ANGULAR DISTRIBUTION OF THE POLARIZATION OF NEUTRONS FROM THE $C^{12}(d, n)N^{13}$ *REACTION*

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The angular distribution of the polarization of neutrons from the stripping reaction $C^{12}(d, n)N^{13}$ was measured for $l_p = 1$. The results are compared with the data of Levintov[2] and with the variation of polarization in the stripping reaction $C^{12}(d, p)C^{13}$.

1. INTRODUCTION

THE study of the polarization in stripping reactions is of great interest for the understanding of the mechanism of these reactions. At present there is a rather large amount of experimental material on the polarization of protons from the mirror reaction $C^{12}(d, p)C^{13}$ over the broad energy range from 4.05 to 15 MeV. Considerably less experimental data are available on the dn reaction on C^{12}. Haeberli and Rolland[1] studied the angular dependence of $P(\theta_1)$ for $E_d \approx 3$ MeV, while Levintov and co-workers[2] did the same for $E_d = 11.8$ MeV. Robson[3] calculated the polarization for the $C^{12}(d, p)C^{13}$ reaction at $E_d = 8.9$ MeV with the optical model without allowance for Coulomb effects and did not obtain agreement with experiment either with or without the spin-orbital term in the optical potential. No calculations were made for the $C^{12}(d, n)N^{13}$ reaction.

Our problem was to compare the shape and magnitude of the angular distribution of the polarization for the reaction in which neutrons are emitted with the available data on the mirror reaction.

2. EXPERIMENTAL

We measured the angular distribution of the polarization of neutrons from the $C^{12}(d, n)N^{13}$ reaction for a group of neutrons leading to the production of N^{13} in the ground state ($l_p = 1$, $j = 1/2$). In the experiment we used 6.6-MeV deuterons from the Radium Institute synchrotron.

The method has been described briefly in[4] and was somewhat improved. The deuteron beam was focused by quadrupole lenses on a 6—7 mg/cm^2 aquadag target. The target area bombarded by deuterons was 0.25 cm^2. The mean deuteron current at the target was 3 μA. The neutrons from the reaction were selected at a given angle θ_1 with the aid of a conical opening in a lead-paraffin shield. The conical collimator had an effective angular spread of about 3°. The polarized neutrons from the $C^{12}(d, n)N^{13}$ were analyzed in a gas scintillation counter at high pressure. The overall pressure of the gas mixture (7% Xe and 93% He^4) was 80 atm. The pulse-height resolution of our counter was $\sim 6\%$.[5]

The neutrons scattered on He^4 nuclei were recorded by plastic scintillators at an angle $\theta_{2\,lab} = 123°$ at which the polarization P_2 is maximum.[6] The gas analyzer was 40 mm in diameter and 70 mm in length; the plastic scintillator was 45 mm in diameter and 25 mm thick. The distance between the centers of the gas counter and the lateral detectors was 20 cm. The α recoil nuclei gave rise to pulses at the anode of an FÉU-13 phototube looking at the gas counter; these pulses were applied through a special cathode follower to a fast coincidence circuit to which pulses from an FÉU-36 phototube looking at the plastic scintillators were also applied. The choice and arrangement of the photomultipliers were connected with the necessity of ensuring great stability and good pulse-height resolution in the recording of the α recoil nuclei pulses and to the desirability of making use of the good time characteristics of the FÉU-36 phototube to obtain sufficient time resolution in the coincidence circuit. The resolving time of the fast coincidence circuit was 5 nsec.

Pulses from the analyzer were also applied to a differential discriminator which selected only those pulses which corresponded to the scattering of the neutrons by 123°. The pulses from the differential discriminator together with the pulses from the fast coincidence circuit were applied to a slow coincidence circuit with a resolving time

θ_{1lab}, deg	28.7	40.0	45.9	48.0	57.2	66.9
θ_{1cms}, deg	31.8	44.1	50.5	52.7	62.6	72.9
ε, %	−5.0	−23.0	−19.1	−19.7	−5.0	+3.6
P_n, %	−5.4±4.0	−25.0±3.0	−20.8±3.0	−21.4±4.0	−5.4±4.0	+3.9±2.0

of 2 μsec. The background was measured by the introduction of a delay line with $\tau_3 \approx 35$ nsec. A gas scintillation counter served as a monitor. To calibrate the equipment we placed a polonium α-particle source inside the analyzer. The adjustment was checked by periodic measurement of "up-down" counts. The accuracy of the adjustment, as measured in terms of a spurious asymmetry, was ≲ 3%.

