EVIDENCE FOR TRANSIENT HYPERFINE FIELDS ON FAST IONS IN FERROMAGNETIC MEDIA*

R. R. Borchers,† B. Herskind,‡ and J. D. Bronson§
University of Wisconsin, Madison, Wisconsin

and

L. Grodzins, R. Kalish, and D. E. Murnick‖
Laboratory for Nuclear Science, Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
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Anomalous precessions have been observed in the perturbed angular correlations of gamma rays following the Coulomb excitation and consequent implantation of the recoil ions into polarized ferromagnetic host materials. The anomalous effects are clearly evident in the systematics of the results of a large number of Larmor precession experiments identical to those described by Borchers *et al.*[1] The nuclear g factors as derived from the data, *assuming static hyperfine-field values*,[2] are consistently in disagreement with radioactivity experiments and theoretical expectations. The assumption of a static magnetic field is shown to be incorrect. The anomalous results can be explained by postulating that a positive transient magnetic field of several megagauss acts for a few picoseconds on the recoil nuclei. The origin of this field has been studied in a series of measurements in which the kinetic energy of the recoil ion is changed by a copper moderator before entering the ferromagnetic backing.

Measurements have been made on even isotopes of Cd, Ru, Pd, and Mo, in addition to those reported on Te,[1] Pt,[3] Hg,[4] and Se.[5] In each case the first 2^+ level was Coulomb excited by ~35-MeV O^{16} ions from the University of Wisconsin tandem accelerator, and the decay γ rays were detected in coincidence with the backscattered oxygen ions. The recoil energy of the excited nuclei (up to 15 MeV) and the target thickness (a few hundred $\mu\mathrm{g/cm}^2$) were such that the recoils were driven through 1 to 2 $\mathrm{mg/cm}^2$ of the chosen backing material. The calculated stopping time for the recoil atoms is $\lesssim 1$ psec. A detailed description and explanation of the experimental geometry and the technique, called IMPACT, can be found elsewhere.[6-9]

Host materials of Fe, Ni, Co, Gd, and Cu were used. No perturbations were observed on implantation into a copper matrix; the measured angular-correlation parameters were in excellent agreement with theoretical calculations. Moreover, no precession of the correlation has ever been observed ($\Delta\theta < 0.002$ rad) using a Cu host, when the aligning field (1-2 kG) was reversed. Thus systematic errors appear to be negligible.[1,6]

The precession angles reported[1] for the 2^+ states of even Te nuclei implanted into iron were considerably *higher* than expected. It was pointed out in that Letter that all phenomena usually considered such as radiation damage, de-excitation in flight, high local temperatures, etc., would *decrease* the precession angles, and that the observed large precession angles might imply the existence of a transient positive field acting on the implanted nuclei. The results below confirm that conjecture and show that the existence of a positive transient field is a general phenomenon occurring on implanted nuclei. More complete reports on these IMPACT experiments are being published.[8,9] The present Letter summarizes those results of particular relevance to the transient-field phenomena, and includes more recent experimental data.

The IMPACT values of $\omega\tau = -g\mu_N(H_{\mathrm{eff}}/\hbar)\tau$ for isotopes of Mo, Ru, Pd, Cd, and Te are presented as a function of nuclear mean life τ, in Fig. 1. Three features of the data indicate the nature of the anomalies. (1) The radioactivity results for $\omega\tau$ (only a few are shown) are *always* more positive than the values from IMPACT. (2) The precession angles for Cd, Mo, Pd^{100}, and Ru^{98} give negative $\omega\tau$ values, whereas one expects positive values on the basis that the static hyperfine fields are negative and the g factors are expected to be positive. (3) For any reasonable assumption about g factors and static hyperfine fields, the precession should approach zero as the lifetime gets smaller, which is not the case for the present data.

These results are consistent with a time-dependent positive field H_1, which approaches the static hyperfine values H_0 with a time con-

