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Transient Fields in Ferromagnetic Iron and Gadolinium

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Experiments studying the velocity dependence of the transient field for ^{196}Pt in Fe and the transient field for ^{194,196,198}Pt in Gd have been carried out in order to make comparisons with the recent Lindhard-Winther theory. Agreement between theory and experiment is good concerning the shape of the velocity dependence, but the experimental value is a factor of 2 larger than theoretically predicted. A large precession due to the transient field ($\phi = -51 \pm 7$ mrad) has been found for Pt in Gd. A transient field precession for Pd and Cd in Gd has been computed on the basis of recent radioactivity results. The internal field for Pt in Gd has been measured to be -780 ± 120 kG, while former internal field values for Mo, Ru, and Hf in Gd have been corrected for transient field effects.

I. INTRODUCTION

Recent angular precession measurements[1,2] of nuclei implanted into polarized ferromagnetic backings using the ion-implantation perturbed-angular-correlation technique (IMPAC) have shown the existence of a large positive magnetic field. This field is several megagauss in magnitude, parallel to the external field, and acts for a time shorter than 1 psec. The origin of this so-called transient field is now believed to be due to the scattering of polarized electrons by the recoiling ion.

Lindhard and Winther,[3] using the idea of electron scattering, have formulated a transient field theory in which they predict the magnitude and velocity dependence of the transient field acting on different nuclei recoiling through different ferromagnetic backings. The basic parameters of the Lindhard-Winther theory which can be tested experimentally are the transient field's dependence upon the recoiling ion's velocity and the dependence upon polarized electron density in the ferromagnetic backing. The former was tested by measuring the angular precession of ^{196}Pt implanted into Fe at different velocities, while the latter was tested by measuring the angular precession of ^{194,196,198}Pt implanted into Gd.

II. EXPERIMENTAL TECHNIQUE AND RESULTS

IMPAC has been described in detail in previous publications.[1,4] In the present experiment, heavy-ion beams of oxygen and sulfur ions are used to Coulomb excite and concurrently implant platinum nuclei into a ferromagnetic backing.

Upon entering the ferromagnetic backing, the recoiling nuclei experience a large aligned time-dependent magnetic field $H(t)$. The excited nuclei then precess with the Larmor frequency $\omega(t) = -g\mu_N H(t)/\hbar$, where g is the nuclear g factor and μ_N is the nuclear magneton. After the nuclei become stationary in the lattice, $H(t)$ becomes constant in time. The only time dependence comes from the transient field which is assumed to be zero after the ion stops. Integrating $\omega(t)$ over the lifetime τ of the excited state and assuming that no excited nuclei decay in flight, one obtains the integral precession

$$\omega\tau = \phi + \omega_0\tau, \quad (1)$$

where ω_0 is the Larmor frequency due to the static internal field (field seen once the impurity nucleus comes to rest), while ϕ is the transient field precession.

The extraction of ϕ can be accomplished in two ways[4]: (a) Extrapolating the angular precessions measured for even-even members of nuclei with the same Z to $\tau = 0$ (see Fig. 3), (b) measuring $\omega_0\tau$ directly in an experiment using a radioactive source. Here a radioactive mother isotope is diffused or implanted into the ferromagnetic host. The precession of the subsequent correlation is then measured, i.e., $\omega_0\tau$. This explicitly assumes that there is no transient field involved. The validity of this assumption is based on the fact that recoil energies involved in radioactivity decay are only of the order of a few eV compared to several MeV for IMPAC. The difference between the IMPAC and radioactivity measurements then yields ϕ, when the former has been corrected for beam-bending effects.

Beam bending is the bending of the incident beam by the fringing field of the polarizing magnet. The incident beam defines the z axis; therefore, any such bending will show up as a precession of the correlation. This precession is positive and has a magnitude dependent upon (a) ion mass and energy, (b) charge state of the incident and backscattered ions, and (c) fringing field geometry.

