 shows the results of our measurements of this type, at 1.0 and 0.7 MeV. For comparison, the figure also shows the values at 1 MeV of the isotropic component, A_0, of the reaction plane correlations. These were normalized to agree with the $\theta = \pi$ correlation at $\theta_n = 0$.

Correlation measurements with the γ detector in the

[13] G. R. Satchler and W. Tobocman, Phys. Rev. 118, 1566 (1960).

reaction plane are given in Figs. 5–9. The errors shown by bars are for counting statistics (including background error) only. Several correlations have been measured previously for this reaction at 1 MeV.[14]

The solid curves shown in the figures are those for a best fit to the function

$$W=A_0'+A_2'\cos 2(\varphi-\phi_0). \qquad (1)$$

Dashed curves are for a best fit to

$$W=A_0+A_2\cos 2(\varphi-\varphi_2)+A_4\cos 4(\varphi-\varphi_4). \qquad (2)$$

Both sets of curves were obtained by a nonlinear least-squares fitting program (adapted from a Chalk River program supplied by Dr. A. J. Ferguson and Dr. J. A. Kuehner) for the Burroughs 205 Computer at the University of Virginia. These results are listed in Table I. In the table, the parameters and their errors have been normalized by division by A_0. The parameters A_2 and A_4 have been corrected for the finite solid angle of the γ detector.[15] The neutron detector solid angle was

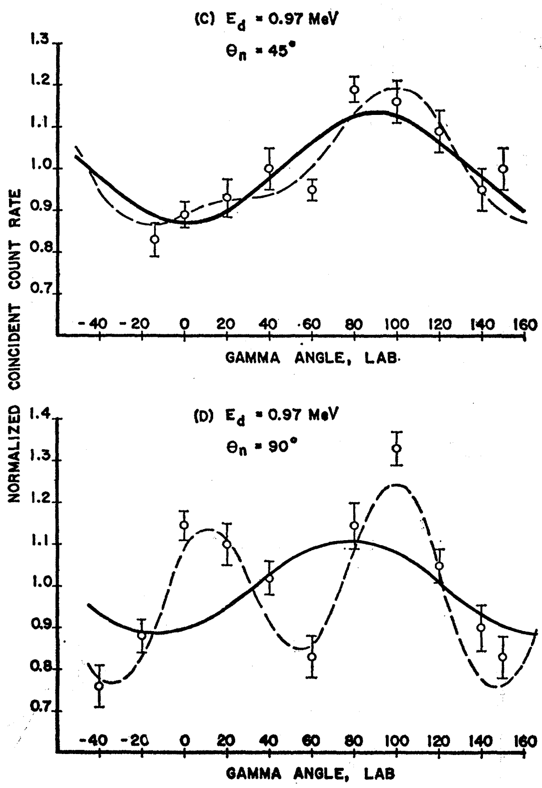

FIG. 6. (n-γ) correlations measured at 1 MeV with the γ detector varied in the reaction plane. The solid curves are: (C) $W=1+0.14\cos 2(\varphi-95°)$; (D) $W=1+0.11\cos 2(\varphi-77°)$. The dashed curves are: (C) $W=1+0.15\cos 2(\varphi-94°)+0.061\cos 4(\varphi-103°)$; (D) $W=1+0.065\cos 2(\varphi-81°)$; (D) $W=1-0.22\cos 4(\varphi-55°)$.

