MeV level of C^{12} found in the present work is slightly higher than the branch of $(1.3\pm0.4)\%$ determined by Cook *et al.*, although the errors overlap. If these separate results are averaged the branch becomes $(1.5\pm0.3)\%$. The previously accepted[9] log ft value of 4.2 for this branch would thus decrease by only 0.05 as a result of the present work.

ACKNOWLEDGMENTS

The author is indebted to Dr. D. H. Wilkinson for valuable discussions and to Dr. Seeger and Dr. Kavanagh for furnishing their final results prior to publication. Dr. R. E. Pixley participated in the development of some of the techniques and collaborated on some of the preliminary experiments.

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Study of the $C^{12}(d,p)C^{13}$ Reaction Mechanism: Polarization and $(d,p\gamma)$ Correlations

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Measurements in the deuteron energy range $5.5<E_d<12$ MeV have been made as follows on the reaction $C^{12}(d,p)C^{13*}$: (a) differential cross sections for protons to C^{13} ground state and C^{13*} (3.09 MeV) as functions of angle and energy, (b) proton polarization to C^{13} ground state and C^{13*} (3.09 MeV) as function of energy at 45° (lab system) and as functions of angle (10° to 120° lab) for protons to 3.09-MeV state at $E_d=8.3$, 9, and 10 MeV, and (c) proton-gamma correlation measurements with the gamma-ray detector on the normal to the reaction plane for reactions to C^{13*} (3.68 MeV) and C^{13*} (3.85 MeV). In (b) and (c) a double-focusing magnetic spectrometer selected the proton group in question; the polarization of the selected protons was measured by observing the "left-right" asymmetry from a carbon scatterer. Backgrounds were made negligible in the polarization work by coincidence methods. All the data show fluctuations with deuteron energy throughout the energy range studied; these fluctuations are attributed to compound-nucleus effects which invalidate a distorted-wave Born approximation (DWBA) stripping interpretation of results at isolated energies although direct interaction is the predominant mechanism. It is shown by taking average values over a wide energy range (~4 MeV) that a DWBA stripping description of the direct-interaction part of the reaction almost certainly will require the use of spin-dependent potentials.

A. INTRODUCTION

SINCE the first theories of deuteron stripping in the intermediate energy region over a decade ago[1,2] there have been many different attempts to improve the agreement with experiment by taking account of effects which were at first ignored. In the most successful of these, the plane waves expressing the motion in relative coordinates of the deuteron and proton (in the (d, p) reaction) are replaced by wave functions distorted by the Coulomb and nuclear fields. The distorted wave functions are calculated assuming that the nucleus is represented by a complex potential well whose parameters have been chosen to give agreement with the results of elastic-scattering experiments. If the scattering parameters have been determined in this way, then the distorted-wave theory yields predictions for the corresponding stripping reactions that can be tested by experiment. One objective is to see whether there exists a form of the distorted-wave theory that gives a description of experimental stripping results adequate for the extraction of spins of residual states and absolute values of reduced nucleon widths from experimental data even when distortions are large and thus to provide a valuable tool in nuclear structure studies. In addition, an understanding of the reaction mechanism in itself is, of course, also of great interest.

The first and simplest form of distorted-wave Born-approximation stripping calculation (henceforth referred to as DWBA stripping calculation) entirely neglected effects of spin-orbit and spin-spin terms in the scattering potentials of both the deuteron and the proton. Under these conditions the polarization, P, of protons emitted in a (d, p) stripping process has been shown to be effectively a measure of the direction of the neutron's orbital angular momentum diminished by the geometric factor $\frac{1}{3}$ arising from the deuteron spin coupling and by an additional factor which arises from the coupling of the neutron's spin $\frac{1}{2}$, and its orbital momentum, l_n, in the final nucleus to give a definite total angular momentum j in the final state. The result is[3,4]

$$\begin{aligned} P&=+\tfrac{1}{3}\frac{1}{l_n+1}\langle l_n\rangle \quad \text{for} \quad j=l_n+\tfrac{1}{2}, \\ P&=-\tfrac{1}{3}(1/l_n)\langle l_n\rangle \quad \text{for} \quad j=l_n-\tfrac{1}{2}. \end{aligned} \tag{1}$$

* Attached from Atomic Energy Research Establishment, Harwell, Berkshire, England.

[1] S. T. Butler, Phys. Rev. **80**, 1095 (1950).

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

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

[4] L. C. Biedenharn and G. R. Satchler, Suppl. Helv. Phys. Acta. **6**, 372 (1961).

Here $\langle l_n \rangle$ is the mean value of l_n in the direction in which the polarization is measured. Two definite predictions follow which may be tested by experiment: (a) the polarization can never exceed $|\frac{1}{3}|$, (b) if l_n is 0 then the polarization is zero. There is already some evidence[5–7] that equations (1) alone are not adequate to describe polarization from stripping and that spin-dependent terms in the distorting potentials must be included. Even where l_n is zero such terms will give rise to polarization which then may be studied free from the polarization effects which arise in connection with the distortion mechanism that leads to Eq. (1).

The above discussion, of course, is no longer applicable if some mechanism other than stripping is making a significant contribution to the reaction yield and in any experimental tests of stripping theory it is necessary to find the extent to which compound nucleus formation is affecting the measurements. In the present work an attempt to do this was made by using the variable energy facility of the tandem accelerator to study the dependence of the polarization and differential cross sections on the incident deuteron energy in the range 6 to 11 MeV.

In a stripping reaction the residual nucleus as well as the protons may be polarized. In fact, alignment of the residual nucleus can occur although the protons are unpolarized. The magnitude but not the sign of the polarization of the residual nucleus can be found from studies of the angular correlation between the de-excitation gamma radiation and the protons feeding the state. Again DWBA stripping theory makes predictions which for selected cases are unique and independent of the details of the distorting potentials provided that these are spin independent. A comparison with experiment, therefore, provides a test of the theory and, without the necessity of determining the optical potentials, can show whether spin-dependent forces play an important role. The special conditions which, in the absence of spin-orbit forces, make the correlation predictable independently of the distortions are that the gamma-ray detector is set along the normal to the reaction plane through the target, that only a single value of l_n is involved and that the value of l_n is either 0 or 1. For these conditions and taking the z axis along $\mathbf{k}_d \times \mathbf{k}_p$, Satchler and Tobocman[8] showed that DWBA stripping theory gives the proton angular distribution measured in coincidence with gamma rays as

$$W_c(\phi) = \left[\sum_k g_k d_{k0} \right] W_p(\phi), \qquad (2)$$

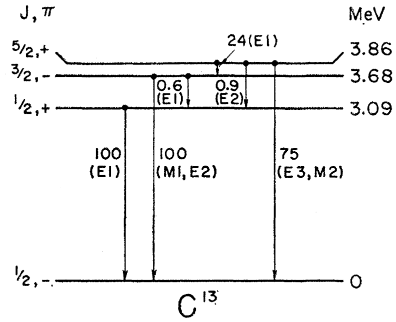

FIG. 1. Properties of low-lying levels in C^{13}.

