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Nuclear Polarization in the $B^{11}(d,p)B^{12}$ Reaction. I*

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Measurements of the polarization of the B^{12} recoils produced in the $B^{11}(d,p)B^{12}$ reaction have been made using a variety of recoil stopping materials. A lower limit of $P \geq +(0.0436 \pm 0.0021)$ is set for the recoil polarization in the direction of $\mathbf{k}_d \times \mathbf{k}_p$ at $E_d = 3.1$ MeV and 53° recoil angle.

I. INTRODUCTION

THIS is the first of two papers reporting the work in progress in this laboratory to make precise measurements of the nuclear polarization of the β^- active B^{12} recoil nucleus resulting from the $B^{11}(d,p)B^{12}$ reaction. The scope of this first paper is largely experimental, and contains a discussion of the experimental procedures and the attempts made to minimize systematic errors. In Paper II we expect to report on more extensive measurements and analysis of the polarization.

The work of Tobocman[1] and Newns and Rafai[2] showed that use of deuteron distorted waves in a stripping model of (d,p) reactions predicts a polarization of the recoiling nucleus. Spin-orbit interactions and compound nucleus formation[3] can also effect nuclear polarization. In the particular reactions producing nuclei which undergo β decay, a technique for measuring the nuclear polarization was demonstrated in 1957 by Wu *et al.*[4] The work of Lee and Yang[5] and of Wu[4,6] has shown for an allowed transition $J \rightarrow J-1$(no), the distribution of the β^- emissions relative to a collection of polarized nuclei of polarization P can be written

$$I(\theta) = I_0[1 - (v_e/c)P \cos\theta], \qquad (1)$$

where θ is the angle between $\mathbf{P}$ and the electron momentum $\mathbf{p}_e$.

Chase and Igo[7] were the first to suggest that the polarization produced in certain particle reactions could be measured by observing the asymmetry of the electrons emitted by the recoil nuclei. They used this technique to measure the polarization of B^{12} recoils in the $B^{11}(d,p)B^{12}$ reaction.[8] They bombarded a 5-μg/cm^2 layer of enriched boron with a 2.8-MeV deuteron beam. The B^{12} recoils from the $B^{11}(d,p)B^{12}$ reactions were collimated to correspond to the stripping peak. The recoils were stopped in hydrogen gas several inches from the target. The deuteron beam was chopped into 16 msec intervals, and while the beam was off, the number of electrons emitted normal to the reaction plane was counted with a triple coincidence telescope. They observed an asymmetry from which they inferred a lower limit for the nuclear polarization of $(17 \pm 5)\%$. This result is not in agreement with the work reported here, however.

The B^{12} polarization is being investigated at this laboratory as a way of studying the (d,p) reaction mechanism and also as a possible tool for determining both the magnetic dipole and electric quadrupole moments of the B^{12} nucleus.

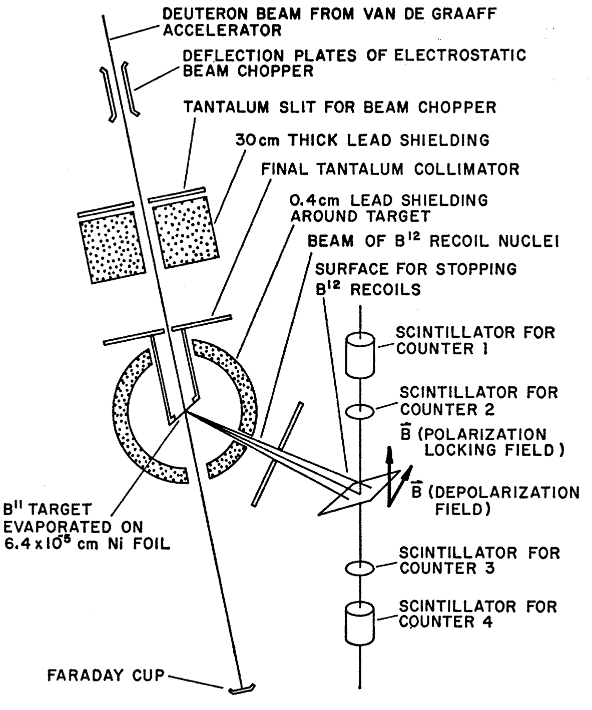

FIG. 1. Scattering geometry of the experiment. The axis of the four β^- counters is normal to the scattering plane formed by the deuteron and recoil moments.

