where

$$I=-\frac{i\pi^2}{2p^3\sin^2(\frac{1}{2}\theta)}\ln\left(\frac{2p\sin(\frac{1}{2}\theta)}{\epsilon}\right),\quad J=\frac{I}{\cos^2(\frac{1}{2}\theta)}-\frac{i\pi^2}{2p^3\cos^2(\frac{1}{2}\theta)}\left[\ln\frac{i\epsilon}{2p}-\frac{i\pi}{\sin(\frac{1}{2}\theta)}\right].$$

These I, J are the limiting values of I, J as $\epsilon\rightarrow 0$, given by Dalitz.[7]

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

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Measurements have been made of the polarization of the B^{12} recoil nuclei resulting from the $B^{11}(d,p)B^{12}$ reaction for E_d in the range 0.90 to 3.20 MeV. The polarization is observed by measuring the β-decay asymmetries of the B^{12} recoil nuclei with respect to the reaction plane. The B^{12} recoil nuclei formed in the ground state are separated kinematically from those in excited states and are then stopped in various solids in the presence of a small magnetic field normal to the reaction plane. The sign of the observed polarization for all measurements is in the direction of the vector $\mathbf{k}_d\times\mathbf{k}_p$. The magnitude of the polarization is strongly dependent on E_d, the recoil emission angle and the material used to stop the recoils. It is found that the polarization of B^{12} nuclei can be maintained in either metallic Pd or Au at room temperature, using holding fields smaller than 20 G. For recoils stopped in Pt metal, a magnetic field of about 200 G is required to maintain the nuclear polarization. The B^{12} recoil polarization plotted as a function of E_d shows definite structure. Polarization resonances are observed at 1.5, 2.1, and 3.0 MeV. At these energies the measured relative polarizations are $+(8.01\pm0.30)\%$, $+(4.29\pm0.30)\%$, and $+(3.86\pm0.27)\%$, respectively, for a Pt metal recoil stopper and a 49° (lab) recoil angle. These resonances are tentatively identified with states of the C^{13} compound nucleus near 20.0 MeV and at 20.52 and 21.28 MeV. It is believed that the polarization resonances may result from an interference between direct interaction and two-particle compound resonance processes.

I. INTRODUCTION

THIS is the second of two papers which report on the work done in this laboratory to measure the polarization of the B^{12} recoil nuclei resulting from the $B^{11}(d,p)B^{12}$ reaction. The first paper[1] (hereinafter called paper I) demonstrated the feasibility of measuring the polarization of B^{12} recoils and discussed the experimental arrangement in some detail, with emphasis on the precautions taken to reduce systematic error. This second paper describes some of the interesting and rather surprising results obtained from a more detailed study of the B^{12} polarization.

For the sake of completeness, a very brief review of the experimental method will now be given. The reader is asked to refer to paper I for details and original references. The method requires first that the reaction of interest provide the recoiling nuclei with sufficient energy to leave the nuclear target and to be implanted in a stopping foil several centimeters away. If the implanted recoil nuclei were originally polarized by the nuclear interaction, then this polarization can be detected, provided that the nuclei decay by a Gamow-Teller β transition and that the polarization is not destroyed in the time before the β decay. For B^{12} recoils, the decay is by β^- emission from a 1^+ to a 0^+ state, with half-life 20.4 msec and endpoint energy 13.4 MeV. Equation (1) in paper I shows that the decay electrons from this transition are preferentially emitted opposite to the nuclear spin polarization $\mathbf{P}$,

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

where θ is the angle between $\mathbf{P}$ and the electron momentum $\mathbf{p}_e$. The experimental technique is then to examine the β^- emission pattern from the implanted recoils and, using Eq. (1), to deduce the polarization.

II. POLARIZATION RESULTS: DEPENDENCE ON NUCLEAR EFFECTS

One of the difficulties in an experiment of this kind is that the observed polarization is found to be a widely varying function of several independent parameters. For this reason, an isolated polarization measurement for a specific set of conditions is of only limited usefulness.

In the present work with B^{12}, an attempt was made to isolate the influences of the following parameters: deuteron bombarding energy, emission angle of the recoil with respect to the deuteron beam, thickness of the B^{11} target layer, type of stopping material, strength

* This work partially supported by the U. S. Atomic Energy Commission.
[1] J. J. Berlijn, P. W. Keaton, L. Madansky, G. E. Owen, L. Pfeiffer, and N. R. Roberson, Phys. Rev. 153, 1152 (1967).