where $W_p(\phi)$ is the directly measured proton angular distribution. The dynamics of the stripping mechanism, including distortion effects are described by the d_{k0} (these are essentially statistical tensors of the angular momentum of the captured neutron) which, in general, are functions of the proton angle ϕ; however, when l_n is 1, then d_{20} has the constant value $-\frac{1}{2}$ provided that spin-dependent potentials are negligible. The coefficients g_k are geometric factors, independent of ϕ, which contain the dependence on the total angular momentum of the captured neutron, the nuclear spins and the gamma-ray multipolarities. For the trivial case with l_n=zero only g_0 and d_{00}, which are both defined to be unity, appear in the sum and $W_c(\phi) = W_p(\phi)$; this, of course, is only true if the stripping assumptions leading to Eq. (2) apply. However, if the gamma-ray emitting state has spin $\frac{1}{2}$ or 0 then the coincidence angular distribution, W_c, must be identical to the direct angular distribution, W_p, independently of the reaction mechanism since, under these conditions the gamma-ray angular distribution is isotropic. This fact was used to calibrate the equipment and to check for systematic errors.

Angular correlations in the $C^{12}(d,p\gamma)C^{13}$ reaction measured with the special detector geometry outlined above are described and discussed in this paper. As in the polarization experiments, the energy dependence of the results was examined in a search for compound nucleus effects. The energy levels of C^{13} involved in these studies are shown in Fig. 1. The coincident correlation involving the $\frac{1}{2}+$level at 3.09 MeV served to calibrate the equipment and that involving the $\frac{3}{2}-$ state at 3.68 MeV ($l_n=1$) is compared with the DWBA stripping predictions. Measurements are also reported involving the $l_n=2$ transition to the $\frac{5}{2}+$ state at 3.85 MeV.

Clearly, it is desirable initially to carry out experiments in which as many as possible of the variables are absent and for this reason it was decided to study in greatest detail the proton polarization for a case $l_n=0$ and p-γ correlations with $l_n=1$. The reactions $C^{12}(d,p)$ C^{13}(3.09 MeV) and $C^{12}(d,p)C^{13}$(3.68 MeV), respectively, were selected because earlier studies[9] showed these to

[5] L. J. B. Goldfarb, in *Proceedings of the Rutherford Jubilee Conference, Manchester, 1961* (Heywood and Company Ltd., London, 1961).

[6] A. Isoya and M. J. Marrone, Phys. Rev. **128**, 800 (1962); A. Isoya, S. Micheletti and L. Reber, *ibid.* **128**, 806 (1962).

[7] E. Boschitz, in *Proceedings of the International Symposium on Direct Interactions and Nuclear Reaction Mechanisms, Padua, 1962* (Gordon & Breach Science Publishers, Inc., New York, 1963).

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

[9] G. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).

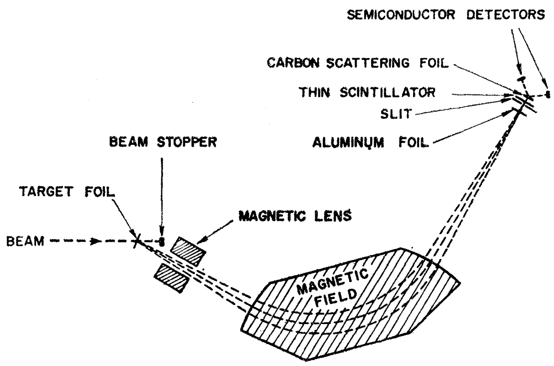

FIG. 2. Schematic diagram of experimental arrangement for polarization measurements.

have large stripping widths and previous polarization studies[5] on the $C^{12}(d,p)C^{13}$ ground-state reaction suggested that here compound nucleus effects were small (at least at forward angles). Because the work reported herein showed marked compound nucleus effects, measurements were also made on the polarization of the ground-state protons to permit direct comparison with earlier work. The results of earlier polarization measurements on the protons from $C^{12}(d,p)C^{13}$ have been summarized by Goldfarb[5] in a review paper presented to the Rutherford Conference in 1961. Additional recent results are given in Refs. 6, 7, 17, 19, 20, and 21 which are discussed below.

B. EXPERIMENTAL METHOD

1. General Arrangement

The experimental arrangement is illustrated in Fig. 2. The deuteron beam from the tandem generator was collimated through a 1.6-mm-diam aperture set 5 cm before the target. The undeflected beam was caught and the current measured at the tantalum stop. Beam intensities of 1 to 4 μA were used in the energy range 5.5 to 12 MeV. Self-supporting carbon-target foils of thickness 1.5 mg/cm^2 were used. These foils as well as the carbon scattering foils in the polarimeter were prepared[10] by spraying a suspension of colloidal graphite onto a glass slide; after drying the films were removed and mounted on suitable aluminum holders.

A magnetic spectrometer which could be rotated about the scattering chamber in the angular range $-10° < \phi_p < 125°$ was used to select protons from the target and to focus them close to the entrance slit of the polarimeter. Angular acceptance of the spectrometer was limited by an aperture to $\pm 2.5°$ in both horizontal and vertical planes. The solid angle was 7×10^{-3} sr.

The use of a magnetic spectrometer between the target and the polarimeter has three important advantages: (i) the high energy resolution of the spectrometer allows clear separation of closely spaced proton groups, (ii) scattered beam and unwanted particle groups do not enter the polarimeter, (iii) problems of background counts caused by neutrons and gamma rays coming from the target and beam stop are reduced by the large target to polarimeter separation ($\sim$2 m) that is used with the spectrometer.

The spectrometer was mounted with its uniform deflecting field normal to the reaction plane to avoid precession of the polarization vector of the protons in the magnetic field. Effects of the nonuniform quadrupole field were computed to result in less than 1% depolarization. The absence of significant effects of the magnetic fields on the polarization is demonstrated by the agreement between experimental and calculated calibration curves which are discussed below.