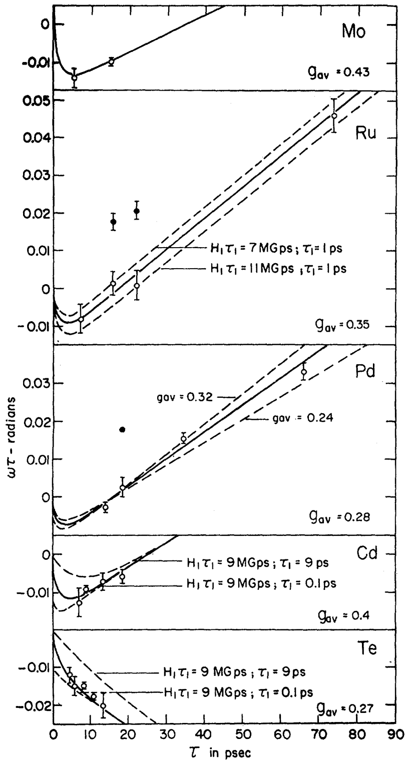

FIG. 1. IMPACT values of $\omega\tau$ as a function of τ for the even isotopes of Mo, Ru, Pd, Cd, and Te. The solid lines represent the $\omega\tau$ values calculated from Eq. (3) with $H_1\tau_1 = 9$ MG psec, $\tau_1 = 1$ psec, and the indicated average g factor for all isotopes of every element. The effect of varying the parameters (one at a time) is also shown: The dashed lines for Ru were calculated with $H_1\tau_1 = 7$ and 11 MG psec. The dashed lines for Pd were calculated with $g_{\text{av}} = 0.24$ and 0.32, and the dashed and dotted lines for Cd and Te were calculated with $\tau_1 = 9$ and 0.1 psec, respectively.

stant τ_1. For a time-dependent Larmor frequency, the time-integrated perturbed angular correlation becomes

$$W(\theta, H, t\to\infty) = \frac{1}{\tau}\int_0^\infty e^{-t/\tau} \times W(\theta - \int_0^t \omega(t')dt')dt. \quad (1)$$

The different nuclear lifetimes in the integral act as pseudotime differential probes of the hyperfine field. A reasonable form for H_1, which itself can be a mean over a distribution, is

$$H_1(t) = (H_1 - H_0)e^{-t/\tau_1} + H_0, \quad (2)$$

from which one obtains for the observed precession angle, assuming $\omega\tau \ll 1$,

$$(\omega\tau)_{\text{IMPACT}} = (\omega_1 - \omega_0)\tau\tau_1/(\tau + \tau_1) + \omega_0\tau, \quad (3)$$

where $(\omega\tau)_{\text{IMPACT}}$ is the effective turn angle obtained in these experiments, $\omega_1 = -g\mu_N H_1/\hbar$, and $\omega_0 = -g\mu_N H_0/\hbar$.

If $\tau_1 \ll \tau$, then the transient field causes an impulse precession of the angular correlation which is proportional to $H_1\tau_1$; the data in that case are sensitive only to that product. The shortest lived states do, however, place an upper limit on τ_1, hence a lower limit on H_1.

Assuming $H_1\tau_1 = 9$ MG psec and $\tau_1 = 1$ psec for all elements studied, and constant g factors for all the isotopes of a given element, one obtains the fit shown as solid lines in Fig. 1. The best values for g for each element are given in the figure. In order to illustrate the sensitivity of the fit to the adjustable parameters, dashed lines in Fig. 1 are drawn for different values of g, $H_1\tau_1$, and τ_1. .

The observed anomalies appear to be causally related to the recoil process. To pinpoint the origin of the anomaly, the implantation energy of the Cd recoils into iron was varied by means of a copper moderator as the center of a three-layer target. These experiments were designed to test the possibility that the transient positive field arises from the net pickup of polarized electrons from the iron as the recoil ion neutralizes. A transient field due to such a mechanism would disappear if the recoil was neutral on entering the ferromagnetic backing. The cadmium isotopes are especially interesting, because the IMPACT results give a negative value of $\omega\tau$ for all isotopes. Radioactivity measurements on Cd^{110} and Cd^{114} give a positive value,[10] indicating that the g factor is, as expected, positive. Figure 2 shows results of runs taken with Cd^{112}, Cd^{114}, and Cd^{116} as a function of moderator thickness. In all cases, the negative value for $\omega\tau$ persisted until a moderator-target thickness of approximately 0.6 mg/cm^2 was reached, at which point $\omega\tau$ became positive. As the copper thickness was increased further, $\omega\tau$ reached a maximum positive value before decreasing back to zero at about 1.0 mg/cm^2, as a result of recoils stopping in Cu.[11] In these experiments, the initial recoil energy of the cadmium nuclei was between 12 and 14 MeV, depending upon where in the approximately 200-μg/cm^2 cadmium target they originated. A copper thickness along the beam axis of 1 mg/cm^2 is expected to decrease the recoil energy by 9-12 MeV,[8,12] the spread arising from the substantial straggling and angular dispersion of the recoil particles.[13] The general features of the curves of Fig. 2, which