Beam bending can be calculated if the fringing field is known or can be measured directly. We measured beam bending directly by measuring the angular precession for the first excited state of ^{150}Sm implanted into a solid ^{150}Sm target of 4 mg/cm^2 thickness.

For 42 MeV 6+ oxygen ions, the beam-bending precession was $\omega\tau = -4.0 \pm 1.5$ mrad. This is comparable to the -4.5 mrad theoretically predicted on the basis of the known field geometry. In all cases, it is an easy matter to convert the above number to different beam energies and beam types. All measurements discussed in this text have been corrected for beam bending.

A. Implantation into Fe Backings

The velocity dependence of the transient field was studied by measuring the angular precession as a function of recoil energy for ^{196}Pt implanted into Fe.[5] The choice of ^{196}Pt was based on the facts that (a) its previously measured transient field was the largest ever measured,[6] (b) its excitation cross section is large, and (c) its heavy mass provides for easy particle discrimination.

The recoil energy for ^{196}Pt was varied by bombarding a 300-μg/cm^2 ^{196}Pt on Fe target with oxygen ions of 26 and 36 MeV and sulfur ions of 56 and 59 MeV. The beam was produced by the Niels Bohr Institute tandem accelerator and imparted recoil energies from 7 to 29 MeV.

Figure 1 shows the measured IMPAC precession ($\omega\tau$) together with the average of two radioactivity results[7,8] plotted versus average initial recoil energy. The filled circle in Fig. 1 is taken from Ref. 6.

The Lindhard-Winther theory is briefly discussed in the Appendix. Calculations based upon Eq. (A3) of the Appendix, using a g factor of 0.31, are shown in Fig. 1. The theoretical curve is normalized to the radioactivity value, i.e., zero recoil energy. It must be pointed out that the significant deviation between theory and experiment might be partially explained by an incorrect g factor and the error in the measured value of $\omega_0\tau$. However, these arguments are insufficient to obtain good agreement between theory and experiment. By changing the theoretical value $C_r \times C_a$ [see Eq. (A2)] by a factor of 2, a much better fit is obtained, indicating that the velocity dependence predicted by the Lindhard-Winther theory is correct.

The Lindhard-Winther prediction for the transient field precession as a function of the impurity ion's atomic number is calculated and shown in Fig. 2(a) for 33 MeV oxygen ions as projectiles. The experimental points are mostly taken from the work of the Wisconsin-MIT group combined with numerous radioactivity results.

In the cases where more than one radioactivity value exists for a given isotope, the average value was taken if the radioactivity values had overlapping errors. References for the radioactivity values

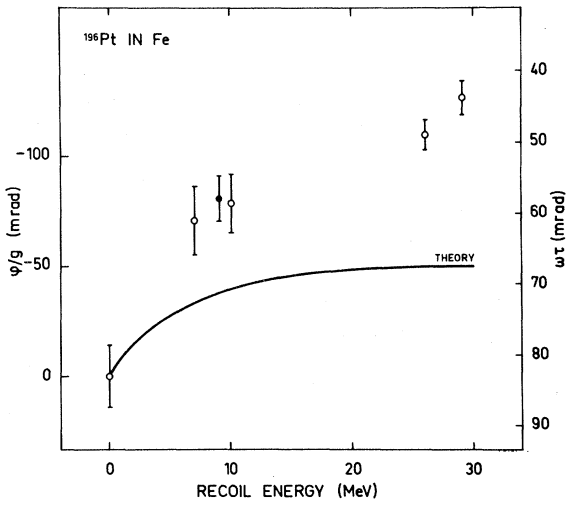

FIG. 1. Transient field precession ϕ/g measured for ^{196}Pt recoiling in polarized Fe backings as function of initial recoil energy. The solid line shows numerical calculations based on the Lindhard-Winther theory (see Appendix).