2. The Spectrometer

The theory of the spectrometer used in this work has been given by Enge.[11] The combination of magnetic quadrupole lens and uniform magnetic field gives focusing in both the vertical and horizontal planes. The geometry was arranged to produce a stigmatic image of the target spot at the polarimeter entrance slit for a group of monokinetic particles emitted from the target. The magnification in the spectrometer was expected[11]

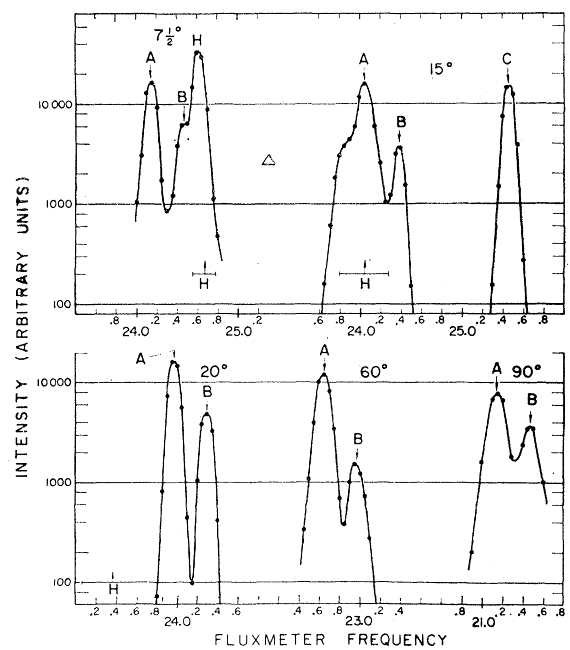

FIG. 3. Proton spectra observed with the spectrometer as set up for the $(d,p\gamma)$ correlation studies. "A," "B," and "C" indicate the positions of proton groups corresponding to states in C^{13} at excitation energies of 3.85, 3.68, and 3.09 MeV at each of the indicated angles. Recoil protons from hydrogenous contaminants in the target have energies that lie in the region of the horizontal bars labeled "H." The base of the triangle in the upper figure shows the resolution computed from the geometry with a 7-mm-wide detector slit.

[10] J. E. Evans and M. A. Grace, Nucl. Phys. 15, 646 (1960).

[11] H. A. Enge, Rev. Sci. Instr. 29, 885 (1958).

to be about 0.5 in the horizontal plane and about 10 in the vertical plane. This would result, then, in an image 1.6 cm high×0.08 cm wide. In fact, at the polarimeter slit (1.1 cm×0.20 cm), the image was appreciably wider than the slit because of energy spread caused by finite target thickness (1.5 mg/cm²) and small $dE/d\theta$ effects.

In practice, the quadrupole lens was adjusted to give maximum transmission through the polarimeter slits which were fixed in place. This was more convenient than using the correct procedure described by Enge which is to move the image slits to the appropriate position to get compensation for $dE/d\theta$ effects which change somewhat with energy and angle. It should be noted that any changes in the effective transmission of the spectrometer resulting from adjusting the quadrupole lens do not affect the polarization measurement which is self-monitoring in that a right-left ratio is observed for those particles which enter the polarimeter; such changes in transmission would of course be intolerable if cross-section measurements were being made. Some typical proton spectra obtained with the spectrometer are shown in Fig. 3.

3. The Polarimeter

Protons entering the polarimeter slit passed first through a plastic scintillator about 1 MeV thick for 7-MeV protons (see Fig. 4) and then through a carbon scattering foil (12 mg/cm²) placed 1.9 cm beyond the slit. Undeflected protons were detected in a silicon diffused junction. Protons scattered to the left and the right at angles of 50°±10° were detected also in silicon-diffused junctions. These side counters, made from 3000 Ω p-type Si, were each stopped to an area of 12 mm×24 mm.

The pulses from each Si-diffused side counter that were coincident with pulses from the plastic scintillator

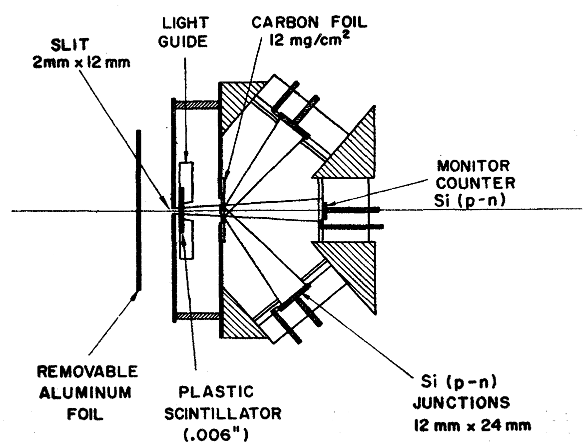

FIG. 4. Details of the polarimeter assembly. The side counters are at a mean angle of 50° to the particles incident on the carbon foil.

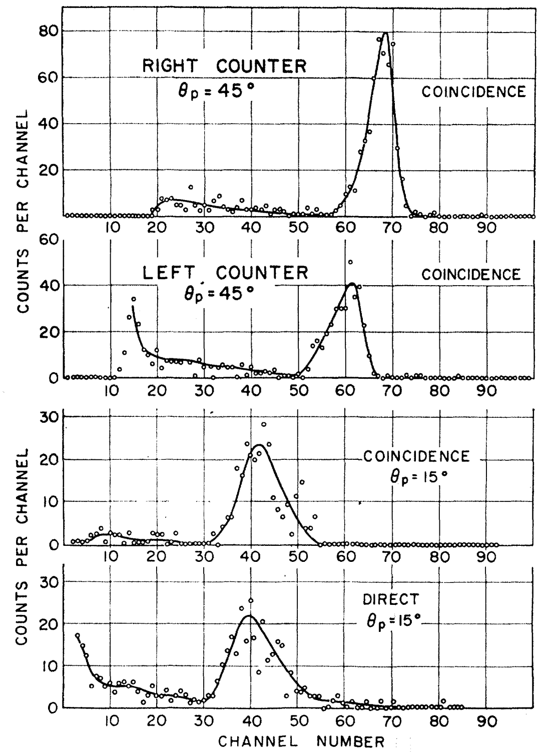

FIG. 5. Spectra from side counters in polarimeter observing protons from the $C^{12}(d,p)C^{13*}$ (3.09) reaction at the indicated angles to the beam. The deuteron energy was 9.0 MeV. A comparison of the lowest curve with that above it illustrates how the coincidence arrangement discriminates against background pulses from neutrons.

were recorded on a 100-channel pulse-height analyzer. A coincidence resolving time, 2τ, of 2 μsec was used. This coincidence arrangement was necessary in order to reduce the background of pulses from neutron interactions in the counters to a negligible value. Representative spectra with and without the coincidence arrangement are shown in Fig. 5.

