Evidence for the Polarization of B^{12} Nuclei Produced in a (d,p) Reaction*

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Evidence is presented that a lower limit for the polarization of B^{12} nuclei produced in the (d,p) reaction at 2.8 Mev is 17±5%. The sign of the polarization P_R is in disagreement with the Newns model, and it is in agreement with a modified classical model. The sign of the proton polarization determined by Hillman and by Juveland and Jentschke is also in agreement with the modified classical model.

MEASUREMENTS of proton angular distributions from (d,p) reactions have been interpreted in terms of stripping theory.[1] More recently the polarization of protons from (d,p) reactions has been observed[2–4] and interpreted in terms of final-state interactions.[5–10]

Newns[5] correctly predicted that the protons produced in a stripping reaction should be polarized. He introduced a classical model to illustrate the expected direction of polarization of the proton. This is illustrated in Fig. 1(a) for a proton scattered to the left and the total angular momentum of the absorbed neutron j_n equal to $l-\frac{1}{2}$, where l is the orbital angular momentum carried into the nucleus. The sign of the proton polarization P_p is negative. The vector polarization is defined as $\mathbf{P}_p=P_p\ (\mathbf{k}_p\times\mathbf{k}_d)/|\mathbf{k}_p\times\mathbf{k}_d|$ where $\mathbf{k}_p$ and $\mathbf{k}_d$ are the momenta of the proton and deuteron respectively. In Fig. 1(a) $\mathbf{k}_p$ is perpendicular to $\mathbf{k}_n$, the momentum of the neutron. Newns stressed that the classical picture would be approximately correct only for large $\mathbf{k}_p,\mathbf{k}_d$ and for a well-localized deutron. He also pointed out that the $m=0$ component of the deuteron spin function is neglected, and that it is a two-dimensional model. If the latter two conditions are removed, the sign of P_p is unchanged. It is interesting to note that the Newns model also predicts that the recoil nucleus with momentum $\mathbf{k}_R$ should be polarized. In Fig. 1(a) the recoil nucleus polarization P_R is positive.

The sign of P_p measured by Hillman in the $C^{12}(d,p)C^{13}$ reaction with deuteron kinetic energy T_k of 4.05 Mev and by Juveland and Jentschke[4] in the $C^{12}(d,p)C^{13}$ and $Si^{28}(d,p)Si^{29}$ reactions ($T_k=11.9$ Mev) is opposite to the prediction of the Newns model. The sign of P_R obtained in the $B^{11}(d,p)B^{12}$ reaction ($T_k=2.8$ Mev) described in this paper also is opposite to the Newns model.

The calculations of Newns,[5] Horwitz and Messiah,[6] and Hittmair[9] are based on a model in which the proton wave is distorted but the deuteron wave is a plane wave. All three give the wrong sign for the polarization. The Newns model [Fig. 1(a)] also implicitly assumes that the mean free path of the deuteron λ_d is greater than the nuclear radius r and that the proton mean free path λ_p is comparable to r.

The correct sign of P_p is obtained by Cheston[7,8] and Weidenmüller[10] who use distorted wave functions for proton and deuteron. Weidenmüller pointed out that the distortion of the deuteron wave function must exceed that of the proton wave function. The polarization produced by deuteron distortion is opposite in sign and must be larger than the polarization produced by the proton distortion to account for the experimental sign of the polarization.[10]

These considerations suggest the modified classical picture§ illustrated in Figs. 1(b), 1(c), and 1(d) which yields the correct signs for P_p and P_R. In Fig. 1(b) the same scattering event depicted by the Newns model ($\lambda_d>r$, $\lambda_p\cong r$) in Fig. 1(a) is described by the modified classical model ($\lambda_d\cong r$, $\lambda_d<\lambda_p$). The (d,p) reaction does not occur in the hatched area, since the deuterons will not penetrate so far into nuclear material. Events occuring in region 1 and region 2 will contribute oppositely to P_p (and P_R). Since region 1 is larger than region 2, the polarizations P_p and P_R will have the signs indicated in Fig. 1(b). The magnitudes of P_R and P_p will be small and opposite in sign to those in Fig. 1(a). When $\lambda_p>\lambda_d<r$, region 2 disappears and larger values of P_R and P_p are expected. In Fig. 1(d) a proton scattering to the right and $j_n=l+\frac{1}{2}$ for $\lambda_p>\lambda_d<r$ is depicted.