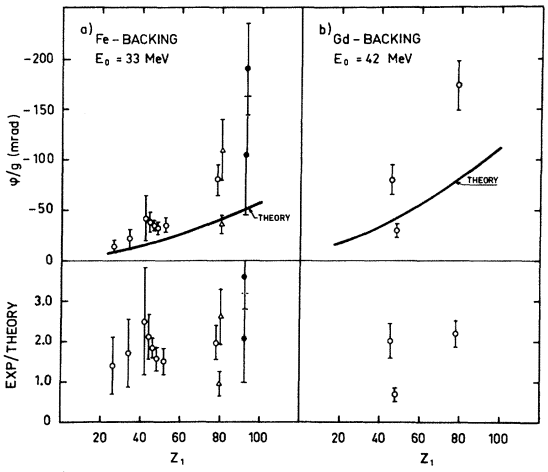

FIG. 2. Lindhard-Winther predictions for the transient field precessions as a function of Z_1 (solute atomic number) are shown as solid lines. The experimental points are discussed in the text. Part (a) represents impurities slowing down in Fe, while (b) represents impurities slowing down in Gd. For Fe a ζ value of 2.2 was used while for Gd a value of 7.2 was used. Also shown are the ratios of the experimental to theoretical transient field values for Fe and Gd. All points are normalized to 33-MeV incident oxygen ions.

can be found in Ref. 4. In the case of Hg, the two existing radioactivity measurements[8,9] differed by a factor of 3, which was far outside the error limits. Consequently, the transient precession obtained from each value has been plotted separately.

The g factor has been divided out so as to make possible a direct comparison between experiment and theory. The errors shown are absolute errors including the uncertainties in g, $\omega\tau$, and $\omega_0\tau$.

The points at $Z = 92$ are extracted from the most recent measurements. The static precession for the first 2+ state of ^{234}U in Fe was measured using a radioactive source.[10] Assuming only that the g factor for the ground-state bands of ^{234}U and ^{238}U are equal, the static precession for the 4+ rotational state of ^{238}U can be calculated ($\omega_0\tau = 170 \pm 18$ mrad). Combining this result with the IMPAC measurement of Münchow *et al.*[11] ($\omega\tau = 126 \pm 21$ mrad), one obtains the lower of the filled circles (using $g = 0.3$) in Fig. 2(a). Kaufmann *et al.*[12] have measured $\omega\tau$ for both the 4+ and 6+ states of ^{238}U, using 80 MeV sulphur ions. Combining their values with the static measurement, one obtains inconsistent transient precessions of $\phi_{4+} = -100 \pm 19$ and of $\phi_{6+} = -57 \pm 15$ mrad. The latter of these (which is consistent with Münchow *et al.*) has been divided by $g = 0.3$, and is shown as the upper of the filled circles in Fig. 2(a). Also plotted in Fig. 2(a) are the ratios between the experimental and theoretical transient field values. As can be seen, many of the experimental values are nearly a factor of 2 larger than the theoretical values.

B. Implantation into Gd Backings

According to the simple picture of electron scattering, the transient field should be proportional to the density of polarized electrons, all other quantities being equal. For the cases of Fe, Co, and Ni, one expects the transient precessions to be in the ratio of 0.76 : 0.25, respectively. Experimentally, the ratios have been found[13] to be 1 : (0.79 ± 0.16) : (0.54 ± 0.14) for Ge, and 1 : (0.62 ± 0.51) : (0.17 ± 0.34) for Se, which are in reasonable agreement with the theoretical values.

Early IMPAC studies have shown little, if any, transient field for the case of ferromagnetic Gd. This is inconsistent with the Lindhard-Winther theory, which predicts that the transient field for Gd should be nearly a factor of 2 larger than that of Fe.

Platinum, having a large transient field in Fe, is a good probe for studying the transient effects in Gd. Platinum has the advantage of being heavier than Gd, allowing for clean particle discrimination.

Gd unlike Fe, Co, and Ni has a Curie temperature below room temperature ($T_c = 283\,^\circ$K). Consequently, all Gd targets must be cooled.