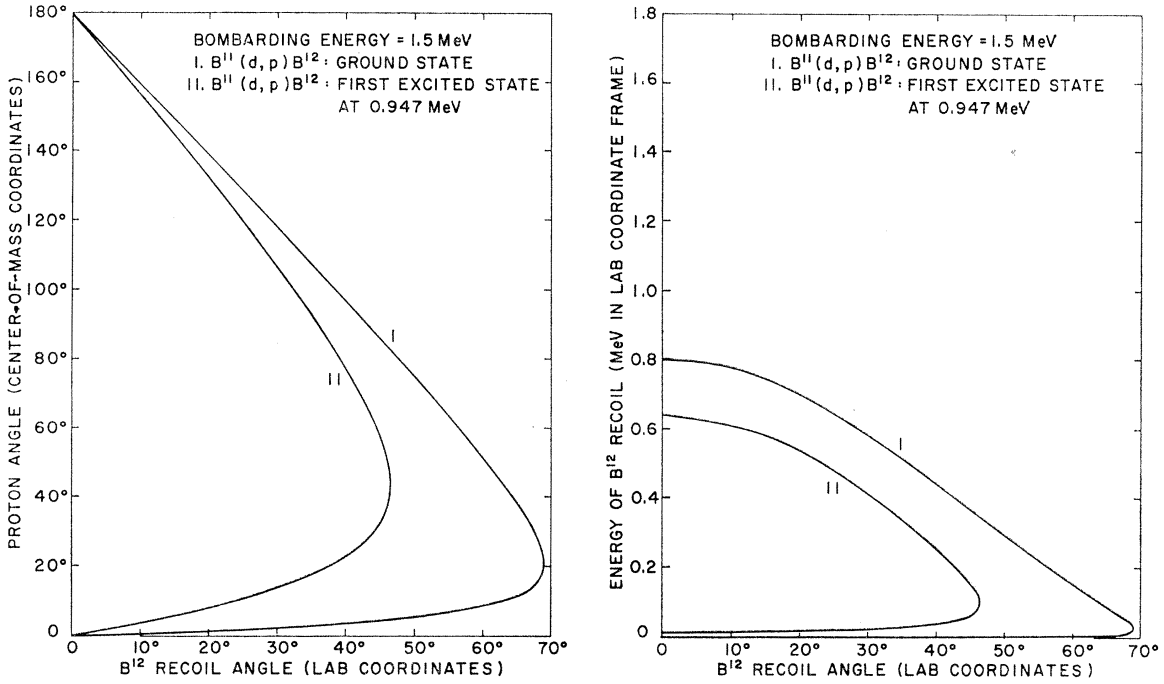

FIG. 1. The kinematics of the $B^{11}(d,p)B^{12}$ reaction at $E_d = 1.50$ MeV.

of the magnetic holding field at the stopping foil, and elapsed time before observing the decay of the implanted B^{12}. The behavior of the polarization as a function of deuteron energy and recoil angle should contain nuclear information about the mechanism of the (d,p) reaction. The polarization as a function of the other parameters, conversely, should provide some insight into the various atomic interactions which cause the recoils to become depolarized. We discuss first the nuclear parameters.

A. Dependence on Bombarding Energy

The polarization of the ground-state B^{12} recoils was observed as the bombarding energy E_d was varied between 0.90 and 3.20 MeV. Recoils which are originally formed in one of the excited states of B^{12} are again kinematically excluded by the method described in paper I. The kinematic curves for the reaction at $E_d = 3.10$ MeV have been given in Fig. 2 of paper I. Similar curves obtained for $E_d = 1.50$ MeV are shown here in Fig. 1. In comparing the two sets of curves, one sees that the angular cone of the ground-state recoils in the lab system opens from 54° to 69° as E_d is decreased, whereas the kinematic cone for the excited-state recoils is enlarged only slightly, from 44° to 46°. The recoil angle thus has a larger usable range (consistent with exclusion of the excited-state recoils) for low-energy deuterons.