The elastic scattering cross sections for deuterons on heavy nuclei break away from the Rutherford value at large apsidal distances. This has been interpreted by Porter[11] as evidence that $\lambda_d<r$. The mean free path for nucleons is large compared to r at low energies and reaches a minimum value comparable to the radius of

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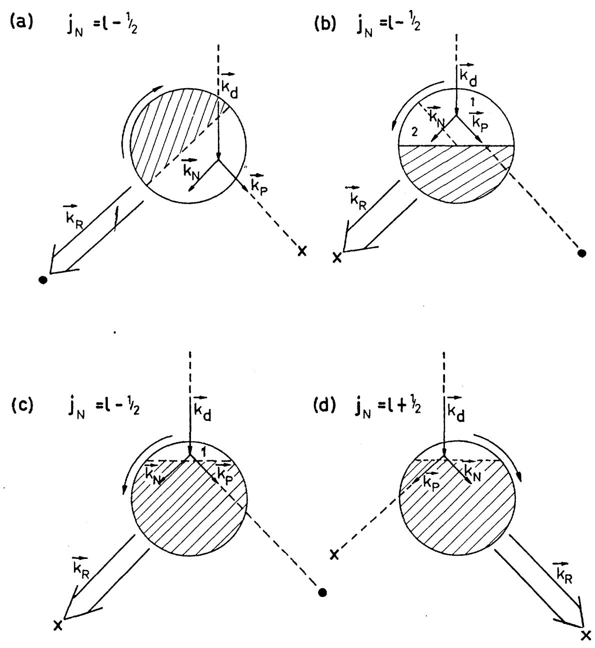
[1] See, for example, S. T. Butler and O. H. Hittmair, *Nuclear Stripping Reactions* (John Wiley and Sons, Inc., New York, 1957).
[2] P. Hillman, Phys. Rev. **104**, 176 (1956).
[3] J. C. Hensel and W. C. Parkinson, Bull. Am. Phys. Soc. **2**, 228 (1957).
[4] A. C. Juveland and W. Jentschke, Phys. Rev. **110**, 456 (1958).
[5] H. C. Newns, Proc. Phys. Soc. (London) **A66**, 477 (1953).
[6] J. Horowitz and A. M. L. Messiah, J. phys. radium **14**, 731 (1953).
[7] W. B. Cheston, Phys. Rev. **96**, 1590 (1954).
[8] J. Sawicki, Phys. Rev. **106**, 172 (1957).
[9] O. Hittmair, Z. Physik **144**, 499 (1956).
[10] H. A. Weidenmüller, Z. Physik **150** 389 (1958).

§ *Note added in proof.*—Professor Jentschke kindly pointed out to the authors that the modified classical model had been proposed earlier in the unpublished thesis report of A. C. Juveland at the University of Illinois. See also G. R. Satchler, *Comptes rendus du congrès international de physique nucléaire* (Dunod, Paris, 1959), p. 101.
[11] C. E. Porter, Phys. Rev. **99**, 1400 (1955).

a light element.[12] Therefore Fig. 1(c) and Fig. 1(d) where $\lambda_p > \lambda_d < r$ represent the correct classical picture. Further considerations of the model shows that P_p is zero in the forward and backwards directions, and it decreases rapidly for larger angle scattering. Cheston has shown that the relative sign of P_p and P_R predicted by the classical models is correct.[13]

The polarization of the B^{12} ions was determined by looking for an asymmetry in the angular distribution of high-energy beta particles emitted in the decay of B^{12}. A pancake-shaped, 18-inch diameter scattering chamber was specially constructed for this purpose (see Fig. 2). When protons in the stripping peak are produced in the plane of the scattering chamber on opposite sides of the beam line, B^{12} ions recoil at a maximum angle of 53° with respect to the beam direction



$$\vec{P} = P\,\frac{(\vec{k}_P \times \vec{k}_d)}{|\vec{k}_P \times \vec{k}_d|}$$