The observation from which the polarization was deduced consisted of the right/left scattering ratios. False asymmetries would arise if the mean direction of the protons was not along the polarimeter axis, and were sought using unpolarized protons for which the right/left ratio is necessarily unity. Unpolarized protons were obtained both by sending a proton beam directly from the accelerator into the spectrometer set at 0° and also by scattering from a high Z target. In the first case ($\theta=0°$) the right/left ratio was 0.99±0.04. As θ was varied in the range ±2°, this ratio changed in agreement with the value calculated using the known angle to the polarimeter axis. When protons scattered from gold or tantalum ($\theta=90°$) were used, the right/left ratio was 1.0±0.04. If the spectrometer field was changed from the value corresponding to the center of the particle peak to a value where the counting rate was 50% of the peak then the resulting change in the

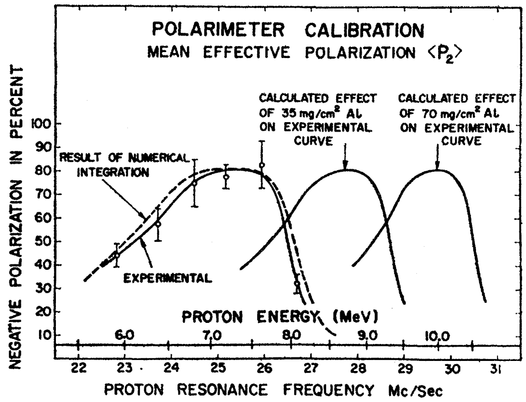

FIG. 6. Polarimeter calibrated curves. The dashed curve was computed from published data; the solid curve drawn through the calibration points determined experimentally was used in the analysis of the $C^{12}(d,p)C^{13}$ polarization results. The effect of inserting aluminum foil in front of the polarimeter is indicated.

right/left ratio was close to $\pm 10\%$. This effect reflected changes in the mean angle of the protons through the polarimeter. In actual practice the spectrometer was always set directly on the peak and it was established by repeated checks that drifting was negligible. It was also shown that the above results remained unchanged when the polarimeter was inverted.

The mean polarization, $\langle P_2 \rangle$, of the polarimeter was determined using protons of known polarization, P_1, obtained by elastic scattering from a thin carbon target. The value of the product, $\langle P_2 \rangle P_1$, was derived from the measured right/left scattering ratio, R/L, through the relation

$$\langle P_2 \rangle P_1 = ((R/L)-1)/((R/L)+1).$$

The resulting values of $\langle P_2 \rangle$ are shown as a function of the proton energy selected by the spectrometer in Fig. 6. Also shown in the figure by a dashed curve is the result of a computation of $\langle P_2 \rangle$ from published data[10,12,13] by numerical integration over the spread in angles and energies used in the polarimeter. The agreement between the measured and computed values is considered satisfactory and shows that depolarization effects in the magnetic fields are insignificant.

Examination of Fig. 6 shows that the efficiency of the polarimeter decreased rapidly above 7.5-MeV proton energy. Therefore, when protons of higher energy were selected by the spectrometer their energy was reduced to a suitable value by inserting aluminum absorbers in front of the polarimeter slit. The calculated extensions of the usable energy range of the polarimeter achieved by the insertion of 35 mg/cm² and of 70 mg/cm² aluminum absorbers, respectively, are also shown in Fig. 6.

The proton groups from $C^{12}(d,p)C^{13}$ were identified unambiguously by their measured energies which agreed precisely with those computed from the known Q values at all energies and angles. No impurity groups except knock-on protons from hydrogen in the target were observed. The polarization of the protons selected by the spectrometer was deduced from the measured right/left scattering in the calibrated polarimeter. Asymmetries due to geometrical effects were estimated and found to be insignificant in comparison with the standard errors associated with the final results.

4. $(d,p\gamma)$ Correlations

Angular correlations between protons and gamma rays were measured in the special geometry discussed in the Introduction. A cylindrical NaI(Tl) scintillation detector 5 in. in diameter and 4 in. long was fixed with its axis normal to the reaction plane and passing through the target spot. The angular aperture was restricted to a half angle of 24° at the target by a suitably machined conical hole in a 2-in.-thick lead shield placed in front of the scintillator. The protons were detected by a CsI(Tl) scintillation detector mounted immediately behind the detector slit (7 mm×25 mm) of the magnetic spectrometer. The output pulses from both the gamma ray and the proton detectors that were in coincidence (resolving time $2\tau \approx 50\times 10^{-9}$ sec) were recorded on 100-channel pulse-height analyzers using conventional fast-slow coincidence circuitry. In addition

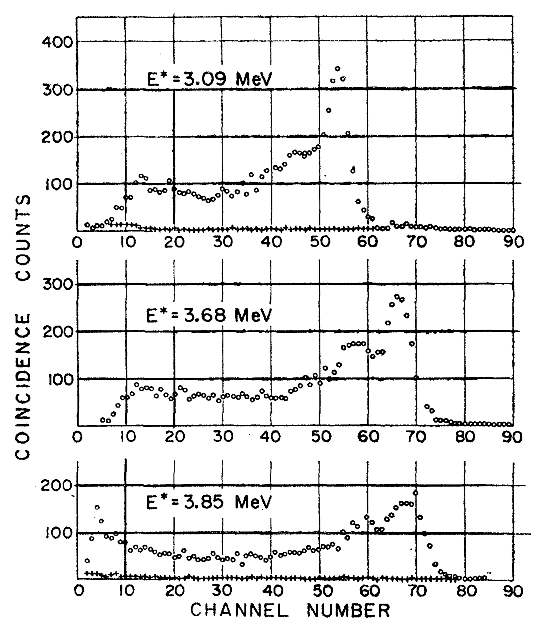

FIG. 7. Gamma-ray spectra observed in coincidence with proton groups feeding levels at the indicated energies in C^{13}. The "+" points show the measured random background. The bottom spectrum contains both 3.85-MeV radiation from the ground-state transition and 3.68-MeV radiation from the cascade branch through the corresponding level.

[12] J. E. Evans, Nucl. Phys. **27**, 41 (1961); S. J. Moss, R. I. Brown, D. E. McDonald, and W. Haeberli, Bull. Am. Phys. Soc. **6**, 226 (1961).
[13] T. A. Tombrello, R. Barloutaud, and G. C. Phillips, Phys. Rev. **119**, 761 (1960).

a scaler recorded the total number of protons detected.