The experimental results showing the ground-state B^{12} polarization as a function of bombarding energy at several recoil angles are given in Fig. 2. It is seen in this figure that the magnitude of the polarization has definite structure as a function of E_d. Apparent polarization resonances are observed for deuterons with energies at 1.5, 2.1, and 3.0 MeV. It is interesting to observe that each resonance appears at two recoil angles in independent measurements. This effect is most striking in the resonance at 1.5 MeV. Here, the resonant structure is clearly preserved for measurements at both recoil angles, even though the relative magnitudes of the polarization differ by a factor of 2.

The vertical arrows at 3.08, 2.18, and 1.6 MeV in Fig. 2 mark the excitation energies of excited energy levels in the C^{13} compound nucleus. These levels are, respectively, 21.28, 20.52, and 20.0 MeV above the C^{13} ground state. The levels at 21.28 and 20.52 MeV have been well established[2–4] by excitation studies of the 15.1-MeV γ decay from the reaction $B^{11}(d,n\gamma)C^{12}$. The existence of the level at excitation 20.0 MeV is not firmly established, but it is clearly suggested by recent work at several laboratories.

Almond,[5] for example, in a recent study of the $B^{11}(d,n)C^{12}$ reaction observed a large excitation resonance centered about $E_d = 1.6$ MeV in the zero degree n_0 and n_1 neutron excitation curves. Other hints of resonance behavior have recently been noticed in the

[2] R. W. Kavanagh and C. A. Barnes, Phys. Rev. **112**, 503 (1958).
[3] H. Kuan, P. R. Almond, G. U. Din, and T. W. Bonner, Nucl. Phys. **60**, 509 (1964).
[4] T. Lauritsen and F. Ajzenberg-Selove, *Energy Levels of Light Nuclei* (National Academy of Sciences–National Research Council, Washington, D. C., 1962).
[5] P. R. Almond, dissertation, Rice University, Houston, Texas, 1965 (unpublished).

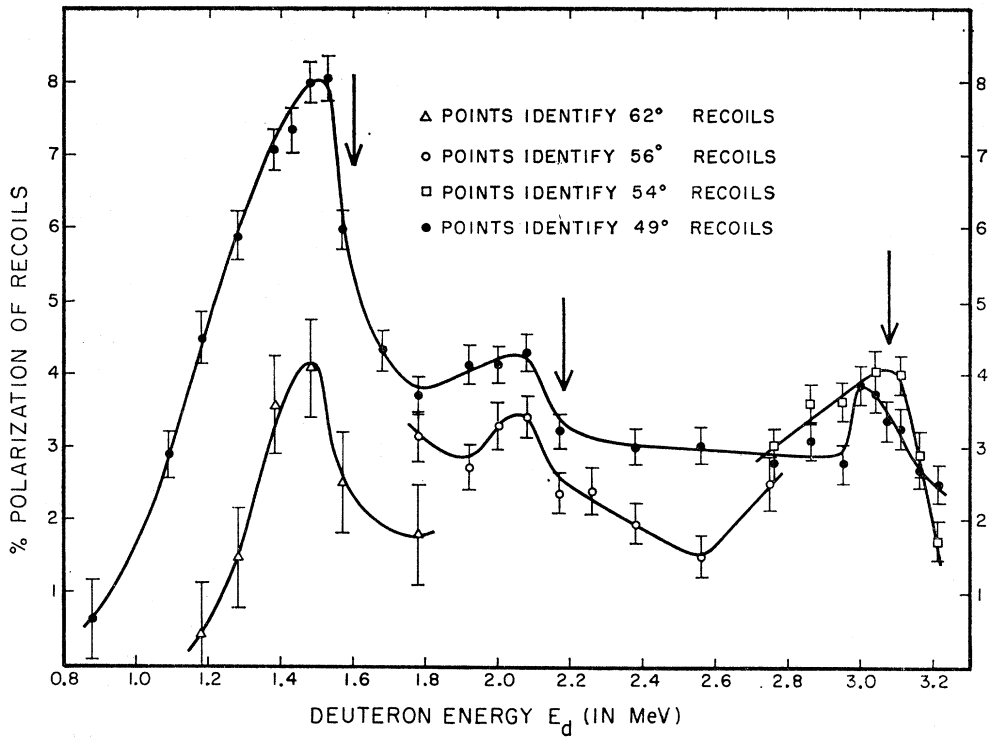

FIG. 2. The experimentally observed polarization displayed as a function of the deuteron bombarding energy and the recoil angle. The data were taken using a platinum stopping foil and an 80-μg/cm^2-thick B^{11} target. The smooth curves are empirically drawn. The error bar shown for each point corresponds to one standard deviation.