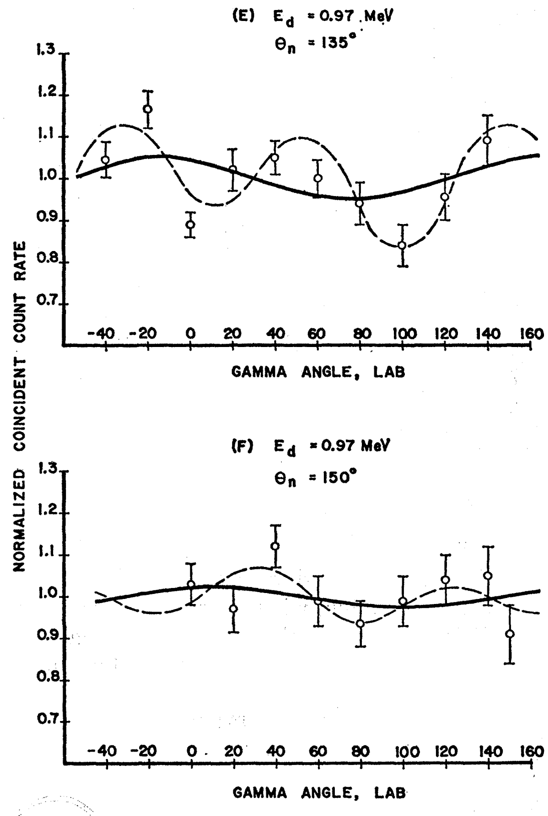

FIG. 7. (n-γ) correlations measured at 1 MeV with the γ detector varied in the reaction plane. The solid curves are: (E) $W=1+0.051\cos 2(\varphi+14°)$; (F) $W=1+0.025\cos 2(\varphi+10°)$. The dashed curves are: (E) $W=1+0.052\cos 2(\varphi-1°)+0.13\cos 4\times(\varphi-56°)$; (F) $W=1+0.025\cos 2(\varphi-25°)-0.057\cos 4(\varphi-77°)$.

only $\frac{1}{6}$ as large, and such corrections were not applied to it.

The sign of A_2 is changed if φ_2 is shifted 90° and the sign of A_4 is changed if φ_4 is shifted 45°. Thus, there is a certain arbitrariness in the listed signs of A_2 and A_4 and in the values of φ_2 and φ_4.

We have chosen φ_2 (and φ_0) so that A_2 is positive. Only a positive choice for A_2 is compatible with the calculated stripping correlation for this reaction when $l=1$ captures are considered and when the distortion parameter, λ, is defined as in references 13 and 16. Such a choice allows easier comparisons with stripping theory, although it does not have much meaning when the A_4 term is large enough to preclude the accuracy of $l=1$ stripping theory. The sign of A_4 was arbitrarily chosen, in Table I, to give the closest argeement of φ_4 to the classical recoil axis.

The need for the A_4 term is apparent in some cases. Both the relatively large value of A_4 compared to A_2, and the strong reduction in error when A_4 was included, are evidence for this. In some cases, the latter criterion must be replaced by the following one.

Table II lists the standard deviation of the points from the computer curve, in each case. These are defined

[14] G. C. Neilson, W. K. Dawson, F. A. Johnson, and J. T. Sample, Suffield Technical Paper No. 176, 1960 (unpublished).
[15] M. E. Rose, Phys. Rev. 91, 610 (1953).

TABLE I. Angular correlation parameters for computed best fits to Eqs. (1) and (2). Column 1 lists the nominal incident deuteron energy. The neutron detector angle is given in column 2. In column 3 the normalized value A_2 from Eq. (1) is listed. The corresponding φ_0 is given in column 4. Columns 5 through 8 list parameters from best fits to Eq. (2), but A_2 and A_4 have been normalized by division by A_0.