FIG. 1. The symbols ● and × stand for the directions of polarization of the recoil nucleus with momentum $\mathbf{k}_R$ or of the proton with momentum $\mathbf{k}_p$ which are produced when a deuteron of momentum $\mathbf{k}_d$ is stripped of a neutron of momentun $\mathbf{k}_n$. The symbols ● and × denote polarization parallel to or antiparallel to $\mathbf{k}_p \times \mathbf{k}_d$. In Fig. 1(a) the Newns model ($\lambda_p < \lambda_d$; $\lambda_p \cong r$) predicts "spin-up" recoils and "spin-down" protons when the protons are scattered to the left and $j_n = l - \frac{1}{2}$. In Fig. 1(b), the modified model ($\lambda_p > \lambda_d$, $\lambda_d \cong r$) predicts opposite signs for the polarization, since region 1 is larger than region 2. The polarization will be small. In Fig. 1(c) the modified model ($\lambda_d > \lambda_d < r$) predicts large polarizations opposite from the Newns model under the same conditions. Figure 1(d) illustrates proton scattering to the right for the case $i_n = l + \frac{1}{2}$ and $\lambda_p > \lambda_d < r$. The (d,p) reaction does not occur in the shaded regions of the nucleus.

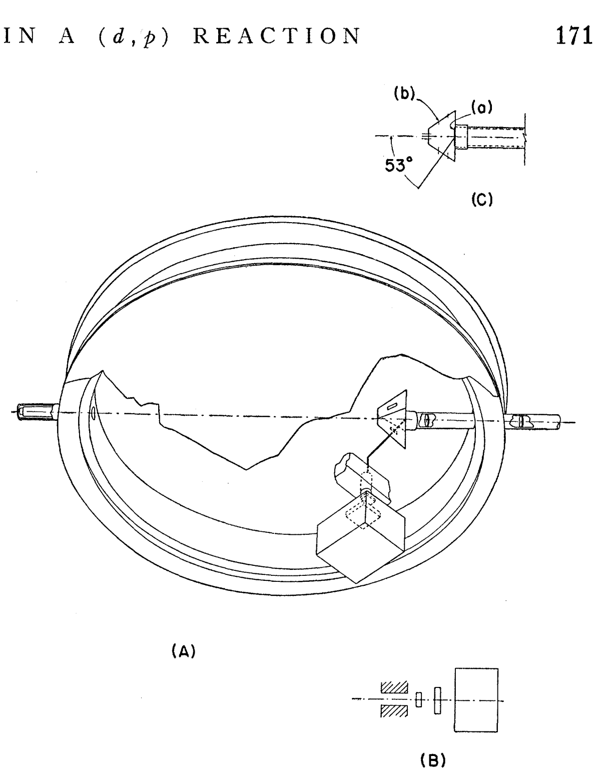


FIG. 2. (A) depicts a cut-away drawing of the front of the pancake-shaped scattering chamber showing the beam line, ion collimator, the Faraday cup, the $\frac{1}{16}$-in. Al covers, and the counter telescope. (B) and (C) are special views of the counter telescope and ion collimator, respectively (see text). In (A) the counter telescope is in a position for a measurement at a point on the +53° line.

and are stopped in the chamber in hydrogen gas at a distance of several inches from the boron target. In subsequent decays of B^{12} nuclei, beta particles emitted in a direction normal to the thin Al covers of the pancake-shaped scattering chamber may be detected by a counter telescope. The collimator in the counter telescope restricts the gas volume in which beta particles can originate and still reach the detectors to about one cubic inch. Measurements are made over those regions of the scattering chamber where the recoil ions from the stripping reaction stop in order to delineate the spatial distribution of recoil ions. Two broad distributions are found on opposite sides of the beam line along the ±53° radial lines (see Fig. 2). The counting rates for beta rays emitted along the ±53° lines were found to differ. The relative values reversed when the counter telescope was moved to the opposite side of the chamber.

In this experiment, a collimated 1/2-μamp beam of 2.8-Mev deuteron ions from the Stanford cyclotron was incident on a 5-μg/cm^2 layer of enriched boron (>99% B^{11}) deposited on a 0.00002-in. Ni foil.[14] The B^{12} recoil ions produced in $B^{11}(d,p)B^{12}$ reactions when the proton comes off in the stripping peak are energetic enough ($T_k \sim 200$ kev) to pass through the 5-μg/cm^2

[12] F. L. Friedman and V. H. Weisskopf, *Niels Bohr and the Development of Physics* (Pergamon Press Limited, London, 1955), p. 159.

[13] W. B. Cheston (private communication).

[14] The enriched boron layer was prepared by the Atomic Energy Research Establishment, Harwell, Berks., England.

