PHYSICAL REVIEW C VOLUME 10, NUMBER 4 OCTOBER 1974

# Distortions in angular correlations for the reaction $^{11}B(d,p\gamma)^{12}B^*(0.95$ MeV) at low energy

U. Karfunkel, J. P. F. Sellschop, and M. C. Stemmet
*Nuclear Physics Research Unit, University of the Witwatersrand, Johannesburg, Republic of South Africa*

(Received 10 June 1974)

For the reaction $^{11}B(d,p\gamma)^{12}B^*(0.95$ MeV) at $E_d = 1$ MeV, 15 angular correlation measurements covering the range $\theta_{dp} = 22°$ to 160° give values of the anisotropy ($\epsilon$) and the deviation of the measured symmetry axis from the recoil axis ($\Delta\Phi$). The values of $\Delta\Phi$ remain small and constant throughout, whereas the values of $\epsilon$ increase sharply at backward angles to a high, possibly constant value. These results are surprising in the simplicity of their behavior and are contrary to some features and anticipations of previously reported measurements.

[NUCLEAR REACTIONS $^{11}B(d,p\gamma)^{12}B^*(0.95)$, $E_d = 1.0$ MeV, measured $p$-$\gamma$ coin., $\theta_p = 20-160°$, $\Delta\theta = 10°$. Calculated anisotropies, phase shifts; deduced distortions.]

Simple stripping theories based on the plane wave Born approximation (PWBA) are not expected to provide an adequate description of low-energy deuteron stripping reactions, owing to severe deviations from the basic assumptions underlying these theories. Qualitative arguments by Wilkinson[1] suggested that for stripping reactions of low-$Q$ value, however, the distortions would remain insignificant at low energies so that a plane wave description (PWBA) would fit the data. These ideas have been given some experimental investigation by Sellschop and Mingay.[2] Both Amado[3] and Shapiro[4] have considered the effect of poles in the complex reaction plane on the stripping mechanism and predict also increasingly improved description by PWBA with decreasing deuteron energy in certain particular circumstances.

Angular distributions of the protons are simple in form at low energies and may not provide a sensitive test for these ideas. It has long been appreciated, however, that particle-$\gamma$ angular correlations are a sensitive and powerful probe in the studies of stripping reaction mechanisms. Such measurements are technically difficult and have not been extensively studied at low energies. Such data as exist are generally too sketchy to reveal any systematic behavior. An early survey by Williamson[5] suggested support for Wilkinson's proposals. Borden and Ritter[6] were the first to initiate an extended series of measurements to investigate this feature of stripping reactions. Their choice was the reaction $^{11}B(d,p\gamma)^{12}B^*(0.95$ MeV) chosen for its low-$Q$ value of 0.19 MeV. They measured ten angular correlations in the reaction plane for deuteron energies from 1.0 to 5.5 MeV and emergent protons at forward angles ($\theta_{dp}$) only, from 17° to 70° (lab). These measurements are widely spread so that it is difficult to ascertain unambiguously any systematics or trends. Not surprisingly many questions remained unsettled.

In the work reported here, the same reaction was chosen. Self-supporting, isotopically separated $^{11}B$ targets were bombarded with a stabilized beam of 1 MeV deuterons. Considerable care was taken with alignment and chamber geometry to eliminate all sources of aberrations in the angular correlations. Fifteen angular correlations were measured in the reaction plane at 10° intervals of $\theta_{dp}$, for $\theta_{dp}$ values from 22° to 160°. These were all made for the fixed energy of 1 MeV where two previous measurements at values of $\theta_{dp}$ of 50° and 70° exist. The range of forward angles was therefore extended, and the backward angles where correlations were not attempted before were covered.

Since the captured neutron has $l_n = 1$ in this case, the angular correlation function $W(\theta_\gamma)$ is limited to second-order Legendre polynomials, and is therefore described by two parameters only,[7,8] viz.

$$W(\theta_\gamma) \sim 1 + AP_2[\cos(\theta_\gamma - \Phi_0)]$$

where $\theta_\gamma$ is the angle between the incident beam direction and the $\gamma$ ray, and $\Phi_0$ is the symmetry axis of the correlation. This is equivalent to

$$W(\theta_\gamma) \sim 1 - \epsilon \cos[2(\theta_\gamma - \Phi_0)],$$

where $\epsilon$ is the anisotropy of the correlation.