3. RESULTS OF THE MEASUREMENTS AND DISCUSSION

We measured the polarization for $E_d = (6.2 \pm 0.4)$ MeV at angles $\theta_{1\,lab}$ = 28.7, 40, 46, 48, 57.2, and 67°.[1)] For each angle the number of counts was at least 1500. The overall background was 20%. The polarization was calculated from the right-left asymmetry: $P_1 = \epsilon/P_2$, where the right-left asymmetry is $\epsilon = (N_{left} - N_{right})/(N_{left} + N_{right})$; P_1 is the measured polarization of neutrons from the reaction and P_2 is the polarization arising when unpolarized neutrons are scattered by helium. The value of P_2 was taken from Levintov et al.[6] The geometric corrections to the quantity P_2 were calculated by the weighted-mean method. The corrected value of P_2 for the instrument was 92%. The results of our measurements are shown in the table and in Fig. 1b.

Hence, for neutrons from the $C^{12}(d, n)N^{13}$ reaction, the polarization for three deuterons energies 2.8, 6.2, and 11.8 MeV has been measured at the present time. The obtained angular dependence of the polarization is shown in Figs. 1a, b, c. The differential cross section for the reaction at $E_d = 8$ MeV taken from Middleton et al.[7] is given in Figs. 1a, b, c.

From the available data we can conclude the following:

1. As in the case of the (d, p) reaction, the sign of the polarization in the (d, n) reaction determined in accordance with the Basle convention is negative. This indicates that the distorted-wave theory gives a qualitatively correct picture of the process in stripping reactions. The data for the angular behavior of the proton polarization in the $C^{12}(d, p)C^{13}$ reaction are given in [8,9] for E_d = 6.9 and 10.0 MeV and are also shown in Fig. 1. The general features of the polarization angular distributions for particles emitted in the mirror reactions are complex. The maximum value of the polarization lies approximately in the angular region corresponding to the first minimum of the angular distribution. The value of the proton polarization exceeds 33%, which is given by the distorted-wave theory without allowance for the ls terms in the distorted potentials in the incoming and outgoing channels of the reaction[10] and its absolute value also exceeds that of the neutron polarization by about 20% for $E_d = 6.2$ MeV and by 15% for $E_d = 11.8$ MeV.

2. The difference in the polarization of the emitted particles from the mirror stripping reactions on C^{12} is due to the following: a) the existence of the Coulomb barrier in the distorting potential in the case of proton emission; b) the difference in the Q-value of the reaction and the fact that the final nuclei are different.

The difference in the proton and neutron polarization at small angles can apparently be explained by the difference in Coulomb effects. At large angles the situation is somewhat worse. Yoccoz[11] calculated the polarization arising in stripping reactions if the only distorting potential for the incident deuteron waves is the Coulomb potential. The calculation was carried out for $E_d \approx 1$ MeV in the $Be^9(d, n)B^{10}$ reaction, where $k_d = 2.3 \times 10^{12}$ cm^{-1}, $k_n = 4.6 \times 10^{12}$ cm^{-1}, and $\alpha_d \approx 1$ ($\alpha = Mze^2/\hbar^2 k$). The proton polarization in the stripping reaction for $j = 1/2$ proves to be quite large over the entire forward hemisphere (> 30%). In our case, when $E_d = 6.2$ MeV, the Coulomb parameters are still quite large ($\alpha_d \approx 0.55$ and $\alpha_p \approx 0.33$) and can, to some degree, smooth over the difference in the value of the polarization. The Coulomb effects, however, can scarcely be fully responsible for this difference. The experimental errors are large, and to obtain complete agreement between the polarizations in the mirror reactions it is necessary to consider processes connected with the differences referred to in point b.

3. The difference in the maximum values of the polarizations at $E_d = 6.2$ MeV and $E_d = 11.8$ MeV is small and amounts to ~ 10%. This appears to be evidence of the smoothness of the energy depend-

[1)]The results of the measurements for $\theta_{2lab} = 40°$ have been published earlier.[4]