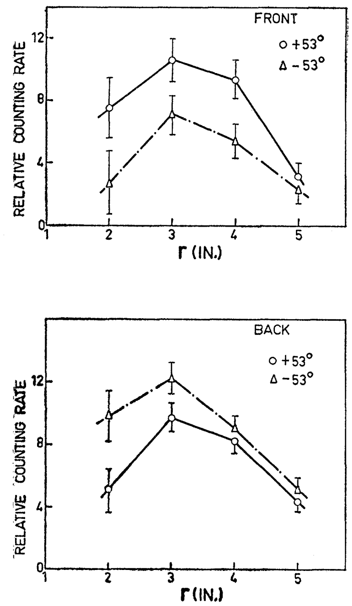


FIG. 3. The relative beta decay counting rates along the ±53° line on opposite sides of the pancake-shaped scattering chamber.

layer of boron and lose less than 10% of their total kinetic energy in the process. The remainder of the kinetic energy is expended in collisions in hydrogen gas. The B^{12} ions are brought to rest in the hydrogen gas with a reasonably well-defined range. Figure 2(A) shows a schematic diagram of the 18-inch diameter recoil chamber in which the B^{12} ions are slowed down by collisions with hydrogen. As shown in Fig. 2(C), the recoil ion collimator (b) stops all recoil ions produced in the boron layer (a) which would otherwise strike the surfaces of the recoil chamber. The gas pressure was maintained at about 22 mm Hg ($T\sim 20°$C) during the experiment. The deuteron beam was pulsed on for 16 msec in order to produce B^{12} ions. During the periods (16 msec) between pulses, the B^{12} ions were detected by observing the beta particles resulting from the beta decay of B^{12} ($t_{\frac{1}{2}}=25$ msec; $T=13.4$ Mev). A counter telescope consisting of a Pb collimator, two plastic scintillators, each thick enough to reduce the energy of a relativistic electron by 1 Mev, followed by a plastic scintillator large enough to stop most of the electrons in the beta spectrum of B^{12} is used [see Fig. 2(B) and 2(A)]. In order to be counted, the beta particles must produce a triple coincidence and must have an initial kinetic energy of at least 3 Mev. The electronic circuitry has been described previously.[15]

Although the counting was done during the periods between beam bursts, there was still a serious triple-coincidence background counting rate due to the residual B^{12} radioactivity in the ion collimator and a general neutron-induced background. The B^{12} radioactivity background produced in the ion collimator was strongly peaked in the vicinity of the boron target (this background correction was only important for the 2-in. point, see Fig. 3) whereas the neutron-induced background was uniform over the scattering chamber. Background counting rates were determined by repeating the experiment with no gas in the chamber and by using the total integrated charge and the singles counting rate in the large scintillator as monitors for the former and latter kinds of backgrounds. The background counting rates were carefully determined to be equal at corresponding distances along the ±53° radial lines, both on the front side and back side of the chamber. The alignment of the recoil ion collimator with the chamber face also was performed with sufficient care so as to rule out the possibility of misalignment of the system to explain the magnitudes of the asymmetries found.

Figure 3 summarizes the results of this experiment. The counting rate is plotted as a function of radial distance along the ±53° lines on both sides of the chamber. It is seen that the asymmetry in the beta counting rate along the ±53° line reverses direction when the counters are placed on the opposite side of the chamber. When the integrated counting rates are compared, the quantity $(N_+ - N_-)/(N_+ + N_-)$ is found to be $+27\pm 10\%$ and $-14\pm 6\%$ on opposite sides of the chamber. The quantity $N_\pm$ is the integrated counting rate along the ±53° line. A polarization of the B^{12} nuclei of at least 17% is required to yield the measured asymmetry in the angular distribution of the beta decays.[16] Since depolarization effects are extremely difficult to estimate, the magnitude of our result is, strictly speaking, a lower limit.[17]

In summary evidence is presented for a lower limit P_R of $17\pm 5\%$ for recoil B^{12} ions produced in a (d,p) reaction. Because the measured asymmetries are small and the experimental uncertainties are large, the polarization is only a few standard deviations away from a null value. Therefore measurements employing higher beam fluxes are highly desirable. Final-state interactions must be evoked to account for our result. With polarized B^{12} nuclei, a measurement of the magnetic moment of B^{12} becomes possible.

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[15] H. I. West, Jr., and L. G. Mann, Rev. Sci. Instr. **25**, 129 (1954).

[16] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).

[17] The B^{12} ions may be depolarized during the stopping process and during the ensuing thermal collisions which occur before beta decay. The authors wish to thank Dr. B. Mottelson for pointing out the additional depolarization effect due to a small residual magnetic field.