$B^{11}(d,p)B^{12}$ reaction itself. Hanke and Kambe,[6] in a study of the energy dependence of the p_0 and p_1 angular distributions, found in each case a local maximum in the stripping peak near $E_d=1.5$-MeV excitation. This was consistent with an earlier result by Mingay,[7] who observed local maxima for $E_d=1.5$ and for 2.2 MeV in the differential cross-section excitation function of forward scattered p_1 protons.

The polarization resonances of Fig. 2 allow us to say immediately that the $B^{11}(d,p_0)B^{12}$ reaction does *not* proceed by a pure stripping mechanism. This follows because the distorted-wave Born-approximation (DWBA) theory of stripping predicts that for a fixed angle the polarization, like the optical parameters, should not vary rapidly with energy. The appearance of polarization resonances and the apparent correspondence of these resonances to the excitation energies of known levels in C^{13} lead us to suggest that the polarization we have observed might be the result of an interference between very fast, two-particle compound resonance processes and the nonresonant background from the direct interaction. This type of process has been discussed by Rodberg[8] and others[9] in connection with the fluctuations sometimes observed in the differential cross section near a compound resonance.

In view of the apparent importance of the C^{13} compound nucleus in this work, we decided to use the 21.28- and 20.52-MeV states of C^{13} as the energy calibration for the polarization data.[10] The well-known structure[2] in the yield of the 15.1-MeV γ from $B^{11}(d,n\gamma)C^{12}$ proved to be very suitable, since it provides a third accurately known calibration point at the threshold of the 15.1-MeV level in C^{12}. The calibration is, however, complicated by the requirement that the deuteron beam pass through a backing foil before striking the B^{11} target (cf. paper I). The nonuniformity in the thickness of this backing foil gave the largest contribution to the assigned $\pm$40-keV error in E_d.

B. Dependence on Recoil Angle

The data in Fig. 2 also show the marked dependence of the polarization on the angle of the emitted recoil. As stated earlier, the kinematic isolation of the ground-state recoils restricts the recoil angle to a narrow range above 46° in the lab system. The large recoil angles at 62°, 56°, and 54° were chosen to correspond kinematically to the stripping peak[6,7] for deuterons at 1.5, 2.1, and 3.0 MeV. The 49° recoil angle was chosen for

[6] G. Hanke and D. Kamke, Z. Physik **190**, 468 (1966).
[7] D. W. Mingay, dissertation, University of the Witwatersrand, Johannesburg, South Africa, 1964 (unpublished).
[8] L. S. Rodberg, Phys. Rev. **124**, 210 (1961).
[9] T. Bonner, J. Eisinger, A. Kraus, and J. B. Marion, Phys. Rev. **101**, 209 (1956).
[10] L. Pfeiffer, dissertation, The Johns Hopkins University, Baltimore, Maryland, 1967 (unpublished).

comparison, as it selects recoils off of the (d,p) stripping in each case. From the data in Fig. 2, one would conclude that the recoil polarization increases in general as one moves to larger angles off of the stripping peak. This interpretation should possibly be qualified in light of a calculation[10] indicating that the 49° recoils have a B^{12} first-excited-state contaminant of $(8\pm8)\%$ at $E_d=3.0$ MeV, and of $(52\pm9)\%$ at $E_d=1.5$ MeV. This leakage of excited-state recoils is caused by an angular spread in the collimator geometry.

If these contaminant recoils from the 2^+ excited state of boron are also polarized by the reaction, it is easily shown[10] that the polarization is preserved in the subsequent $\mathfrak{M}1$ decay to the 1^+ ground state. Unraveling the relative polarizations of these two states would require a very detailed examination of the asymmetry as the recoil angle is swept across the kinematic discontinuity.

III. POLARIZATION RESULTS: DEPENDENCE ON ATOMIC AND SOLID-STATE EFFECTS

In this section, we discuss some of the parameters that control the extent to which the boron nuclei become depolarized. Each B^{12} nucleus is subjected to possible depolarization interactions during its entire existence: in the target, in flight, during the stopping process, and at rest in the stopping material before the β decay. By use of the range-energy formulas of Lindhard and others,[11,12] however, one can estimate[10] that the recoil spends only of the order of 10^{-13} sec in the B^{11} target and 10^{-12} sec stopping. For this reason, the dominant polarization is expected to occur in the 10^{-8} sec flight[13] and after the recoil is stopped.

