Polarization of Neutrons from the $B^{11}(d, n)C^{12}$ Reaction at 2 MeV

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The polarization of five groups of neutrons has been measured at 2.0-MeV deuteron bombarding energy for the $B^{11}(d, n)C^{12}$ reaction corresponding to the ground, 4.43-, 7.66-, 9.66-, and 12.76-MeV states of C^{12}. A liquid-helium time-of-flight neutron polarimeter was used to make the measurements. The polarization of the neutrons to the ground state and first excited state in C^{12} is positive at forward angles and negative at back angles. The polarization of neutrons to the 7.66-MeV level in C^{12} is negative for angles less than 130°. The polarization of neutrons to the 9.66- and 12.66-MeV levels is negative at forward angles and positive beyond 50°.

I. INTRODUCTION

Neutron polarizations for the $B^{11}(d, n)C^{12}$ reaction have been reported by several groups.[1–5] Mason and Sample[3] reported small positive polarizations for the ground-state and first-excited-state neutron groups at a mean deuteron bombarding energy of 1.45 MeV. They also report positive polarizations at forward angles at 1.65- and 1.85-MeV deuteron bombarding energies for the ground-state group. Söhngen[4,5] reports positive polarization at forward angles for both the ground-state group and first-excited-state group at 2.35- and 2.70-MeV deuteron bombarding energy. At 3.0-MeV deuteron bombarding energy, Söhngen reports negative polarization for the ground-state group for all angles less than 100°, whereas the polarization from the first-excited-state group remains positive. Meier *et al.*[6] report measurements for this reaction for deuteron bombarding energies from 2.8 to 4.0 MeV. They report negative polarizations at all angles less than 80° (lab) for the ground-state group over this energy interval. The published angular distribution of Christiansen *et al.*[1] at 2.8 MeV is in disagreement with the angular distribution of Meier *et al.*[6] at 2.8 MeV, although this disagreement is now resolved.[7] The results of Smotryaev and Trostin[2] are for a deuteron bombarding energy of 12.3 MeV and are considerably above the energy range of interest here.

Meier *et al.*[8] have noted the similarity of several neutron polarization distributions for (d, n) reaction on light nuclei which proceed by an orbital angular momentum transfer of one unit. They also noted that existing data on the $B^{11}(d, n)C^{12}$ reaction indicated a deviation from this pattern. The results of Söhngen confirmed that the polarization distributions for the $B^{11}(d, n)C^{12}$ reaction undergo a qualitative change between 2.35 and 3.0 MeV.

In this experiment, neutron polarization distributions were measured at 2.0-MeV deuteron bombarding energy for five neutron groups from the $B^{11}(d, n)C^{12}$ reaction corresponding to the ground, 4.43-, 7.66-, 9.66-, and 12.76-MeV states of C^{12}.

II. APPARATUS AND PROCEDURE

The polarization measurements were made at the Oak Ridge National Laboratory. Since the experimental method and electronics were the same as those previously described,[9] only significant details will be given here. A deuteron beam produced by the ORNL 3-MV Van de Graaff accelerator, operated in the pulsed mode, wa allowed to strike a boron-11 target of 250-μg/cm^2 thickness. The polarization of the emitted neutron beam was determined by observing the asymmetry in elastic scattering from liquid helium. Neutron energy selection was made on the basis of time-of-flight between a beam pickoff placed just before the boron target and the liquid-helium polarizer-analyzer. Figure 1 shows a typical time-of-flight spectrum.

Five neutron groups were analyzed corresponding to the ground, 4.43-, 7.66-, 9.66-, and 12.76-MeV levels in C^{12}. The neutron group corresponding to levels in C^{12} between 9.66 and 12.76 MeV were not analyzed because they were not clearly resolved in this experiment. The

[1] J. Christiansen, G. Söhngen, F. W. Buesser, and F. Niebergall, in *Proceedings of the International Congress on Nuclear Physics, Paris,* 1964 (Editions du Centre Nationale de la Recherche Scientifique, Paris, 1965), Vol. II, p. 921.
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[3] G. R. Mason and J. T. Sample, Nucl. Phys. **82**, 635 (1966).
[4] G. Söhngen, thesis, Hamburg, 1966 (unpublished).
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[6] M. M. Meier, F. O. Purser, G. L. Morgan, and R. L. Walter, Bull. Am. Phys. Soc. **12**, 500 (1967).
[7] It has been brought to the attention of the authors by Dr. F. W. Buesser that the 2.8-MeV energy quoted in Ref. 1 is in error. This energy was the incident energy, not the mean energy in the target (2.7 MeV). Therefore, there is no longer disagreement between the data of Ref. 1 and the 2.8-MeV data of Ref. 6, since the polarization undergoes a transition from positive to negative values in this energy region.
[8] M. M. Meier, F. O. Purser, Jr., and R. L. Walter, Phys. Rev. **163**, 1056 (1967).
[9] T. G. Miller and J. A. Biggerstaff (to be published) (and references included therein).