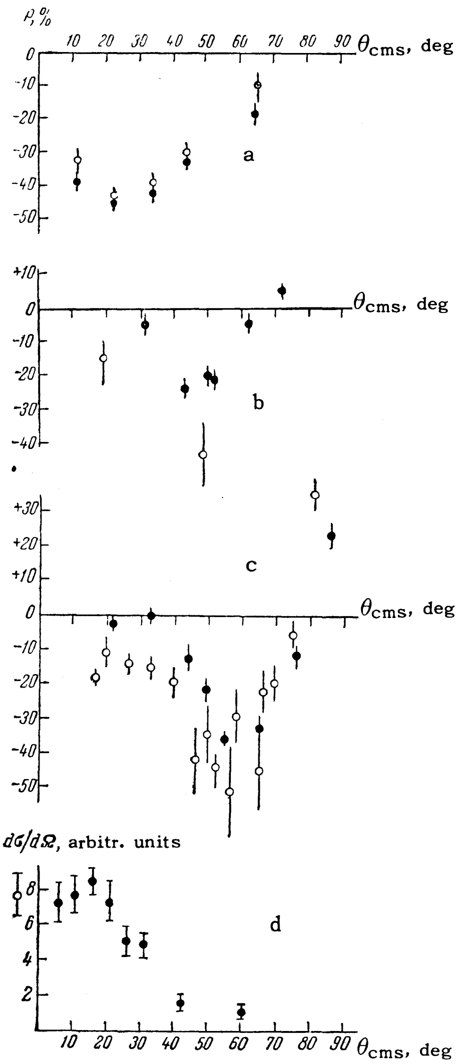

FIG. 1. Angular distributions of polarization of neutrons and protons from the C^{12} + d reaction and the cross sections for $C^{12}(d,n)N^{13}$: a) angular dependence of the neutron polarization for E_d = 2.8–3.0 MeV[1]: ●, ○ – values of P_n for E_d = 2.8 and 3.0 MeV, respectively; b) angular dependence of the neutron polarization from our data at E_d = 6.2 MeV and for protons from the data of [8] at E_d = 6.9 MeV: ○ – proton polarization, ● – neutron polarization; c) the same for neutrons at E_d = 11.8 MeV[2] and for protons at E_d = 10.0 MeV[9]: ○ – proton polarization, ● – neutron polarization; d) differential cross section for the $C^{12}(d,n)N^{13}$ reaction for l_p = 1 at E_d = 8 MeV.[7]

ence P(E) in this energy interval and of the possibility of using the optical potential for the calculation of the stripping reaction on the basis of the distorted-wave technique.

4. From our data and the data of Levintov it follows that the value of the polarization, within the limits of experimental error, never exceeds ⅓. This can be evidence of the fact that the basic contribution to the distorted-wave functions comes from the central potential, while the overall *l*s distortion for the incoming and outgoing channels of the reaction is either small or changes sign with a change in the energy. (The additivity of the *l*s distortions was shown by Robson.) Such a character for the effect of the *l*s potentials brings our results into agreement with the measurements of Levintov. This is also in agreement with the results reported in the survey by Goldfarb[12] for the polarization of protons from the $C^{12}(d, p)C^{13*}$ reaction for the case $l_n = 0$. (In this case the polarization is connected only with the *l*s distortions.): $P_1(37°) = (-11 \pm 14)\%$ for E_d = 11.9 MeV; $P_1(50°) = (+20 \pm 5)\%$ for E_d = 7.8 MeV. It is also in agreement with the recent measurements of Saladin and Reber[13] for the same reaction at E_d = 15 MeV, which showed that the polarization is negative and small ($P_1 \approx -10\%$) between 20° and 60°.

As to the results shown in Fig. 1a, the nature of the polarization for $E_d \approx 3$ MeV is evidently complex and can be explained by the contribution of both stripping and resonance mechanisms with allowance for Coulomb distortion.

Close to $E_d \approx 4$ MeV the $C^{12}(d, n)N^{13}$ reaction has a resonance for a compound nucleus, as was shown by Fulbright and Verba.[14] It was also shown there that at E_d somewhat greater than 4.2 MeV the angular distribution already has a shape more characteristic of the stripping mechanism.

[1] W. Haeberli and W. W. Rolland, Bull. Am. Phys. Soc. II, 2, 234 (1957).

[2] I. I. Levintov and I. S. Trostin, JETP **40**, 1570 (1961), Soviet Phys. JETP **13**, 1102 (1961).

[3] D. Robson, Nuclear Phys. **22**, 34 (1961).

[4] Babenko, Bibichev, Konstantinov, and Nemilov, JETP **44**, 135 (1963), Soviet Phys. JETP **17**, 92 (1963).

[5] Babenko, Konstantinov, and Nemilov, PTÉ, in press.

[6] Levintov, Miller, and Shamshev, JETP **32**, 274 (1957), Soviet Phys. JETP **5**, 258 (1957).

[7] Middleton, Bedewi, and Tai, Proc. Phys. Soc. (London) **A66**, 95 (1953).

[8] Hird, Cookson, Bokhari, Proc. Phys. Soc. (London) **A72**, 489 (1958).

[9] Allas, Shull, Phys. Rev. **116**, 996 (1959); ibid. **125**, 941 (1962).

[10] H. C. Newns, Proc. Phys. Soc. (London) **A66**, 477 (1953).

[11] J. Yoccoz, Proc. Phys. Soc. (London) **A67**, 813 (1954).

[12] L. J. B. Goldfarb, Proc. Rutherford Jubilee Intern. Conf., London, 1961, p. 479.

[13] J. X. Saladin and L. H. Reber, Proc. Intern. Symposium on Direct Interactions and Nuclear Mechanisms, Padua, 1962, vol. I, p. 625.

[14] H. W. Fulbright and J. Verba, Proc. Rutherford Jubilee Intern. Conf., London, 1961, p. 579.

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