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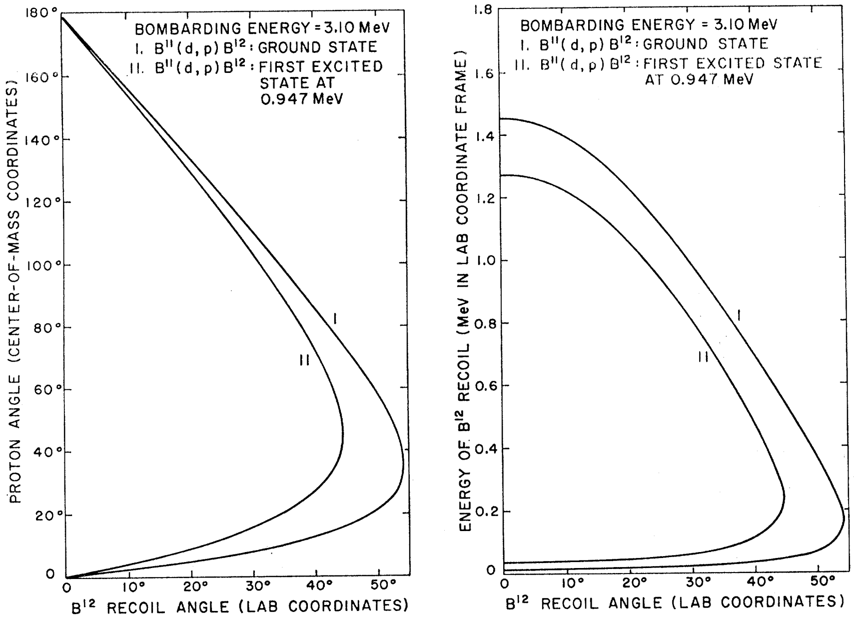

FIG. 2. The kinematics of the $B^{11}(d,p)B^{12}$ reaction at $E_d=3.1$ MeV.

II. DESCRIPTION OF THE EXPERIMENT

The scattering geometry of the experiment is shown schematically in Fig. 1. The complete reaction is $B^{11}(d,p)B^{12}:B^{12}\rightarrow C^{12}+\beta^{-}+\bar{\nu}$ where the half-life is 20 msec and the endpoint energy is 13.4 MeV. The B^{12} recoils are produced in the (d,p) reaction with their nuclear spins normal to the production plane,

$$\mathbf{P}=\pm|P|\cdot(\mathbf{k}_d\times\mathbf{k}_p)/|\mathbf{k}_d\times\mathbf{k}_p|. \qquad (2)$$

The method of the experiment is to examine the β^{-} activity of the recoils and using (1) to deduce the nuclear polarization.

The kinematic curves for the reaction at $E_d=3.1$ MeV are shown in Fig. 2. The B^{12} recoil nuclei are confined to a cone whose axis is along the deuteron momentem vector $\mathbf{k}_d$. From Fig. 2 it is seen that ground state recoils are restricted to 54° cone, whereas the first excited state recoils are restricted to 44.5°. The experiment is designed to study the boron recoils in the ground state; thus, in order to kinematically exclude recoils formed in the first and higher excited states, it was necessary to select only those recoils coming out at angles of 45° or larger In this experiment the recoils were restricted to 53°±3° with respect to the straight through deuteron beam. This recoil angle also corresponds to the proton stripping peak.

The targets used were made by evaporating a 60 $\mu g/cm^2$ layer of 98% enriched B^{11} onto a 6.4×10^{-5} cm nickel backing foil. The deuteron beam is sent through the Ni backing and is then incident on the B^{11} layer. The ground-state B^{12} recoils from the ensuing (d,p) reaction have kinetic energies (cf. Fig. 2) of the order of 200 keV. Range-energy studies[9,10] indicate that about half of this energy is given up in passing through the 60 $\mu g/cm^2$ B^{11} layer; thus the B^{12} recoil atoms leave the target with velocities of the order of 1.3×10^{8} cm/sec.