Some typical coincidence γ-ray spectra are shown in Fig. 7. The random background to be subtracted was found by introducing delay to the output pulses from one counter so as to move them out of time coincidence and never amounted to more than 10% of the total area. The beam current was held to values $\lesssim 10^{-9}$ A, because greater currents led to an increase in the ratio random/real coincidences and, in addition, caused the loss of fast coincidences due to the high rate of gamma-ray detection.

The significant quantities measured in the experiment were values of the ratio,

$$R=\frac{\text{Number of proton-gamma coincidences}}{\text{Number of detected protons}},$$

as a function of proton angle and of deuteron energy. The number of coincidence counts was always computed by summing all pulses of greater than one half the total absorption peak and subtracting the appropriate random background; this number was then divided by the simultaneously recorded total proton count. Referring to Eq. (2) (Sec. A) we get,

$$R/\epsilon=W_c(\phi)/W_p(\phi)=\sum_k g_k d_{k0}\,, \qquad (3)$$

where ϵ is an efficiency factor that takes into account the solid angles and detector efficiencies. The efficiency factor ϵ was determined by observing protons in coincidence with the 3.09-MeV gamma radiation from the $\frac{1}{2}+$ first excited state, for which conservation of spin and parity requires an isotropic angular correlation ($W_c/W_p=1$) independent of the reaction mechanism. Corrections for small changes in the gamma-ray detection efficiency in going from the 3.09 to the 3.68 and 3.85-MeV states were estimated and appropriately applied. The effect of the solid angle subtended by the γ-ray counter is discussed in the Appendix.

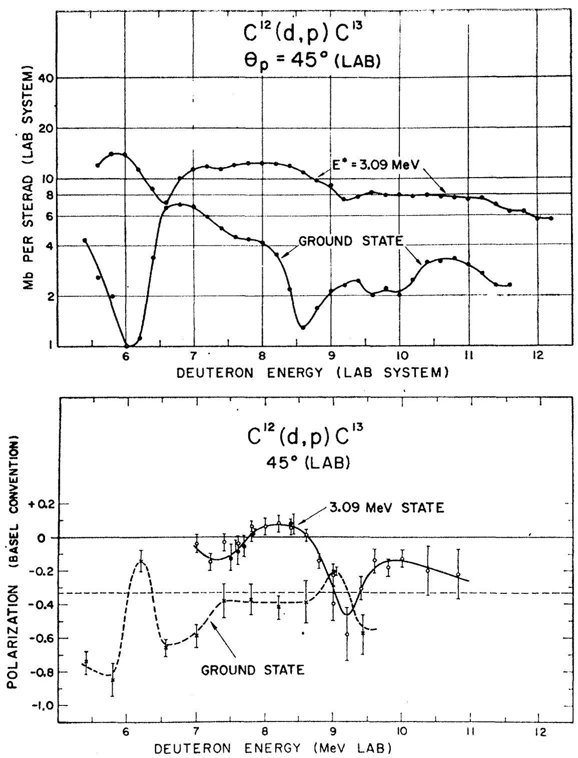

FIG. 9. The measured energy dependence of the differential cross sections and polarizations at 45° in the laboratory for the ground state and 3.09-MeV state reactions. The corresponding center-of-mass angles are 49.1° and 49.7° (±0.3°), respectively, throughout the energy range studied. The differential cross sections shown here should be multiplied by a factor of 1.6.

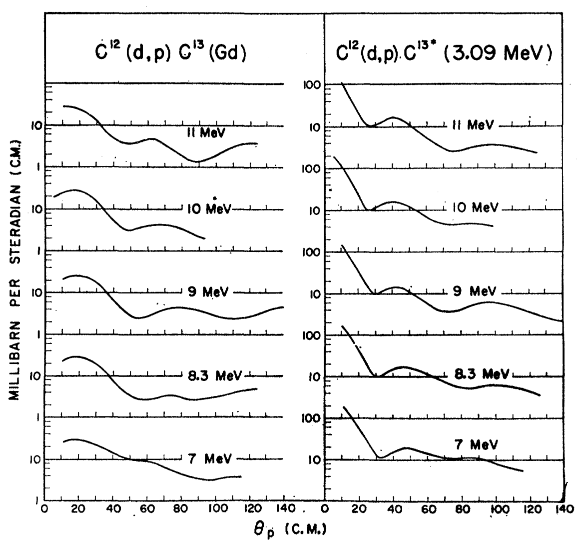

FIG. 8. Angular distributions at selected energies for the $C^{12}(d,p)C^{13}$ reactions to the ground and 3.09-MeV states.

5. Angular Distributions and Yield Curves

The small scattering chamber at the Chalk River Laboratories used for these measurements has already been described.[14] The proton groups were detected and resolved in a silicon diffused junction fixed to a rotating arm. A similar silicon diffused junction was set at 45° (lab) and used as a monitor for the angular distributions. The deuteron beam was caught in a Faraday cup and the total charge collected was used to find the differential cross section as a function both of energy and angle.

C. RESULTS

1. Differential Cross Sections

Angular distributions for the $C^{12}(d,p)C^{13}$ reaction to the ground and 3.09-MeV states in C^{13}, measured at a number of energies, are shown in Fig. 8. The energy

[14] D. A. Bromley, J. A. Kuehner, and E. Almqvist, Phys. Rev., **123**, 878 (1961).

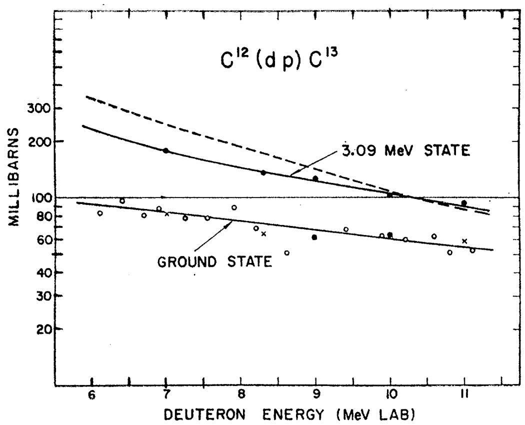

FIG. 10. The energy dependence of the integrated cross section for protons to the ground state and 3.09-MeV state, respectively. Results obtained in the present work are shown by solid dots and crosses; the open circles were derived from the data of Adams (Ref. 15). The solid curves are the result of a distorted-wave stripping calculation [We are indebted to D. McPherson for communicating the results of this calculation to us. The parameters used for deuterons were a Woods-Saxon potential with $V=55$ MeV, $W=15$ MeV, $R=3.43$ F and $a=0.65$ F. For protons the real potential was Woods-Saxon with $V=(57-0.5\ E_p)$ MeV, $R=2.94$ F and $a=0.65$ and a Gaussian imaginary potential with $W=(4\times 0.5\ E_p)$ MeV and $b=1.0$ F]; integration of calculated plane-wave Butler angular distributions ($R=4.5$ F) yielded an energy dependence that was identical to the distorted-wave results for the ground state but gave the dashed curve for the 3.09-MeV state.

dependence of the differential cross section at 45° to the beam is shown in more detail in the upper half of Fig. 9. The absolute cross-section scale was determined by normalization to data obtained earlier at Aldermaston[15] as described below.