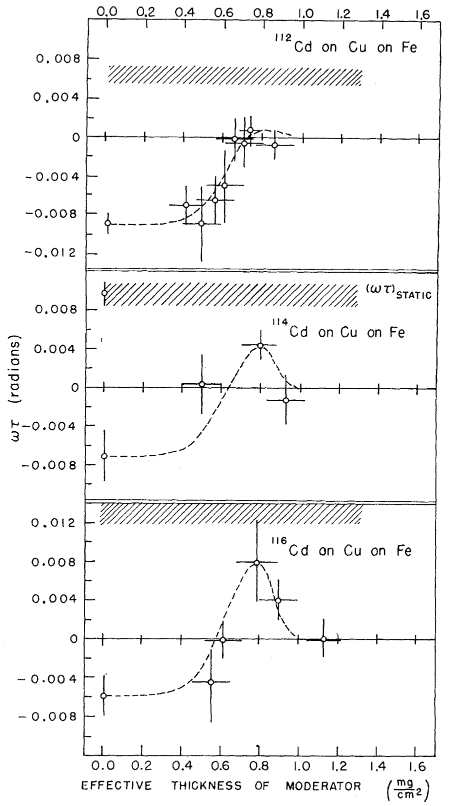

FIG. 2. The variation of $\omega\tau$ as a function of copper moderator thickness in the three-layer-target experiments. The hatched areas indicate the static $\omega\tau$ values. The $\omega\tau$ values for Cd^{112} and Cd^{116} were calculated from the measured value for Cd^{114} (Ref. 10) under the assumption that the g factor is the same for the various Cd isotopes.

are drawn through the points, are what one might expect if the transient polarization originates in a fairly narrow energy range, while the cadmium recoils are still ionized.

Anomalies observed in IMPACT experiments by Ben Zvi et al.[14] were explained by a conical-field model. Such a conical-field model can explain neither the present Te data nor the reversed-field data. Indeed, the invocation of such a model makes the discrepancies worse.

The information so far determined about the transient field is consistent with a model based on the pickup of polarized electrons from the d bands of the polarized iron, nickel, and cobalt hosts:

(1) The transient field is always positive. The spin of a polarized electron in an iron lattice is opposite in direction to the external magnetizing field and those electrons are probably most often picked up without spin flip. Further, it seems reasonable to expect that the large anomalous fields arise from the Fermi contact interaction of s electrons. The field at the nucleus due to s electrons is opposite to the spin direction; hence H is in the direction of the applied aligning field, i.e., positive.

(2) It decays in <5 psec. The relaxation time for a polarized electron on an impurity atom in iron is unknown; but one would expect from a simple uncertainty principle argument that, under the influence of the average saturation field in iron of 20 kG, it would be of the order of 5 psec or less.

(3) The internal field due to a single polarized s electron has a magnitude of order H_1,[15] assuming that τ_1 is 1-2 psec.

(4) The transient field is roughly proportional to the concentration of polarized electrons in the conduction band of the host. This is deduced from the ratio of $\omega\tau$ values on implantation into iron, cobalt, and nickel.[16] The experimental data in Co and Ni have large uncertainties; so the exact proportionality is not determined.

(5) There is as yet no evidence that a transient field exists, either when Gd is a host or when a rare-earth ion is implanted in iron.[16] What data do exist point to the absence of such effects, a not-unreasonable result on the basis of the above model, since the hyperfine fields in these cases are mainly orbital in origin, and the polarized f shell of the rare earth is far better shielded than the polarized d band of iron.

In conclusion, IMPACT experiments have clearly indicated the existence of a transient hyperfine magnetic field acting on fast ions in ferromagnetic media. The assumption that the g factors of the various isotopes of each element are constant to first order seems to be justified.

One can obtain g factors of states having $\tau \gg \tau_1$ with considerable reliability by correcting the experimental $\omega\tau$ values for the transient-field impulse.

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†Alfred P. Sloan Research Fellow.

‡Permanent address: The Niels Bohr Institute, Co-

penhagen, Denmark.

§Present address: Texas A & M University, College Station, Tex.

‖Present address: Bell Telephone Laboratories, Inc., Murray Hill, N. J.

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COLLISIONAL DAMPING OF A PLASMA ECHO

C. H. Su
Division of Applied Mathematics, Brown University, Providence, Rhode Island

and

C. Oberman
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey

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It is shown that the collisional damping on the free streaming motion of plasma can be very important in certain circumstances even though the collisional frequency is small compared with the plasma frequency. Both spatial and temporal echoes are treated in this note. In the latter case, for example, we found that the collisional damping goes as exp[$-\beta\omega_p^2t^3$] (where β is the collisional frequency).

Recently Gould, O'Neil, and Malmberg[1] demonstrated the possibility of generating a plasma echo by applying two pulses of longitudinal waves to a plasma. The theory is based on Vlasov's equation. It is found that the plasma echo was produced by the reconstruction of the phases of the two free-streaming motions of particles due to the applied pulses. In this paper we consider the collisional effect on the motion of particles. It is shown that for small collisional frequencies, even though the collisional effect on the collective motion of particles (plasma oscillations) can generally be neglected, the collisional damping of the free-streaming motion can be quite important in certain circumstances so as to make it impossible for the generation of plasma echoes to occur.

We shall use the simple Brownian motion[2] for the description of collisions between elec-