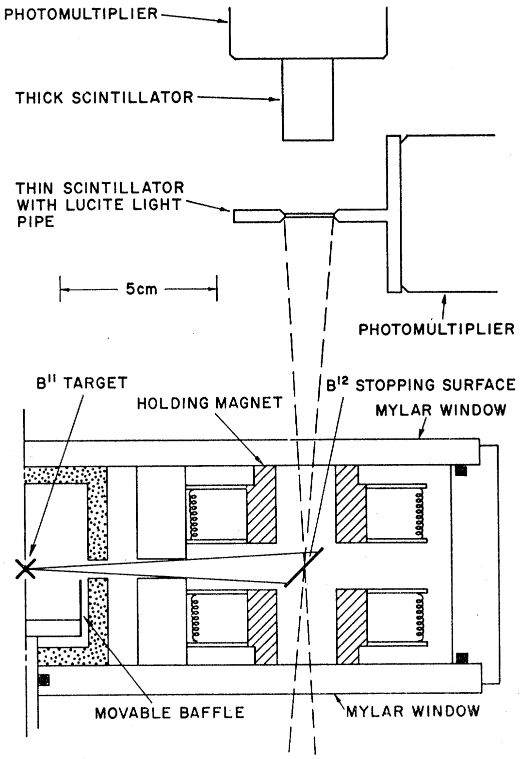

FIG. 3. The scattering chamber and telescope geometry. The lower telescope (not shown) is the mirror image of the upper, with respect to the scattering plane. The background count rate determined by blocking the B^{12} exit hole with the movable baffle.

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To determine whether the B^{12} recoil nuclei in this beam are polarized, the recoils must be stopped or in some way localized for the order of milliseconds until the beta activity can be observed. In this experiment the recoil ions traveled 9.0 cm to a stopping foil placed at 53° with respect to the straight through beam. It is well known, however, that the B^{12} ions may be depolarized both in the process of stopping and on the stopping foil before the beta decay. An attempt is made in this paper to estimate some of the depolarization processes believed to be involved. However, in the strictest sense the method of the experiment sets only a lower limit on the B^{12} polarization.

The β^- counters consisted of two identical double coincidence telescopes located on an axis perpendicular to the scattering plane and passing through the stopping foil. Fig. 3 shows the physical arrangement of the scattering chamber and the upper electron telescope. The lower telescope system is the mirror image of the upper half with respect to the scattering plane. Each telescope consisted of a 0.76-mm-thick, (dE/dx), plastic scintillator with a 6342-A photomultiplier and a 2.5-cm-thick plastic, (E), scintillator with a 6342-A photomultiplier. The 0.76-mm scintillator was held by a Lucite light pipe, which was sealed to the phototube with Dow Corning 200. The whole assembly was then placed in an aluminum box with walls 0.16-cm-thick and a top and bottom consisting of 5.8×10^{-4} cm Al foil.

The 2.5-cm cylindrical plastic scintillator having a 1.6-cm diameter was directly coupled to its phototube, and placed inside an aluminum container 2.5 cm o.d. with 0.16-cm wall thickness. The space in between was packed tightly with magnesium oxide and the whole arrangement covered by a 5.8×10^{-4}-cm Al foil. The resolution of this scintillator system is about 10%.

An electron gives up about 160-keV kinetic energy in passing through the 5.0×10^{-3}-cm Mylar window of the scattering chamber, the 0.76-mm scintillator and the several thin aluminum windows. The rms angle, $(\langle\theta^2\rangle_{\text{av}})^{1/2}$, for multiple scattering of 5-MeV electrons is 3° for the 5×10^{-3} Mylar window on the scattering chamber, 3° for each thin aluminum window and 13° for the 0.76-mm plastic scintillator. Thus the effect of multiple scattering on telescope efficiency is not large, but would tend to wash out the electron asymmetry. Each telescope subtends an angle of 0.015 steradians.

The 0.76-mm plastic scintillator gives a pulse height proportional to dE/dx of the electron. The 2.5-cm plastic scintillator gives a pulse height proportional to the electron energy. One can also say that the thickness of a 2.5-cm plastic scintillator is 5 MeV. Electrons with energies greater than or equal to 5 MeV will thus give the same pulse heights (with a correction for multiple scattering). In order to reduce the background counting rate a discriminator bias for pulses from the 2.5-cm scintillator was set at about 3 MeV. Thus for an event to be accepted the electron must have an energy $E\geq3$ MeV, and the pulses from both scintillators must occur in coincidence.

The background count rate was further reduced by chopping the deuteron beam with an electrostatic chopper and counting only when the beam was off. The chopper consisted of two parallel plates 50 cm long, 5 cm wide, and 2.5 cm apart, located about 3 m from the deflection slit. A potential difference of 4 kV allowed a rise and fall time of less than 20 μsec. The beam was chopped into 30-msec bursts separated by 30-msec intervals. Events were accepted only if they occurred during a coincidence gate pulse. This pulse was initiated 0.5 msec after the beam was turned off and lasted for 28 msec.

The B^{11} target is surrounded by a cylindrical lead shield, (cf. Figs. 1 and 3). The shield has a 0.8-cm-diam hole for the straight through deuteron beam to pass, and a 0.6-cm-diam hole at 53° through which the B^{12} recoils pass before reaching the stopping foil. Provision is made for blocking the B^{12} exit hole with a tantalum foil.