Separated isotopes of ^{194}Pt, ^{196}Pt, and ^{198}Pt were sputtered[14] onto a Gd-In-Cu sandwich backing. The purpose of the thin indium contact was to assure good thermal conductance between the Gd foil and the Cu foil, which was soldered to a cold finger cooled by liquid nitrogen.

To check the saturation properties of Gd, the experiment was carried out at different temperatures and external field values with the conclusion that, at liquid-nitrogen temperatures and with an external field of 3 kG, our Gd foils were saturated. As an added precaution, low beam currents ($\leq$ 15 nA) were used to minimize beam-heating effects.

The experimental angular precessions for ^{194}Pt, ^{196}Pt, and ^{198}Pt are shown in Fig. 3 plotted versus the mean lifetime of their 2+ states.[15] Each of the isotopes has been precessed in Fe,[16] and these have been found to have nearly the same 2+ g factors. Consequently, a straight line, Eq. (1), was fitted through the points with $\tau = 0$ intercept being taken as the transient precession $\phi = -51 \pm 7$ mrad.

Using radioactive sources, the Uppsala group has recently measured the internal fields for ^{106}Pd in Gd and ^{111}Cd in Gd to be -62 ± 9 kG[17] and -310 ± 10 kG,[18] respectively. Further evidence for the transient field in Gd can be obtained by combining these results with the earlier reported IMPAC precession for ^{108}Pd[19] and ^{114}Cd[20] in Gd. The resulting transient field precessions are -25 ± 5 and -13 ± 3 mrad for Pd and Cd, respectively.

These results, together with the Pt in Gd results, are shown in Fig. 2(b). A g factor of 0.35 for Cd

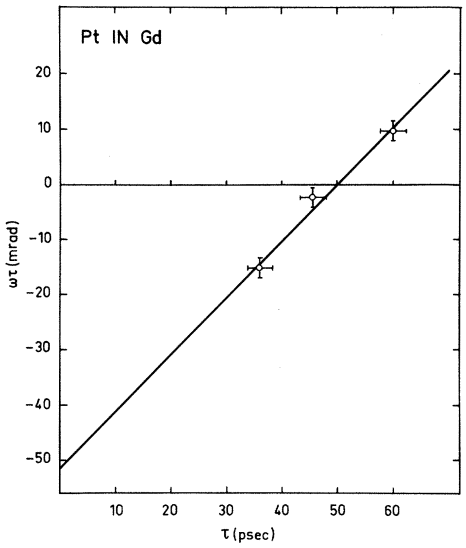

FIG. 3. IMPAC values $\omega\tau$ for polarized Gd backings as function of nuclear lifetime τ for the first excited 2^+ states of ^{194}Pt, ^{196}Pt, and ^{198}Pt. The line is a least-squares fit through the points. The intercept at $\tau = 0$ gives the precession due to transient effects and the slope of the line gives $\omega_0 = -\langle g \rangle H_0 \mu_N / \hbar$.

and Pd and one of 0.29 for Pt have been divided out so as to make possible a direct comparison between theory and experiment. Also plotted in Fig. 2(b) is the ratio between experimental and theoretical transient field values. The transient field for Pd and Pt in Gd appears to be nearly a factor of 2 larger than that of Fe, which is what is expected theoretically. The Cd point appears low, which may be due to incomplete saturation or beam heating in the IMPAC experiment.

C. Internal Fields in Gd

From the slope of the line in Fig. 3, one can extract directly the internal field for Pt in Gd to be $H_0 = -780 \pm 120$ kG.

Earlier reported internal fields for impurities in Gd using IMPAC have been deduced assuming no transient field effects. As has been shown above, these values must be corrected for transient field effects.

Since the transient field is expected to vary smoothly with Z, it is valid to estimate transient field corrections near Pd and Pt.