The angular distributions were extrapolated smoothly to 180° and integrated to yield the total cross sections at a number of energies and are plotted in Fig. 10 together with results of studies made by Barbara Adams[15] at AWRE Aldermaston. The ground state cross-section at 10 MeV was normalized to the Aldermaston value to get the absolute cross-section scale in mb.

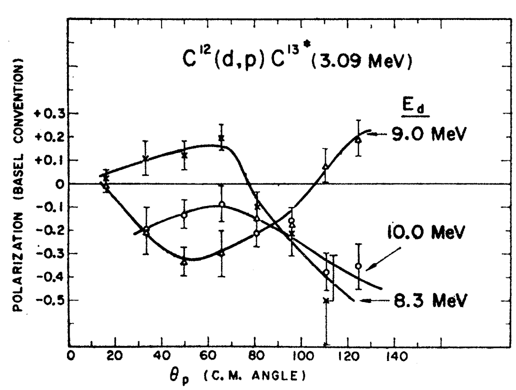

FIG. 11. The angular distributions of the polarization of protons from $C^{12}(d,p)C^{13*}$ (3.09 MeV) at three deuteron energies (laboratory system) as indicated.

[15] Barbara Adams (private communication).

2. Polarization Results

Angular distributions of the polarization of the protons to the 3.09-MeV state in C^{13} are shown for three energies in Fig. 11 and the energy dependence of the polarization of protons emitted at 45° to the beam in the laboratory system is shown in the lower half of Fig. 9 both to the ground state and to the 3.09-MeV state. The sign of the polarization is always defined in accordance with the Basel convention to be positive along $\mathbf{k}_d\times\mathbf{k}_p$ where the subscripts on the momentum vectors $\mathbf{k}$ refer to deuterons and protons, respectively.

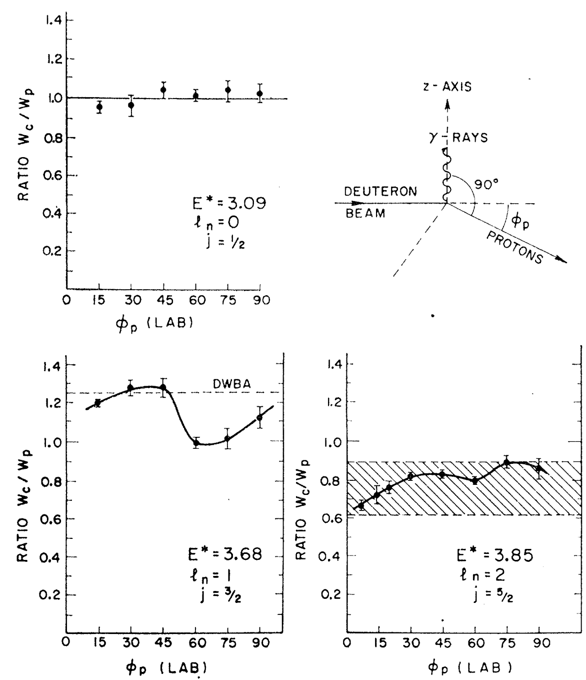

FIG. 12. Angular correlations of protons in coincidence with gamma radiation using the indicated "90°" geometry. The dashed curve (3.68-MeV state) and the cross-hatched area (3.85-MeV state) show the values of W_p/W_c allowed by DWBA stripping theory without spin-dependent distortions.

3. Proton-Gamma Correlation Results

The angular correlations of protons detected in coincidence with de-excitation gamma radiations from the 3.09-, 3.68-, and 3.85-MeV states of C^{13} are shown in Fig. 12 for a deuteron energy of 8.0 MeV. The coincidence counting rate for a number of deuteron energies are shown in Fig. 13 for the case of protons to the 3.68-MeV state being detected at 60°. All these measurements were made using the special geometry discussed in the Introduction.

D. DISCUSSION

The angular distributions shown in Fig. 8 exhibit prominent forward peaking and a diffraction-like form which does not change rapidly with deuteron energy. These features strongly suggest a direct interaction mechanism rather than a compound nucleus process. Other evidence of a dominant direct interaction mechanism is the fact that earlier measurements[5] of the polarization of the ground-state protons made at a number of isolated energies did not reveal any strong dependence of the polarization on bombarding energy. These earlier data are summarized in Fig. 14. The above facts led to the hope that further study of the $C^{12}(d,p)C^{13*}$ reactions might give a better understanding of the direct interaction mechanism and in particular to reveal something about the importance of spin-dependent forces in DWBA stripping calculations.

The first measurements made were angular distributions of proton polarization at 9.0 MeV and of protons

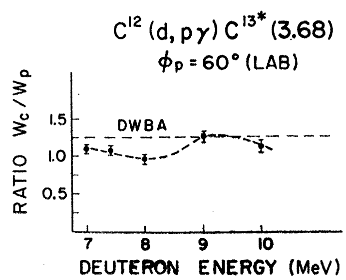

FIG. 13. Comparison of the measured $(d,p\gamma)$ coincidence correlation with the prediction of DWBA theory without spin-dependent distortions (horizontal dashed line) for a number of deuteron energies.

in coincidence with gamma radiation at 90° to the reaction plane at 8.0-MeV bombarding energy. As discussed in the Introduction (Sec. A), proton groups were chosen for which the DWBA stripping theory without spin-dependent forces makes unique predictions, namely the protons to the 3.09-MeV state ($l_n=0$, hence the polarization is predicted to be zero) and proton-gamma correlations to the 3.68-MeV state ($l_n=1$, hence, correlation is predicted to be isotropic). The initial results, which are included in Figs. 11 and 12, are in strong contradiction to these predictions.