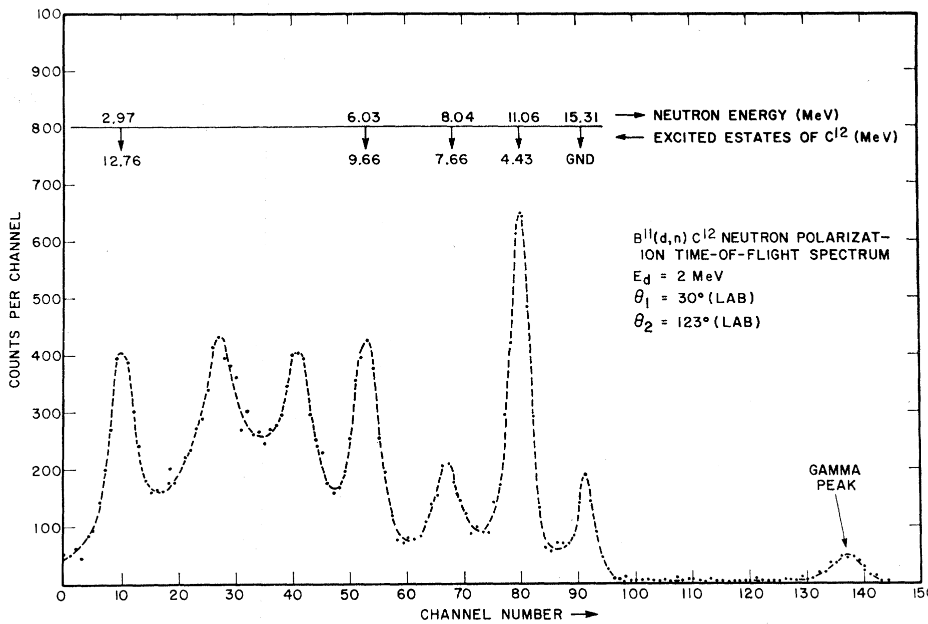

FIG. 1. Typical gated time-of-flight neutron spectra.

analysis of the data was complicated for neutron groups above the 7.66-MeV level because of the rather large background. This background is due to the large Γ_α for this region, where Γ_α represents the partial width for α-particle emission. The technique used for unfolding the Gaussian peaks to obtain the counts under each peak and the associated errors has been described elsewhere.[9]

The polarization of the neutron groups was determinded from the measured asymmetry by a computer code that has been described elsewhere.[9] The code uses the phase shifts of Hoop and Barschall[10] to compute the necessary parameters, the angular distribution $d\sigma/d\Omega$, the polarization P, and the spin rotation parameter β needed for consistent tracking of polarization effects in successive scattering in the spin-zero-nuclei helium. The code adjusts the initial input polarization needed to reproduce the measured asymmetry. Since the code uses the actual geometry of the experiment, the data are automatically corrected for finite geometry and multiple scatterings. The code calculates polarization effects for up to four scatterings and assumes zero polarization for the fourth- or higher-order scatterings. The measurements reported here are in agreement with the Basle sign convention.[11]

III. RESULTS AND DISCUSSION

The results of the neutron polarization measurements are presented in Fig. 2 for neutrons to the ground, 4.43-, 7.66-, 9.66-, and 12.66-MeV states in C^{12} for 2.0-MeV duetron bombarding energy. Results of Brüning *et al.*[12] for 2.0-MeV average bombarding energy for the ground and first excited states are included in Fig. 2. The agreement is good. The standard deviations shown include, in addition to statistical uncertainties, standard deviations involved in the Monte Carlo calculation used to derive the neutron polarization from the measured asymmetry. Figure 3 (top) compares the present results with published results for the $B^{11}(d,n_0)C^{12}$ polarization measurements at around 2.0-MeV deuteron bombarding energy. The results for Mason *et al.*[3] are for a deuteron bombarding energy of 1.85 MeV, whereas Söhngen's[4] results are for a deuteron bombarding energy of 2.35 MeV. The agreement is quite good for the three measurements, indicating that the polarization distributions do not change appreciably from $E_d=1.85$ to 2.35 MeV. Figure 3 (bottom) shows the polarization distribution obtained by Söhngen at 3.0-MeV deuteron bombarding energy. The results of Meier *et al.*[6] also indicate negative polarizations at 3.0-MeV deuteron bombarding energies at all angles less than 80°. There is a large change of the polarization distributions from 2.7 to 3.9 MeV. This rather large change in the polarization distributions for a relatively small change in the deuteron bombarding energy has not been noted in other d, n reaction on light nuclei.[8,13]

Recent calculations by Cohen and Kurath[14] on the spectroscopic factors for the $1P$ shell for pickup and stripping reactions indicate that the first excited state is

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[11] Helv. Phys. Acta Suppl. **6**, 436 (1961).
[12] R. Brüning, F. W. Buesser, H. Dubenkropp, and F. Niebergall, II, Institut für Experimentalphysik, Hamburg (private communication).
[13] T. R. Donoghue, W. L. Baker, P. L. Beach, D. C. DeMartini, and C. R. Soltesz, Phys. Rev. **173**, 925 (1968).
[14] S. Cohen and D. Kurath, Nucl. Phys. **A101**, 1 (1967).