(1) E_d (Lab) MeV	(2) θ_n Degrees	(3) A_2'	(4) φ_0 Degrees	(5) A_2	(6) φ_2 Degrees	(7) A_4	(8) φ_4 Degrees
1.0	0	0.072±0.02	175±7	0.054±0.03	171±10	−0.037±0.03	175±9
1.0	10	0.075±0.03	150±12	0.067±0.01	143±5	0.069±0.01	159±3
1.0	45	0.14 ±0.03	95±7	0.15 ±0.03	94±6	0.061±0.03	103±8
1.0	90	0.11 ±0.08	77±19	0.065±0.03	81±12	−0.22 ±0.03	55±2
1.0	135	0.051±0.05	−14±32	0.052±0.03	1±19	0.13 ±0.03	56±4
1.0	150	0.025±0.03	−10±?	0.025±0.03	25±36	−0.057±0.03	77±8
0.7	0	0.24 ±0.02	177±2	0.18 ±0.01	177±0	−0.066±0	179±1
0.7	45	0.18 ±0.03	112±5	0.17 ±0.02	113±4	0.063±0.02	127±5
0.7	90	0.054±0.07	103±36	0.060±0.01	117±6	−0.21 ±0.01	49±1
0.7	150	0.055±0.04	100±20	0.079±0.03	90±9	0.11 ±0.02	52±4

in the conventional way:

$$\delta_M = [\textstyle\sum_i \omega_i (y-y_i)^2/(N-M-1)]^{1/2}, \qquad (3)$$

where ω_i is the normalized weight of the ith point, y_i is its measured W value, y is the computed value from the "best" fit, N is the number of data points in the fit, and M is the number of coefficients used (3 or 5).

The tabulated values of δ are to be compared with the *a priori* estimated experimental errors. In a previous section these were estimated to be about 0.06, although they vary slightly with detector positions. At $E_d=0.7$ MeV and $\theta_n=0°$ the 5-parameter fit is much better than expected, probably because of the (necessarily) small number of data points in that case, 7, relative to the number of adjustable parameters. However, for neutron

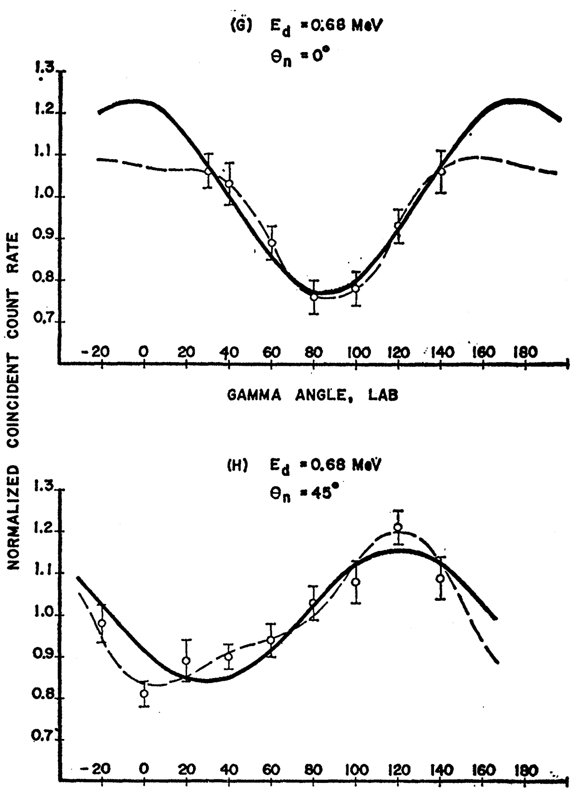

FIG. 8. (n-γ) correlations measured at 0.7 MeV with the γ detector varied in the reaction plane. The solid curves are: (G) $W=1+0.24\cos2(\varphi-177°)$; (H) $W=1+0.18\cos2(\varphi-112°)$. The dashed curves are: (G) $W=1+0.18\cos2(\varphi-177°)-0.066\cos4\times(\varphi-179°)$; (H) $W=1+0.17\cos2(\varphi-113°)+0.063\cos4\times(\varphi-127°)$.