The thickness of the B^{11} target evaporation might be expected to influence the depolarization, in view of the fact that recoils escaping the target have, on the average, more energy if the B^{11} layer is thin. To check this possibility we observed the polarization as a function of target thickness, using a platinum stopping foil and a deuteron bombarding energy of 1.5 MeV. The results of this work show that the observed polarization increases gradually from $(6.68\pm0.56)\%$ to $(9.03\pm0.56)\%$ as the B^{11} evaporation thickness is reduced over the range 165 to 15 $\mu g/cm^2$.

There are two mechanisms for expecting less depolarization from high-energy recoils, either of which could be large enough to account for the effects observed. One consideration is that the fraction of singly ionized recoils is larger for recoils leaving the target at high energies,[10,14] and so by the argument summarized in Sec. V of paper I (cf. Ref. 13), one would expect less depolarization from hyperfine interactions in flight. The other possibility is simply that the low-energy recoils are being stopped and subsequently depolarized in the surface regions of the platinum foil.

Experiments were also done to determine the relationship between the amplitude of the magnetic holding field (cf. paper I) and the observed polarization. The results are summarized in Fig. 3, which shows the holding field on a logarithmic scale and the polarization on a linear scale. The smooth curves shown in the figure are in each case three-parameter fits assuming a relaxation time of the form $T_{\text{relax}}=a+bH^2$. The best fits were obtained with the following values for a and b: for Au, $a=1.0\times10^{-2}$ sec, $b=1.9\times10^{-3}$ sec/G^2; for Pd, $a=4.5\times10^{-3}$ sec, $b=1.2\times10^{-3}$ sec/G^2; for Pt, $a=3.0\times10^{-3}$ sec, $b=1.3\times10^{-5}$ sec/G^2. The empirical value of the polarization for large holding fields was the third parameter used in the fitting program.

The behavior of the polarization is similar for the three materials. In each case, the observed effect appears to be constant above a certain threshold but breaks abruptly and tends toward zero for holding fields below

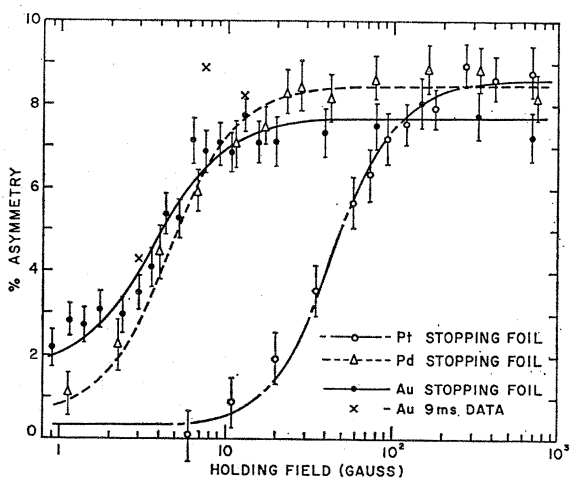

FIG. 3. The experimentally observed polarization displayed as a function of the magnetic holding field. The data were taken using a 49° recoil angle, an 80 $\mu g/cm^2$-thick B^{11} target, and a 1.50-MeV deuteron bombarding energy. The smooth curves are three-parameter fits to the data. The error bar shown for each point corresponds to one standard deviation.

[11] J. Lindhard, M. Schraff, and H. E. Schiott, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. 33, No. 14 (1963).

[12] V. A. J. Van Lint, M. E. Wyatt, R. A. Schmidt, C. S. Suffrelini, and D. K. Nichols, Phys. Rev. 147, 242 (1966).

[13] In Sec. V of paper I, it was inadvertently stated that the recoils in the $P_{3/2}$ electronic state are depolarized to 59% of their original value as a result of hyperfine interactions in flight. The 59% figure accounts only for the depopulation of the $m=+1$ nuclear spin component. The up-down asymmetry depends, however, on the difference between the $m=+1$ and -1 populations. When one accounts for this effect, an in-flight depolarization to 42% is obtained for recoils in the $P_{3/2}$ state. A second point is that the expression given in paper I for the B^{12} in-flight depolarization can be generalized to include recoils which are doubly ionized. The generalized expression for the polarization retained by B^{12} recoils reaching the catcher foil is (see Ref. 10):

$$P_{\text{final}}=P_{\text{initial}}\{\Phi_0[\tfrac{2}{3}(0.42)+\tfrac{1}{3}(0.78)]+\Phi_1+\Phi_2(0.78)\},$$

where Φ_0 is the neutral recoil fraction, and Φ_1 and Φ_2 are the singly and doubly ionized fractions. Numerical values of the Φ_i for boron are given in Ref. 14.