The background was measured by comparing the count rate with the B^{12} exit hole open and closed. The background was 3% and was independent of the beam current. The true to accidental ratio was about 900 to 1 and was measured by inserting 400-nsec delay in the pulses from the dE/dx counters. An additional background check was made by running the experiment with a plain Ni backing foil. The results of this experiment indicate that the backing contributes only about 0.4% to the count rate.

III. CONTROL OF SYSTEMATIC ERROR

Serious systematic error in experiments of this kind can come about from either geometric or electronic asymmetries in the apparatus.

In the present work geometric asymmetries were largely accounted for by alternately accumulating data with one of two magnetic field conditions at the stopping surface. One of these field conditions was a 500-G magnetic field perpendicular to the reaction plane. This field should tend to preserve the orientation of those B^{12} recoils produced with spins aligned normal to the reaction plane. Provision was made for switching off the 500-G field and switching on a 15-G depolarizing field directed in the plane of the reaction. Making an estimate of 1 nm for the magnetic moment this field would depolarize the B^{12} nuclei within 22 μsec.

The pole faces of the 500-G magnet were bored with a 1.9-cm-diam hole to allow passage of the β electrons to the telescopes. This causes a 5% inhomogeneity in the 500-G field across the stopping surface. This inhomogeneity would have the effect of slightly reducing the observed electron asymmetry. The effect that the magnetic fields have on the scattering of the electrons was determined by accumulating equal amounts of

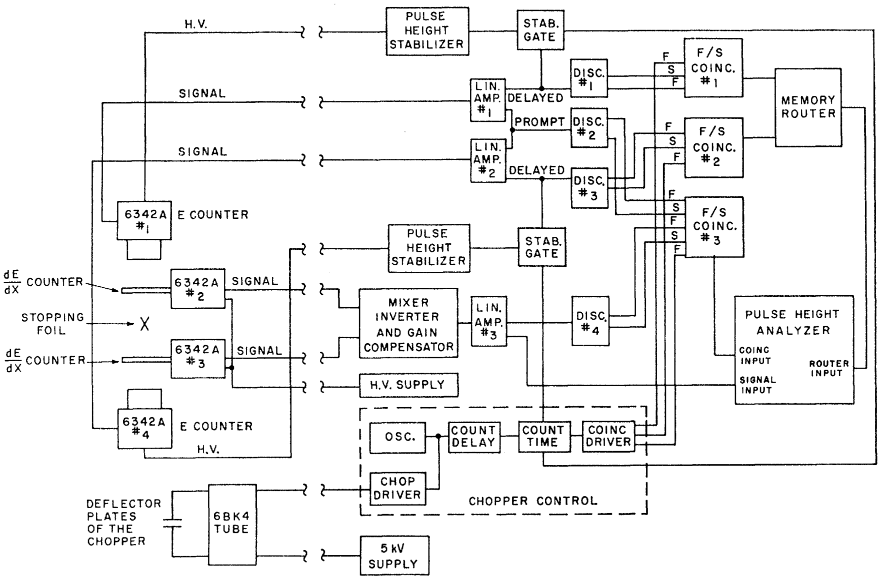

FIG. 4. Block diagram of the counter electronics. The linear amplifiers, discriminator single-channel analyzers, and coincidence buses are standard commercial units. The stabilizer gates and chopper control were built in this laboratory. The stabilizer gate shorts out the feedback input to the adjacent pulse-height stabilizer during the time the beam is on. This has the effect of reducing the beam-generated noise seen by the stabilizer as it is referenced on the Bi^{207} conversion electron peak.

data for both senses of current in the windings of each of the two magnets.

Another check of the geometry was made by measuring the polarization effect at both positive and negative recoil angles without changing the orientation of the magnets or the stopping surface.

A block diagram of the counter electronics is shown in Fig. 4. The most serious source of systematic error introduced by the counter electronics would be for the relative β electron counting efficiencies of the two telescopes to change during the experiment. In an effort to localize sources of electronic drift it was decided to pair the dE/dx counter outputs into a single discriminator (number 4) and to set the 3-MeV cutoff of the E counters with a single discriminator (number 2). Output pulses from these two discriminators along with the count time gate from the chopper control are required to be in coincidence for an event to be recorded in the analyzer.

The information determining whether the count occurred in the upper or lower telescope was obtained from the delayed outputs of the linear amplifiers 1 and 2 which were sent to separate discriminators 1 and 3, respectively. The bias of each of these discriminators was set at 2 MeV so as to have no effect on the counting efficiency of the telescopes. If an output pulse from either of these discriminators was in coincidence with the count time gate a signal was sent to the memory router which determined in what quarter of the analyzer a coincident input count was to be stored.