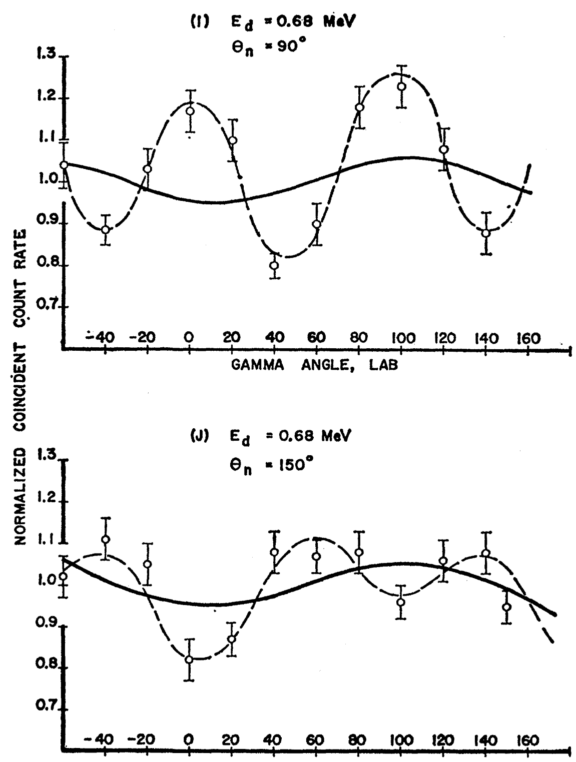

FIG. 9. (n-γ) correlations measured at 0.7 MeV with the γ detector varied in the reaction plane. The solid curves are: (I) $W=1+0.054\cos2(\varphi-103°)$; (J) $W=1+0.055\cos2(\varphi-100°)$. The dashed curves are: (I) $W=1+0.060\cos2(\varphi-117°)-0.21\cos4(\varphi-49°)$; (J) $W=1+0.079\cos2(\varphi-90°)+0.11\cos4(\varphi-52°)$.

angles beyond 45°, δ_5 is in each case nearer 0.06 than is δ_3. Therefore, because the 3-parameter fit is inadequate at backward angles, we have only made comparison with $l=1$ stripping theory for neutron angles 0°, 10°, and 45°. In notation similar to that of reference 13 the reaction plane correlation is

$$W_{\text{II}}=1+\alpha\cos^2(\varphi-\varphi_0), \tag{4}$$

where φ_0 is the shift angle of Eq. (1) listed in Table I.

The correlation in the plane perpendicular to the symmetry axis of W_{II} is

$$W_{\perp}=1+\beta\cos^2\theta. \tag{5}$$

W_{II} is obtained by transforming the above 3-parameter fit, (1). The ratio, $W_{\perp}(\pi/2)/W_{\perp}(\pi)$ was obtained by combining data from the reaction plane and $\theta=\pi$ correlations.[9] Values of α and β are listed in Table III. The parameter λ in column (5) is the distortion parameter defined by Huby *et al.*[16] and Satchler and Tobocman.[13] It is related to α and β as follows:

$$\lambda=\frac{1}{1-2\beta/\alpha}. \tag{6}$$

Only 3 of the 5 values of λ listed in Table III fall in the $l=1$ stripping range, $0\leq\lambda\leq 1$. However, for $\theta_n=10°$ and $E_d=1$ MeV, the errors almost include $\lambda=1$. (The errors in λ have peculiar ranges due to the hyperbolic character of λ vs β/α.) In Table III, only for $E_d=1$ and $\theta_n=45°$ does the data clearly exclude an $l=1$ stripping value for λ.

IV. DISCUSSION

Figure 10 shows our approximate angular distributions along with those taken at Manchester with higher bombarding energies. These curves suggest that the reaction processes are changing in the encompassed energy range. The dip at 0° in the 1-MeV curve, and the "humps" at about 90° for both the 1-MeV and 0.7-MeV angular distributions seem to be real. Additional runs at specific points confirmed this. These extra data were not included in the points of Fig. 10, as they were for incomplete angular distributions, and were not compatibly normalized.