[14] C. S. Zaidins, California Institute of Technology Report, 1962 (unpublished); (private communication).

threshold. The threshold is about 20 G for Pd, and about 200 G for Pt. For Au, the threshold occurred at 10 G, and a residual $+(1.15\pm0.41)\%$ polarization effect was observed without any holding field (other than the magnetic field of the earth). The asymptotic value of the polarization observed for holding fields above 200 G was approximately the same for Pd and Pt foils, but definitely lower for Au. This is in agreement with the earlier results for these metals, given in Table II of paper I.

In an effort to investigate the mechanism of these depolarization thresholds, an experiment was done using a special palladium stopping foil containing 0.35% of the isotope Pd^{105}. This is the only naturally occurring palladium isotope (22% abundant) having a nuclear ground-state spin. A comparison of the polarizations obtained with the natural and with the isotopically separated palladium provides a measure of the importance of the spin-spin interaction between the B^{12} and the Pd^{105} nuclei. The results of the Pd^{105} experiments with the foil containing the separated isotope were identical, within statistics, with the results on the natural Pd shown in Fig. 3. This seems to indicate that the nuclear spin-spin interactions are not responsible for the depolarization thresholds.

The holding field parameter for the gold foil was also studied as a function of the average time elapsed in the foil before β decay. This was done by varying the chop cycle of the deuteron beam and count gate (cf. Sec. II of paper I). The three points marked with an $\times$ in Fig. 3 correspond to recoils of average lifetime 9.6 msec in the gold stopping foil. (The error bars of $\pm0.60\%$ are not shown for these points, to avoid further congestion.) All of the other data in the figure involve lifetimes in the stopping foil of about 19.3 msec. Comparing the 9.6-msec points with the 19.3-msec gold data, we see that the threshold field does not change over this range of lifetimes, although the magnitude of the polarization may be slightly larger for the 9.6-msec points.

IV. CONCLUSIONS

A new lower limit can be assigned for the polarization of B^{12} recoil nuclei from the (d,p) reaction. By extrapolating the polarization observed at the $E_d=1.5$ MeV resonance to zero-thickness targets and correcting for the 3% noise background (cf. paper I), we obtain $P\geqslant+(9.55\pm0.48)\%$. If we now include only the depolarization due to hyperfine mixing in flight, and if we assume, following Zaidins,[14] that the 300-keV recoils are 24% neutral, 57% singly ionized, and 19% doubly ionized, then the new lower limit for the recoil polarization is $P\geqslant+(11.26\pm0.56)\%$.

This work has demonstrated the usefulness of the β-decay recoil technique for examining nuclear reaction mechanisms and solid-state depolarization mechanisms. We believe the recoil technique has special value as a way of studying nuclear polarization effects, because the recoil method is in a sense complementary to the more conventional nucleon double scattering method. Double scattering is better suited to finding the angular dependence of the reaction polarization; the recoil method is better for studying the energy dependences. The methods are also complementary in that with double scattering one observes the polarization of the outgoing nucleon, whereas with this method, one observes the residual nucleus. It might be of interest to use both methods on a single reaction, as this would allow a comparative study of the polarizations of the two final-state particles.

Another application of the recoil method is in the recently active study of heavy ion implantation in solids. It is believed that the technique of implanting *polarized* nuclei will prove to be of value as a tool for observing the local environment at an implantation site. Measurement of the depolarization of the implanted nuclei as a function of holding field, lattice temperature, lattice impurity content, time before decay, and isotopic composition of the lattice, should allow one to unfold the contributions of each of the various depolarization mechanisms,[10] and in this way deduce the local fields which act on the implanted nuclei.

Finally, the techniques described here should make possible magnetic-moment measurements on β-active nuclei. Magnetic moment experiments on N^{12} and B^{12} immediately come to mind, but the technique is potentially of value for any reasonably short-lived isotope which β decays by a Gamow-Teller transition.

ACKNOWLEDGMENTS

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