The pulse-height spectra of the minimum ionization peaks of the two dE/dx counters were separated in this way and stored in two separate quarters of the analyzer memory. Displaying the memory after each run made it possible to monitor the gains of the dE/dx counters. The number of β decays counted by each telescope was obtained by integrating the counts under the minimum ionization peak.

Because a single discriminator bias was used for both of the 2.5-cm scintillation counters, it was important to insure that the gain of each counter-amplifier branch remained constant. A Sturrup No. 4201 pulse-height stabilizer was used to supply the high voltage to the photomultiplier of each E counter. The stabilizers were referenced on the 1-MeV internal-conversion-electron peak of Bi^{207}. Separate 2-μCi Bi^{207} sources supported on a 6.2×10^{-4}-cm Mylar foil were placed over the front of each 2.5-cm scintillator. The conversion electrons were also used to set the discriminator levels and to monitor the gain and count rate stability of the system. Periodic checks using this stabilization procedure insured that the relative gain of the two E counters was constant to within 0.3%. Because of the 3-MeV rejection level in the E counters and the small solid angle seen by the dE/dx counters, the Bi^{207} source introduced no noticeable increase in background count rate.

An additional precaution against systematic error was taken by physically transposing the telescopes every half-hour during the data accumulation.

IV. EXPERIMENTAL RESULTS

The experimental measurement made is the β^- emission asymmetry, which is conventionally written

$$A_{\text{lab}}=\frac{N_{\text{up}}-N_{\text{down}}}{N_{\text{up}}+N_{\text{down}}}\pm(N_{\text{up}}+N_{\text{down}})^{-1/2}, \qquad (3)$$

where N_{up} and N_{down} refer to the number of counts recorded by the upper and lower telescopes. When the asymmetry is written this way, the reaction plane is assumed to be horizontal, and "up" and "down" are

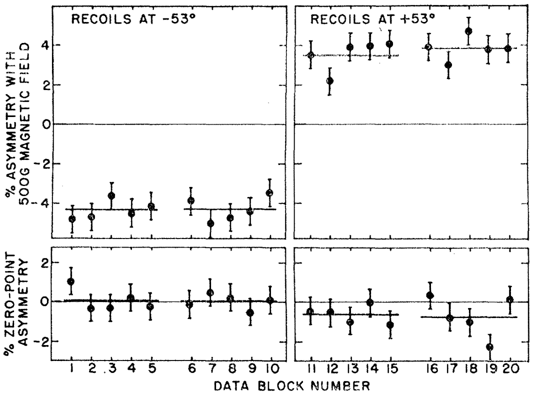

FIG. 5. An example of the β^- electron–count-rate asymmetry observed in the $B^{11}(d,p)B^{12}$ reaction. The recoil stopper was a 5×10^{-4}-cm-thick platinum foil, and the incident deuteron energy E_d was 3.1 MeV. A data block is defined in Table I. Each data block is a statistically independent measurement of the asymmetry; thus the figure shows the consistency of the effect. Data blocks 1–5 and 11–15 were taken with the 500-G field vector up and the 15-G field vector toward positive angles; data blocks 6–10 and 16–20 were taken with the 500-G field vector down and the 15-G field vector toward negative angles. The measurement at $-53°$ recoil angle implies a polarization $P=+(4.37\pm0.29)\%$; the independent measurement at $+53°$ recoil angle implies $P=+(4.34\pm0.31)\%$.

referenced with respect to the floor of the laboratory. Positive and negative recoil angles are angles to the left and right of the deuteron momentum vector, $\mathbf{k}_d$. An asymmetry of nuclear origins changes sign in this coordinate system when one goes from positive to negative recoil angles.

Nuclear polarization, however, is conventionally written using a coordinate system fixed in the reaction, $\mathbf{k}_d\times\mathbf{k}_p/|\mathbf{k}_d\times\mathbf{k}_p|$. In this coordinate system the sign of the polarization is uniquely specified.

An additional point to remember is that the β^- electrons are preferentially emitted in the direction opposite to the nuclear spin. This can be seen from Eq. (1), which becomes:

$$I(\theta)=I_0(1-P\cos\theta) \tag{4}$$

after noting $v_e/c\approx1$ for electrons able to satisfy the 3-MeV discriminator. Thus the expression for the nuclear polarization becomes

$$\mathbf{P}=\pm|A_{\text{lab}}|\ (\mathbf{k}_d\times\mathbf{k}_p)/|\mathbf{k}_d\times\mathbf{k}_p|\,, \tag{5}$$

where the sign of the polarization is obtained by determining the sign of the asymmetry in reaction coordinates and multiplying this by -1. Measurements reported in this paper indicate the sign of the polarization is positive.