The experimental reaction plane correlation parameters are summarized in Figs. 11 and 12. (φ_4 is not plotted in Fig. 11, as its 45° redundancy, including sign changes in A_4, allows little confidence in the systematic variation which would be determined.) Curves showing the recoil axis are shown for comparison. The Man-

TABLE II. Errors estimated by the computer fitting program. Column 1 lists the nominal incident deuteron energy. In column 2 the neutron detector angle is listed. Column 3 gives the number of data points used in each fit. Columns 4 and 5 are the calculated standard deviations for fitting the data to Eqs. (1) and (2), respectively. The values of δ are calculated from Eq. (3).

(1) E_d (Lab) MeV	(2) θ_n Degrees	(3) N	(4) δ_3	(5) δ_5
1	0	8	0.055	0.055
1	10	8	0.086	0.031
1	45	10	0.110	0.102
1	90	11	0.276	0.098
1	135	10	0.125	0.079
1	150	9	···	0.070
0.7	0	7	0.028	0.004
0.7	45	9	0.070	0.045
0.7	90	11	0.292	0.051
0.7	150	12	0.094	0.059

TABLE III. Parameters estimated for comparison with DWBA stripping theory for forward neutron detector angles. Column 1 gives the nominal deuteron bombarding energy and column 2 lists the neutron detector angle. In column 3, α is listed as calculated from Eq. (4). In column 4, β is listed as calculated from Eq. (5) and the method mentioned in the text. The distortion parameter of Eq. (6) is listed in column 5. Under each value of λ is given the range of λ allowed by the extremes of the listed errors in α and β. See the text for further details.

(1) E_d (Lab) MeV	(2) θ_n Deg	(3) α	(4) β	(5) λ
1	0	0.15±0.02	0±0.06	1 (0.6 to 13)
1	10	0.15±0.03	0.08±0.06	17 (−0.8 to 1.3)
1	45	0.31±0.04	0.30±0.07	−1.06 (−0.6 to −3.1)
0.7	0	0.60±0.05	0±0.05	1 (0.9 to 1.2)
0.7	45	0.39±0.05	−0.20±0.05	0.49 (0.4 to 0.6)

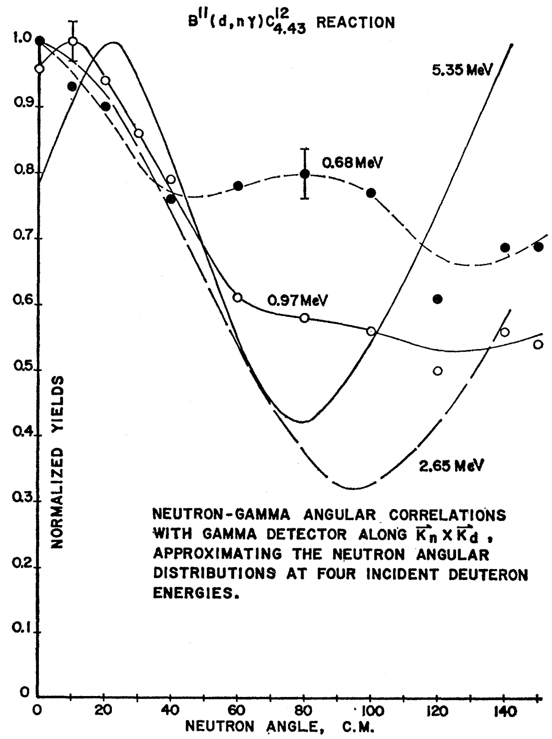

FIG. 10. Comparison of approximate angular distributions at 4 energies. The curves at 2.65 and 5.35 MeV are from reference 1. $Q=9.30$ MeV.