The additional studies of the effect of varying the bombarding energy presented in Figs. 9 and 13 show rapid fluctuations in the reaction properties within energy intervals of a few hundred keV. For example (see Fig. 9) near 6.1 MeV both the ground-state cross section and polarization show large excursions from neighboring values and again near 9.0 MeV both the ground-state and excited-state polarization as well as the cross sections show smaller fluctuations. Such correlated and sharp fluctuations are a strong indication that resonant compound nucleus processes are contributing to the reaction yield and interfering with the stripping process. Under these circumstances the DWBA stripping theory by itself can not be expected

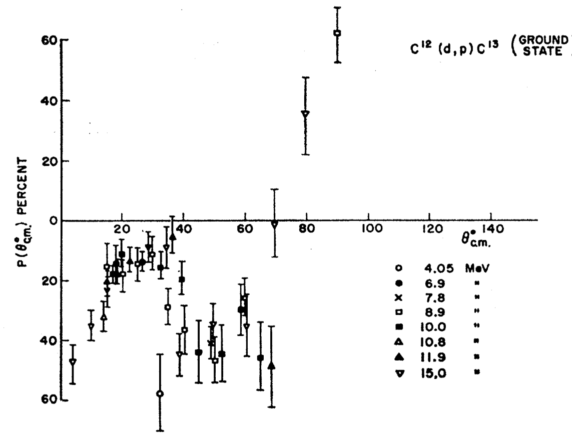

FIG. 14. Summary of early proton polarization measurements. The review article by Goldfarb (Ref. 5) gives references to all the data shown.

to provide an adequate description of the reaction mechanism and a detailed comparison of the $C^{12}(d,p)C^{13}$ polarization and p-γ correlation angular distributions obtained herein with predictions of the DWBA theory has little value. However, if the observed fluctuations are the result of interference between stripping and a relatively weaker but fluctuating compound-nucleus amplitude, then average values taken over many fluctuations may be meaningfully compared with DWBA calculations as discussed below.

That resonance fluctuations exist at lower energies in the $C^{12}(d,p)C^{13}$ reaction is well known[16] and there are recent polarization measurements that suggest that even at higher energies,[6] 15 and[7] 21 MeV, the polarization results change considerably with energy. The resonance fluctuations that invalidate comparisons between measurements made at single energies and DWBA stripping calculations in this case are likely a consequence of using a very light target nucleus. For heavier nuclei there is a growing body of evidence that DWBA stripping calculations can be applied with some success to both correlation[17] and polarization results.[6]

Figure 10 gives the estimates of the total cross section obtained by integrating the measured angular distributions. Except for a fluctuation in the region 7.5–9 MeV the resulting values decrease smoothly with increasing deuteron energy in the fashion expected for a direct interaction. The absence of strong resonance fluctuations in this case is consistent with dominant direct-interaction amplitudes interfering with weaker resonant compound-nucleus amplitudes. It can be shown[18] that the only interference terms that con-

[16] T. W. Bonner, J. T. Eisinger, A. A. Kraus, and J. B. Marion, Phys. Rev. **101**, 209 (1956).

[17] J. P. Martin, K. S. Quisenberry, and C. A. Low, Phys. Rev. **120**, 492 (1960); J. A. Kuehner, E. Almqvist, and D. A. Bromley, Nucl. Phys. **19**, 614 (1960).

[18] L. I. Schiff, *Quantum Mechanics* (McGraw-Hill Book Company, Inc., New York, 1949), p. 105.

tribute to the total cross section are those that arise between deuteron waves of the same l values. Since the compound nucleus will be formed chiefly in head-on collisions (low l values) while stripping is predominantly a surface phenomenon (higher l values), interference effects in the total cross section are expected to be small and resonances will not be seen if the compound nucleus intensity is weak with respect to that of the direct interaction. In the case of the differential cross sections and the polarization, however, interference between amplitudes for different incoming l values can amplify resonance effects so that even a small compound nucleus amplitude will lead to large fluctuations in these quantities such as are observed.

If the observed fluctuations in polarization result from interference between large direct-interaction amplitudes and small, random, compound-nucleus amplitudes then the fluctuations are expected to average to zero over an energy interval wide enough to contain many resonance. The mean value in these circumstances will represent that from the dominant direct-interaction mechanism. In Fig. 9 all the measured values for the ground-state polarization except two maxima of fluctuations lie below the dashed curve which indicates the extreme value, 0.33, permitted by DWBA theory without spin-dependent forces. At[6] 15 and[7] 21 MeV incident energy negative polarizations in excess of -0.33 are also observed at proton angles near 45° to 50° (c.m. system) to the beam. The observation that such large polarization persists at the same angle over wide energy ranges is strongly suggestive that spin-dependent forces will be required in any DWBA description of the direct-interaction mechanism involved. It is interesting to note that the DWBA calculation of Robson[19] for the $C^{12}(d,p)C^{13}$ (ground state) including spin-orbit potentials shows a minimum in the polarization near 40° of -0.35, whereas his calculations without spin-orbit potentials do not show polarizations below -0.20 until beyond 60° and, of course, can never go more negative than -0.33.

The results for the 3.09-MeV ($l_n=0$) state over the range 7- to 11-MeV deuteron energy averages -0.15 for the polarization, again suggesting the necessity of including spin-dependent potentials in any DWBA description of the mechanism. It may be questionable whether the energy range used here is sufficiently large to average compound nucleus interference effects to zero and additional measurements at still higher energies would be of interest to check this point. Certainly no angular distributions measured at isolated energies and that fluctuate as greatly in form as those shown in Fig. 13 can be meaningfully compared with DWBA stripping calculations.

The observed interference between compound-nucleus resonant processes and direct interaction just discussed in connection with the polarization also precludes any detailed comparison between DWBA stripping theory and the measured $(d,p\gamma)$ correlations. Nevertheless, the DWBA predictions without spin-dependent forces are shown by dashed lines in Figs. 12 and 13, for comparison with the experimental results. The theoretical predictions which are based on Eq. (2) of Sec. A, include an attenuation factor appropriate to the finite solid angle of the gamma-ray detector. It can be shown (see the Appendix) that no additional terms are introduced into Eq. (2) by a finite gamma-ray detector angle which is symmetric about the normal to the reaction plane.