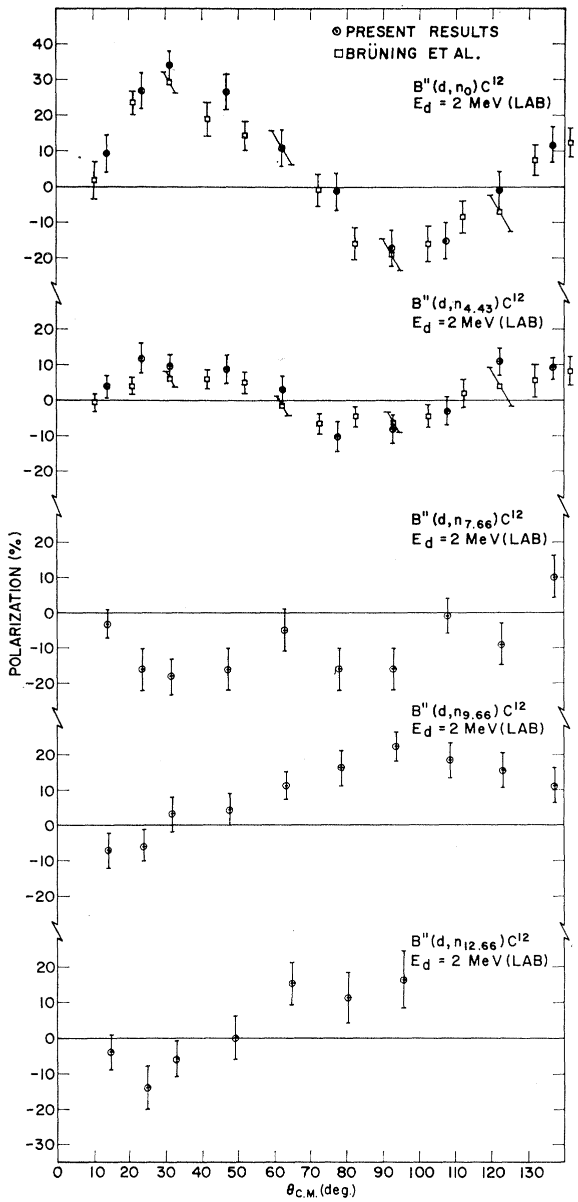

FIG. 2. Center-of-mass polarization distributions for five groups of neutrons from the $B^{11}(d, n)C^{12}$ reaction for 2-MeV deuteron bombarding energy. The unpublished results of Brüning *et al.* for the ground and first excited states are indicated by open squares.

formed predominantly by a $1P_{1/2}$ interaction, i.e., $J=l_P-\frac{1}{2}$. Since the ground state is a $1P_{3/2}$ transfer or $J=l_P+\frac{1}{2}$, the sign of the polarization for the ground-state group should be opposite to that of the first-excited-state group if the simple sign rule proposed by Newns[15] for stripping reactions is to hold. The present results (Fig. 2) indicate the same sign for the ground-state and first-excited-state groups; hence, the Newns sign rule does not hold at 2.0 MeV, although

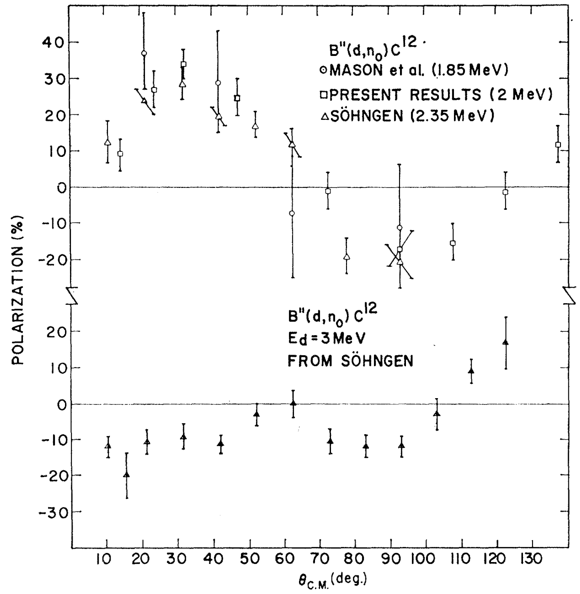

FIG. 3. Top: comparison of the present results for the $B^{11}(d, n_0)C^{12}$ neutron polarization to published results close to 2 MeV. Bottom: polarization distribution for the $B^{11}(d, n_0)C^{12}$ reaction at 3-MeV deuteron bombarding energy (from Ref. 4).

attempts to fit the experimental cross sections using stripping theory have been moderately successful[16] at 2.0 MeV. This is an indication that the rather simple model proposed by Newns is inadequate for this reaction at this energy. Söhngen's data at 3.0 MeV are consistent with Newns's rule.

Attempts to fit both the cross section and the polarization data using the DWBA code JULIE[17] have been unsuccessful so far, although this effort is continuing. Possible explanation for this failure has been discussed elsewhere.[9]

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