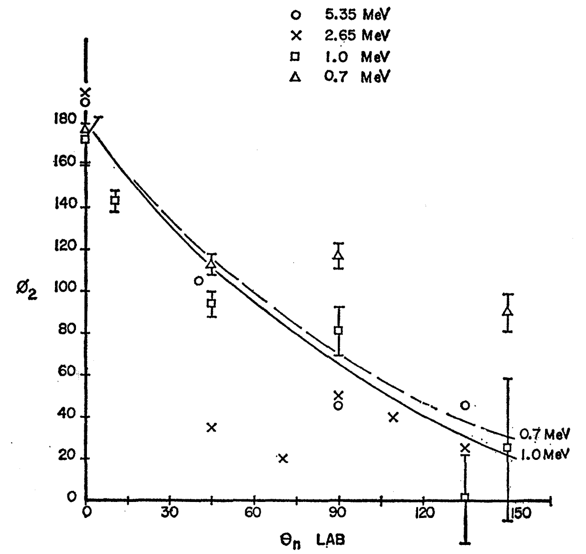

FIG. 11. Symmetry angles of second order component in "best fits" of reaction plane correlations vs neutron detector angle. The open circles and crosses (without error bars) are data from reference 1.

chester data at 2.65 MeV and 5.35 MeV are also plotted (without error bars). At neutron angles 90° and greater, the higher energy data are nearer the recoil axis. However, the deviations of the lower energy data from the recoil axis are not in one direction only; it seems unlikely that even a qualitative inference about the reaction mechanism can be drawn at this time from the angles of the symmetry axis.

In Fig. 12, the general similarity of the 1.0 and 0.7 MeV coefficients, within experimental errors, is striking. Ordinarily, this would be improbable for a compound nuclear process, either of an isolated resonance or of the "Ericson fluctuation" type.[17] However, the relatively thick targets which were used could have masked such effects.

The A_4 term dominates for neutron angles 90° and higher. This is significant in considering the reaction mechanisms. However, present theories have not yet been carried to the point of a detailed quantitative prediction of this nature. Previous analyses of this reaction have not included the following three effects in any detail: (1) compound nucleus effects; (2) ordinary (distorted wave) stripping with an $l_p=3$ component; (3) heavy-particle stripping which allows a complexity ≥ 4 in the angular correlation. It is probable that at least one of these is needed to explain the low-energy data.

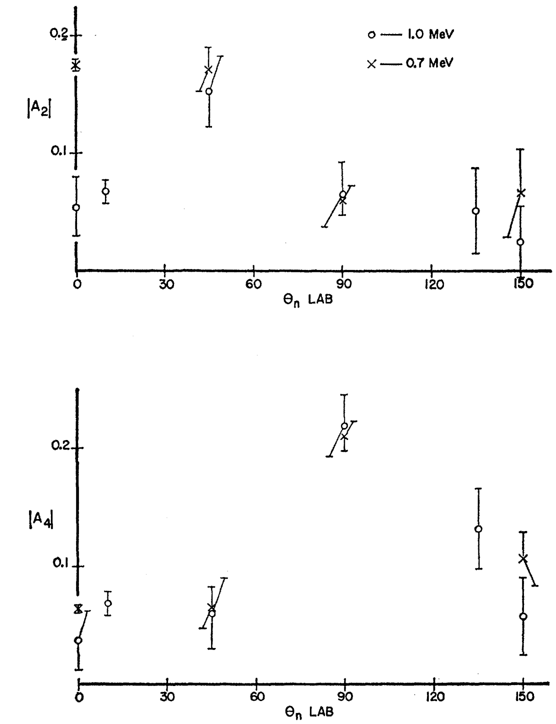

FIG. 12. Magnitudes of normalized coefficients from "best fits" of reaction plane correlations vs neutron detector angle.

ACKNOWLEDGMENTS

This work has benefitted from discussions with Dr. Frank L. Hereford and Dr. S. Berko. We also want to acknowledge the considerable help of Dr. Alan Batson in adapting the computer program, and of Mr. L. van der Zwan in proofreading the manuscript.

[16] R. Huby, M. Y. Refai, and G. R. Satchler, Nucl. Phys. **9**, 94 (1958/59).

[17] Torlief Ericson, Advan. Phys. **9**, 425 (1960); also, in Proceedings of the International Symposium on Direct Interactions and Nuclear Reaction Mechanisms, Padua (to be published).