This means that the internal fields for Mo, [19] Ru, [19] and Hf[21] can be corrected. The corrected internal fields for Mo, Ru, and Hf are -480 ± 240, $+270 \pm 90$, and -620 ± 80 kG, respectively, as compared to the old values $+330 \pm 100$, $+330 \pm 70$, and -305 ± 30 kG. The errors shown include a 20% uncertainty in the estimate of the transient field correction. However, it must be pointed out that systematic errors due to beam heating and the consequent nonsaturation effects can be present since no special precautions have been taken to eliminate these.

III. Conclusions

The velocity dependence of the transient field is well explained by the Lindhard-Winther theory as is the functional dependence of the transient field upon the solute atomic number Z. However, in both cases, there is nearly a factor of 2 discrepancy between the magnitudes of the experimental and theoretical transient fields. This discrepancy is most probably due to an incorrect estimate of the C factors.

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APPENDIX: SUMMARY OF LINDHARD-WINTHER THEORY

The recent theoretical study of the transient field by Lindhard and Winther has resulted in a general formula containing the functional dependence on recoil energy, recoil atomic number, and host atomic number.

Theoretically, one may picture the slowing down of a moving ion as an electron scattering process which, in the case of an ion moving through a ferromagnetic media, is tantamount to scattering in a polarized electron gas. This scattering process amplifies the elctron density and hence magnetic moment density at the nucleus of the recoiling ion. This enhanced density, via the Fermi contact interaction, produces a magnetic field

$$B(v) = \frac{16\pi^2}{3} \mu_B \zeta N C_r C_a Z_1 \times \begin{cases} v_p/v, & v > v_p \\ 1, & v < v_p \end{cases} , \quad \text{(A1)}$$

where $\mu_B = e\hbar/2m_0c$ is the Bohr magneton, ζ is the number of polarized electrons per atom, N is the number of atoms per cm^3, v_p is the velocity of the polarized electron which in this case is set equal to the Bohr velocity, while Z_1 and v are the atomic number and recoil velocity of the recoil ion, respectively. C_r is a correction factor due to finite nuclear size, relativistic effects close to the nucleus, while C_a is a correction factor due to atomic binding. The best estimates of C_r given by Lindhard and Winther are

$$C_r \simeq 1 + \left(\frac{Z_1}{84}\right)^{5/2} . \quad \text{(A2)}$$

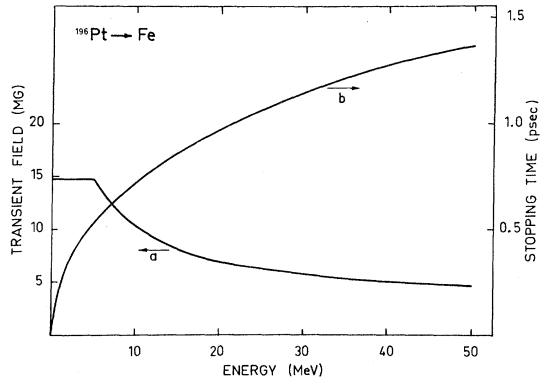

FIG. 4. (a) Transient field acting on a ^{196}Pt nucleus moving in polarized Fe as function of recoil energy. (b) Slowing down time as function of energy for a ^{196}Pt ion moving in Fe.

C_a is set equal to unity and consequently disregarded.

Assuming a continuous slowing down of the recoils, the transient precession for an ion with initial velocity v_1 is given by

$$\phi(v_1) = -\frac{g\mu_n}{\hbar} M_1 \int_0^{v_1} \frac{B(v)dv}{NS(v)} , \qquad \text{(A3)}$$

where g is the nuclear g factor, M_1 is the mass of the recoiling ion, and $S(v)$ the stopping cross section per atom.

Numerical calculations of Eq. (A3) have been carried out and are shown in Figs. 1 and 2.

A plot of the transient magnetic field versus recoil energy is shown in Fig. 4 for Pt in Fe. Also shown is the stopping time versus energy calculated on the basis of the Lindhard stopping formalism. As can be seen, most of the recoil's slowing down time is spent near low velocities where the transient field is largest. Consequently, most of the transient precession occurs near the end of the recoil ion's path.

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