Data were accumulated in successive blocks taken under identical conditions to build up adequate statistics. Each block consisted of four runs, the conditions for which are given in Table I.

The duration of each of the four runs was determined by integrating a specific amount of beam current and was typically about 15 min. The beam current was limited by beam heating of the target backing foil. The first data were taken using a 6.4×10^{-5}-cm Ni backing and a 0.7-μA beam current. Subsequent data were taken using a 13×10^{-5}-cm Cu target backing foil (again with a 60-μg/cm^2 B^{11} evaporated target) and a 2.0-μA beam current. The total coincident count rate in both telescopes was about 4 counts/sec with the Ni target backing and about 12 counts/sec with the Cu backing.

An example of the accumulation procedure is given in Fig. 5, which displays the asymmetries measured under the various field conditions taken using a platinum stopping surface. The sign change observed in the asymmetry after the recoil angle was changed from positive to negative is strong evidence of the nuclear origins of the effect. This interpretation is especially compelling in view of the fact that the orientation of the magnet and the stopping surface was not changed when the recoil angle was changed from positive to negative.

The net asymmetry is obtained by subtracting the zero-point depolarization asymmetry from the asymmetry observed with the polarizing field. In the case of the platinum stopping foil, the net asymmetry was $-(4.37\pm0.29)\%$ for recoils observed at $-53°$, and $+(4.34\pm0.31)\%$ for recoils at $+53°$. This consistency indicates that the small zero point asymmetry of $-(0.64\pm0.23)\%$ observed for recoils at $+53°$ was probably due to a slight misalignment of the counters. A later experiment directly confirmed this interpretation. Thus the lower limit for the nuclear polarization implied by the platinum stopper experiment is

$$\mathbf{P}=+(0.0436\pm0.0021)\ (\mathbf{k}_d\times\mathbf{k}_p)/|\mathbf{k}_d\times\mathbf{k}_p|$$

for $E_d=3.1$ MeV and a 53° recoil angle.

Although it is not evident in the data of Fig. 5, a small instrumental asymmetry dependent on the sense of the 500-G field was observed. It was found when the current in the windings of the 500-G magnet was reversed that on the average the relative up-down count rate would shift by 0.6%. The sign of this instrumental asymmetry was always in the direction opposite to the 500-G field vector, and did *not* reverse when the sign of the recoil angle was changed. An auxiliary experiment involving blocking the direct electron paths between the stopping foil and the counters indicated that the field sensitive asymmetry was caused by electrons scattering from the iron core of the 500-G

TABLE I. Data-accumulation procedure.

Run	Magnetic field	Position of telescope 1 relative to scattering plane
1	500-G pol. condition	up
2	500-G pol. condition	down
3	15-G depol. condition	down
4	15-G depol. condition	up

TABLE II. Polarization observed as a function of stopping material.