The predictions in Figs. 12 and 13 for the 3.68-MeV state were computed assuming a pure $M1$ gamma-ray transition. The effect of $E2$ admixture on the predicted ratio $W_c(\phi)/W_p(\phi)$ is shown in Fig. 15. This admixture is not known. If it is assumed that resonance interference effects are minimized when the protons are detected near the stripping peak then the measured ratio at 30° and at 45° suggests that the radiation is predominantly $M1$ with the $E2$ width less than 80% of that for $M1$ radiations. This result agrees with that deduced by Fletcher *et al.*[20] from correlation studies on the reaction $C^{12}(d,p\gamma)C^{13*}$ at lower energies. At angles beyond the stripping peak the compound nucleus process is expected to contribute relatively more to the proton yield. However, the *average* ratio 1.10 of the 60° points between 7 and 10 MeV (Fig. 13) may be expected to reflect largely the contribution of the direct interaction. It appears from Fig. 15 that the ratio 1.1 leads to amplitude mixtures which are not consistent with the limits deduced above from the spin-independent theory.

The $(d,p\gamma)$ correlation for the 3.85-MeV ($l_n=2$) state is for protons in coincidence with both the 3.85 MeV ground-state radiation and the 3.68-MeV radiation from the cascade de-excitation branch via the 3.68-MeV level. The low-energy primary gamma ray of

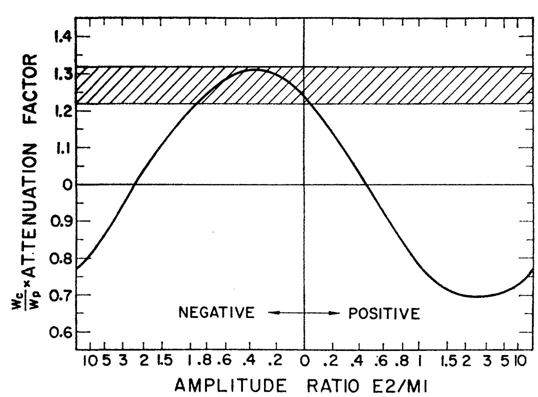

FIG. 15. The coincidence correlations W_c/W_p, as a function of the multipole mixing for the 3.68-MeV state. The geometric attenuation factor discussed in the Appendix is included.

[19] D. Robson, Nucl. Phys. 22, 34 (1961).

[20] N. R. Fletcher, D. R. Tilley, and R. M. Williamson, Nucl. Phys. 38, 18 (1962).

0.17 MeV was not included in the gamma-ray spectra. The DWBA predictions for this situation shown by a dashed line in Fig. 12 were computed using the known branching ratios[9] and assuming pure $M2$ for the ground-state transition, pure $E1$ for the unobserved 0.17-MeV primary transition and pure $M1$ for the 3.68-MeV cascade transition.

Any further discussion of the $(d,p\gamma)$ results are unwarranted in view of the uncertainties of resonance contributions and of the spin-dependent distortions in the DWBA theory, as well as of the multipolarities involved. Again it appears that such measurements should be made with heavier nuclei where the greater level densities and larger number of open channels will lessen the effect of compound nucleus contributions.

E. SUMMARY AND CONCLUSIONS

It has been shown that pronounced compound nucleus effects appear in $C^{12}(d,p)$ stripping even up to $E_d = 11$ MeV. For protons leading to the excited states of C^{13} these effects prevent the measured polarization and $(d,p\gamma)$ angular correlations from giving any conclusive evidence for the presence of a spin-dependent distortion. Evidence of the need for such terms in the distorting potentials, however, comes from the measured polarization of protons to the ground state which exceeds $|\frac{1}{3}|$ over almost the full range 5.4 MeV $< E_d <$ 9.5 MeV when observed at $\theta_p = 45°$ lab. Over such a wide energy range resonant interference terms are expected to average to zero and the average value is attributed to direct interaction. At higher energies[6,7,21] the polarization near 45° is also known to exceed the maximum value $|\frac{1}{3}|$ given by DWBA theory without spin-dependent distortions giving additional support to the need of including spin-dependent terms in the optical potentials. The results demonstrate that comparisons of stripping theory with data taken at a single energy may lead to erroneous conclusions. It is concluded that measurements made to test direct interaction theories would be better made on heavier nuclei where both the higher level densities and the greater number of open reaction channels will reduce compound nucleus interference.

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One of us (J.E.E.) is grateful to support from A.E.R.E. Harwell during the time this work was done.

[21] W. P. Johnson and D. W. Miller, Phys. Rev. **124**, 1190 (1961); R. G. Allas and F. B. Shull, *ibid.* **125**, 941 (1962); I. I. Lavintov and I. S. Trostin, Zh. Eksperim. i Teor. Fiz. **40**, 1570 (1961) [translation: Soviet Phys.—JETP **13**, 1102 (1961)].

APPENDIX: EFFECTS OF FINITE SOLID ANGLE OF GAMMA-RAY DETECTOR ON $(d,p\gamma)$ CORRELATION WITH SPECIAL "90°" GEOMETRY

According to Satchler and Tobocman[8] the $(d,p\gamma)$ angular correlation measured with a point gamma-ray detector placed at polar angle θ and azimuthal angle ϕ with the z axis taken along $\mathbf{k}_d \times \mathbf{k}_p$ is

$$W(\theta\phi) = \sum_k g_k \left\{ d_{k0} P_k(\cos\theta) + 2 \sum_{q>0} (-1)^q \times \left[\frac{(k-q)!}{(k+q)!}\right] P_k{}^q(\cos\theta) |d_{kq}| \cos q(\phi - \alpha_{kq}) \right\}.$$

The d_{kq} are tensor parameters of the orbital momentum of the captured neutron which depend on the direction of observation of the proton. α_{kq} is a phase angle and g_k is a geometric factor which contains dependencies on gamma-ray multipolarities and nuclear spins.

The cosine factor in the second summation term obviously vanishes on integrating $W(\theta\phi) \sin\theta d\theta d\phi$ over all azimuthal angles, ϕ, from 0 to 2π. Therefore, the average value of $W(\theta,\phi)$ over a detector surface symmetric about the z axis and subtending a half-angle of θ_0 contains only the $q=0$ terms and is

$$W_{\text{av}} = \int_0^{\theta_0} \sum_k g_k d_{k0} P_k(\cos\theta) \sin\theta d\theta \Big/ \int_0^{\theta_0} \sin\theta d\theta .$$

The only effect of the finite gamma-ray detector angle for this situation is to attenuate each term in the sum [Eq. (2), Sec. A] by the factor,

$$\frac{1}{1-\cos\theta_0} \int_0^{\theta_0} P_k(\cos\theta) \sin\theta d\theta .$$