Values of the two parameters $\Phi_0$ and $\epsilon$ are extracted from these data by computer fitting. The results for $\Phi_0$ and $\epsilon$ are presented as a function of the emergent proton angle $\theta_{dp}$ and the relative distance from the pole $D$ (MeV). The latter parameter is given analytically by Warburton and Chase.[9] At small values of $D$, the simple stripping mecha-

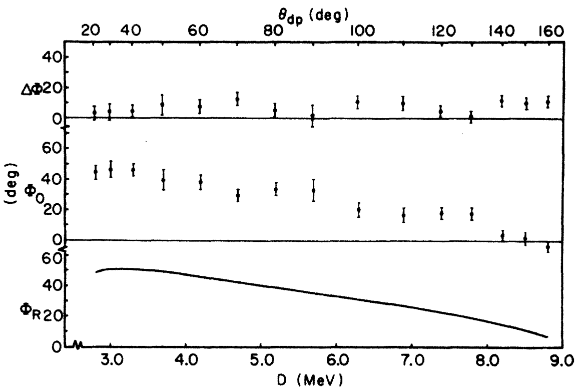

FIG. 1. (a) Calculated recoil axis $\Phi_R$ (lab), (b) measured correlation symmetry axis $\Phi_0$ (lab), and (c) deviation $\Delta\Phi = \Phi_R - \Phi_0$ versus $\theta_{dp}$ (lab) and $D$ (MeV).

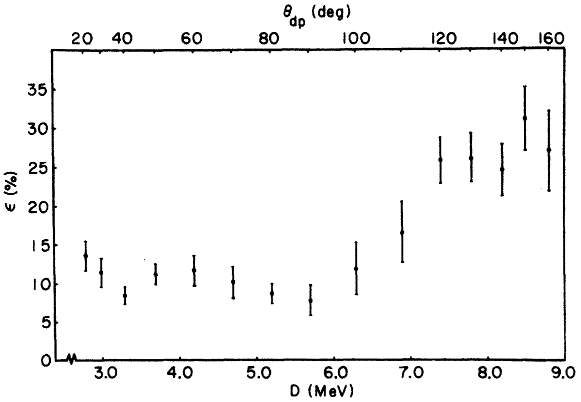

FIG. 2. Measured correlation anisotropy ε (%) versus $\theta_{dp}$ (lab) and $D$ (MeV).

nism may be expected to dominate. In Fig. 1, $\Phi_0$ shows a smoothly decreasing value with increasing $\theta_{dp}$. The calculated recoil angle ($\Phi_R$) for the residual nucleus shows exactly this trend. The difference between these two ($\Delta\Phi = \Phi_R - \Phi_0$) is found to be remarkably constant at a small positive value throughout the range. The value ΔΦ is expected to be zero for the plane wave case, and indeed may provide a sensitive indication to distortions. This over-all result differs from that of Borden and Ritter[6] who found the general behavior of ΔΦ to be constant and small at low-$D$ values in accord with this work, but rising rapidly to very large negative ΔΦ values for values of $D$ greater than ~5 MeV. It should be observed that their larger $D$ values were obtained for higher deuteron energies (and forward angles) so that different reaction mechanisms may have entered.

The anisotropy ε is similarly plotted against $\theta_{dp}$ (and $D$) in Fig. 2. Here also systematic trends are apparent. At forward angles (corresponding to low-$D$ values) ε is small and almost constant at or close to the constant PWBA value of 11.7% tentatively adopted by Borden and Ritter[6]; there seems in fact to be a definite trend (not seen in Ref. 6) of a gradual decrease in ε with angle in this forward region. In the backward angles, however, ε increases rapidly to what may be a limiting value of approximately 26%: This behavior is certainly in disagreement with Borden and Ritter[6] and with PWBA theory which predicts a constant value of ε for all energies and angles.

It was stressed by Satchler and Tobocman[8] from their distorted wave Born approximation calculations for $(d, p\gamma)$, that opposing effects of deuteron and proton distortions could result in small values of ΔΦ even for cases of significant distortions as shown by values of ε attenuated as compared with the maximum limiting value predicted by PWBA calculations. Such cancellation effects may play a role resulting in small ΔΦ values over the full range covered in this work, and in this event, do not appear to influence the values of ε in the expected way. The substantial increase in ε for backward angles (and large $D$ values) if considered to exceed the PWBA limit must therefore be ascribed to different reaction mechanisms rather than deuteron and proton distortion effects.

In the light of the considerable experimental difficulties involved in such measurements, it is gratifying to find such clear and simple systematic trends in the behavior of both ΔΦ and ε. The main features of ΔΦ being constant and small, and ε being small and then increasing rapidly to a possibly limiting value, are suggestive of a reaction mechanism which may be relatively simple over at least the range of lower-$D$ values. These data clearly justify extensive theoretical analysis and further experimental work.

The authors acknowledge with appreciation support from the Gold and Diamond Mining Industries of South Africa and from the South African Council for Scientific and Industrial Research as well as the helpful assistance of their colleagues.

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

[2] J. P. F. Sellschop and D. W. Mingay, in *Proceedings of the Conference on Direct Interactions and Nuclear Reaction Mechanisms*, edited by E. Clementel and C. Villi (Gordon and Breach, New York, 1963), p. 425.

[3] R. D. Amado, Phys. Rev. Lett. 2, 399 (1959).

[4] I. S. Shapiro, Nucl. Phys. 28, 244 (1961).

[5] R. M. Williamson, in *Proceedings of the Conference on Direct Interactions and Nuclear Reaction Mechanisms* (see Ref. 2), p. 695.

[6] A. P. Borden and R. C. Ritter, Phys. Rev. 159, 875 (1967).

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

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

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