Stopping material	Thickness of stopper (in cm)	Recoil angle with respect to d beam	E_d (in MeV)	Asymmetry[a] with 500-G field	Zero-point[a] asymmetry	Nuclear polarization
LiF single crystal	3.8×10^{-2}	+53°	2.5	$(1.27\pm0.47)\%$ up	$(1.23\pm0.47)\%$ up	$+(0.04\pm0.66)\%$
Cu foil	2.5×10^{-3}	+53°	2.5	$(1.79\pm0.28)\%$ up	$(0.47\pm0.28)\%$ up	$+(1.32\pm0.40)\%$
Cu foil (repeat)	2.5×10^{-3}	+53°	2.5	$(1.65\pm0.23)\%$ up	$(0.30\pm0.23)\%$ up	$+(1.35\pm0.32)\%$
Cu foil	2.5×10^{-3}	+53°	2.9	$(2.60\pm0.25)\%$ up	$(0.51\pm0.25)\%$ up	$+(2.09\pm0.34)\%$
Cu foil	2.5×10^{-3}	+53°	3.1	$(3.18\pm0.24)\%$ up	$(0.11\pm0.25)\%$ down	$+(3.29\pm0.34)\%$
Cu foil	2.5×10^{-3}	−53°	3.1	$(2.32\pm0.24)\%$ down	$(0.49\pm0.25)\%$ up	$+(2.81\pm0.34)\%$
Xe solid crystals at 30°K	1.0×10^{-2}	+53°	2.5	$(0.36\pm0.23)\%$ up	$(0.71\pm0.23)\%$ down	$+(1.07\pm0.33)\%$
Xe solid crystals at 30°K	1.0×10^{-2}	+53°	2.9	$(0.80\pm0.24)\%$ up	$(0.89\pm0.24)\%$ down	$+(1.69\pm0.34)\%$
Al foil	2.5×10^{-3}	−53°	3.1	$(1.48\pm0.18)\%$ down	$(0.66\pm0.18)\%$ up	$+(2.14\pm0.26)\%$
Mylar foil	2.5×10^{-3}	−53°	3.1	$(0.08\pm0.22)\%$ down	$(0.14\pm0.22)\%$ down	$-(0.06\pm0.30)\%$
Teflon cleaved foil	2.5×10^{-2}	−53°	3.1	$(0.09\pm0.19)\%$ down	$(0.01\pm0.20)\%$ down	$+(0.08\pm0.27)\%$
Carbon amorphous slab	5.0×10^{-2}	−53°	3.1	$(0.79\pm0.20)\%$ down	$(0.42\pm0.20)\%$ up	$+(1.21\pm0.28)\%$
Be foil	2.5×10^{-3}	−53°	3.1	$(1.20\pm0.21)\%$ down	$(0.16\pm0.21)\%$ up	$+(1.36\pm0.30)\%$
V foil	2.5×10^{-3}	−53°	3.1	$(0.05\pm0.26)\%$ down	$(1.13\pm0.26)\%$ up	$+(1.18\pm0.36)\%$
Si single crystal	1.8×10^{-2}	−53°	3.1	$(2.06\pm0.22)\%$ down	$(0.30\pm0.22)\%$ down	$+(1.76\pm0.31)\%$
Mn slab	2.0×10^{-2}	+53°	3.1	$(1.35\pm0.27)\%$ up	$(0.58\pm0.27)\%$ up	$+(0.78\pm0.38)\%$
Au foil	5.0×10^{-4}	−53°	3.1	$(2.24\pm0.19)\%$ down	$(1.39\pm0.19)\%$ up	$+(3.64\pm0.24)\%$
Pd foil	1.5×10^{-3}	−53°	3.1	$(3.52\pm0.20)\%$ down	$(0.81\pm0.20)\%$ up	$+(4.33\pm0.28)\%$
Pt foil	5.0×10^{-4}	−53°	3.1	$(4.32\pm0.20)\%$ down	$(0.05\pm0.21)\%$ up	$+(4.37\pm0.29)\%$
Pr foil	5.0×10^{-4}	+53°	3.1	$(3.70\pm0.22)\%$ up	$(0.64\pm0.23)\%$ down	$+(4.34\pm0.31)\%$

[a] "Up" and "down" are defined in the text.

magnet. In any case, the effect is eliminated from the results because the nuclear asymmetry is determined by averaging over both senses of current in the magnet windings.

The nuclear polarization of the boron recoils was observed using a variety of other stopping materials. A listing of the results is given in Table II.

The error stated in each case is the probable error. The consistency of the asymmetry measurements as the experimental parameters were varied suggests that the residual systematic errors in the experiment introduce asymmetry effects of about 0.2%.

It is apparent that the depolarization is a widely varying function of the stopping material. The noble metals exhibited the least depolarization effect possibly because of the absence of surface contaminants. All of the metal foils were cleaned in baths of water, ethyl alcohol, acetone, trichlorethlene, acetone, ethyl alcohol, and acetone.

Referring to Table II one sees that the organic materials, Mylar and Teflon, completely depolarize the B^{12} nuclei. This is in agreement with the work of Love *et al.*[11,12] which indicated complete depolarization of B^{12} recoils in pentane. It is also consistent with the work of Sugimoto *et al.*[13] who found in an experiment similar to the present one, that Teflon completely depolarized F^{17} recoils.

As part of some preliminary work[14–16] on the boron problem in this laboratory an attempt was made to repeat the work of Chase and Igo.[8] A deuteron beam of energy $E_d = 2.8$ MeV was incident on a 20 μg/cm² B^{11} target. The B^{12} recoils were collimated at 53° and stopped in helium gas at a pressure of 2 mm. As in the Chase and Igo experiment, no magnetic fields were applied in the stopping region. The coincident count rate was very low and the observed asymmetry was consistent with a zero polarization, $P = +(2.5\pm8.0)\%$. This work and the other measurements summarized in Table II are not in agreement with the large $17\%\pm5\%$ effect reported by Chase and Igo.[17]

The solid-xenon stopping foil was formed by condensing xenon gas onto a 2.5×10^{-3}-cm thick copper-foil substrate maintained at 30°K. For the xenon experiments the chamber windows were aluminum not Mylar

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[15] P. W. Keaton, dissertation, Johns Hopkins University, 1963 (unpublished).

[16] J. J. Berlijn, dissertation, Johns Hopkins University, 1964 (unpublished).

[17] On the basis of the geometry in the second figure of the Chase and Igo paper (Ref. 8) we believe that the sign of the effect they observed is in agreement with our work. The discrepancy is in the magnitude of the effects reported. A possible reason for the discrepancy could be due to the small statistical sample used in their work. Possibly also they encountered asymmetries due to certain systematic effects in the apparatus. We found in the course of this work that reliable measurements could not be made until the efficiencies of the electron counters were carefully stabilized, and the asymmetries in the scattering geometry were determined. The method of the transverse field to depolarize the nuclei and the stabilization of the electronics are described in the body of this paper.

and a copper shield was installed surrounding the xenon surface. This shield was kept at 35°K to insure that the xenon surface was not contaminated by cryopumping. The vacuum in the target chamber during the xenon experiment was 1×10^{-7} mm, and the vacuum within the cold shield was estimated to be 5×10^{-10} mm. The deposition of the xenon surface and the cooling equipment have been described elsewhere.[18]

V. DEPOLARIZATION PROCESSES

It is not possible to determine the true initial value of the polarization because neither the atomic conditions[19] in the stopping material nor the atomic configuration of the recoils is precisely known. One can, however, make estimates of the size of each of the depolarization mechanisms by making some assumptions about the unknown conditions. A rather complete treatment of the possible depolarization mechanisms for B^{12} recoils has been made using this approach.[15,16] We will present the principal results of this treatment with the view of assigning upper and lower limits to the depolarization process.

A lower limit for depolarization of the recoils can be made by considering only the depolarization due to hyperfine mixing in flight. Let F be the neutral fraction of recoils leaving the target and $1-F$ be the singly ionized fraction.[20] The ionized B^{12} recoils have a closed shell of electrons and are not expected to be depolarized. The neutral recoils are in $P_{1/2}$ or $P_{3/2}$ electronic states with statistical population ratios of 2:4. Standard configuration mixing calculations[15] indicate that the $P_{1/2}$ and the $P_{3/2}$ states depolarize in flight to 78 and 59%, respectively. Thus starting with completely polarized B^{12} recoils the fraction of polarization retained when the recoils reach the stopping foil is $(1-F)+F[\frac{2}{3}(0.59)+\frac{1}{3}(0.78)]$. Best estimates from hydrogen and lithium data[21,22] indicate that the B^{12} recoils are about 70% neutral and 30% singly ionized. Thus the maximum polarization we could expect to measure would be 76%.

Other effects could substantially reduce this number. For example, the interaction of the quadruple moment of the B^{12} nucleus with strong electric field gradients of the boron atom could cause additional nuclear depolarization as large as 50%.[23] In addition, a calculation by Bloch[23] indicates that electron captures and losses during the stopping time could reduce the polarization an additional 12%.

Taken together, these effects indicate that the polarization could be reduced to 33% of its original value.

VI. CONCLUSION

A lower limit for the nuclear polarization of recoils produced in the $B^{11}(d,p)B^{12}$ reaction at $E_d=3.1$ MeV has been set at $P\geq+(4.36\pm0.21)\%$. An experimental survey of stopping materials indicates that the noble metals Au, Pt, and Pd preserve the B^{12} polarization, and the organic materials Teflon and Mylar cause complete depolarization. The work has demonstrated the possibility of maintaining nuclear polarizations using low holding fields. The details of the reaction including a study of the polarization as a function of incident deuteron energy and recoil angle will be reported in Paper II. The technique described here should be suitable for a determination of both the magnetic dipole and electric quadrupole moments of B^{12}. These studies are in progress in this laboratory.

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[18] L. Pfeiffer and P. W. Keaton, Jr., Nucl. Instr. Methods **40**, 357 (1966).

[19] Studies of the behavior of the nuclear moment in the stopping foil are in progress to ascertain the electronic configuration associated with the stopped boron recoil.

[20] Experiments designed to measure the fraction F are now in progress in this laboratory.

[21] S. Allison, Rev. Mod. Phys. **30**, 1137 (1958).

[22] I. S. Dmitriev, Zh. Eksperim. i Teor. Fiz. **32**, 570 (1957) [English transl.: Soviet Phys.—JETP **5**, 473 (1957)].

[23] B. L. Bloch, Carnegie Institute of Technology Report (unpublished).