Nuclear magnetic moments of very short-lived states via the transient-field implantation perturbed-angular-correlation technique

G. K. Hubler* and H. W. Kugel
Rutgers University,† New Brunswick, New Jersey 08903

D. E. Murnick‡
Bell Laboratories, Murray Hill, New Jersey 07974

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The Lindhard and Winther equations for the transient magnetic field effect have been numerically integrated with the inclusion of a decays-in-flight correction and using the best available stopping power formulas. The calculations are carried out for an iron host and curves are generated from which the transient-field angular shift may be predicted for any $Z > 12$ to an accuracy of $\sim 20\%$. The transient-field calculations are employed in the analysis of angular shift data for the first 2^+ states of ^{104}Pd, ^{106}Pd, ^{108}Pd, and ^{110}Pd isotopes implanted into an $Fe_{0.8}$-$Co_{0.2}$ alloy and for ^{54}Fe and ^{56}Fe implanted into iron. The g factors of the six isotopes are obtained and the hyperfine field of Pd in the alloy is determined. Evidence is presented which suggests that the hyperfine fields measured in oxygen beam implantation perturbed-angular-correlation experiments for Ru, Pd, Cd, and Te in Fe are consistently reduced from the hyperfine fields measured by other methods. In light of these results and the decays-in-flight corrections to the transient-field theory, angular shift data of previous workers on even-even isotopes of Ge, Ru, Pd, Cd, and Te have been reanalyzed. With the exception of ^{70}Ge, all the g factors are in agreement with a collective model.

[NUCLEAR REACTIONS ce, transient-field IMPAC technique. Measured $\gamma(\theta)$, deduced hyperfine fields, $g(2^+)$ for ^{104,106,108,110}Pd in $Fe_{0.8}$-$Co_{0.2}$, for ^{54,56}Fe in Fe. Reanalysis of previous $g(2^+)$ for ^{70,72,74,76}Ge, ^{98,100,102,104}Ru, ^{104,106,108,110}Pd, ^{110,112,114,116}Cd, ^{120,122,124,126,128,130}Te.]

I. INTRODUCTION

Numerous nuclear g-factor measurements have been performed with the implantation perturbed-angular-correlation technique (IMPAC).[1-3] In this method, excited levels are populated by means of heavy-ion Coulomb excitation and the subsequent recoil motion of the nucleus is utilized for implantation into a ferromagnetic material. The spin precession of the excited nucleus in the large internal hyperfine fields is measured as a perturbation of the angular correlation between the decay γ ray from the excited state and backscattered particles. In addition, as the excited nuclei slow down they experience transient magnetic fields due to Coulomb scattering with polarized electrons in the host. For excited-state lifetimes less than a few psec, the spin precession of the nucleus in the transient field may be greater than the spin precession from the internal field. In this case the excited-state g factor may be obtained directly from the transient-field angular shift provided a reliable estimate of the reduced transient-field shift φ/g exists.

This paper reports on the results of calculations of the angular shifts experienced by very short-lived excited nuclei as they slow down in magnetized iron and new experimental results for ^{104}Pd-^{110}Pd and ^{54}Fe. The calculations are carried out in the framework of the Lindhard and Winther[4] model with the inclusion of decays-in-flight corrections. Section II outlines the calculation of the transient-field angular shift as set forth in Ref. 4 and compares the calculated angular shifts with experimental data. In Sec. III the transient-field theory is applied to some measurements on the first 2^+ states of even-even Pd and Fe isotopes. Included in Sec. III is a reanalysis of IMPAC g-factor data of other workers in the light of decays-in-flight corrections and evidence for reduced hyperfine fields upon implantation. Section IV is a discussion of results and a comparison of the various techniques for obtaining g factors of very short-lived states.

II. TRANSIENT FIELD

A. Lindhard and Winther model

The average magnetic field in iron may be written:

$$B = (8\pi/3)\mu_B N\delta\,, \tag{1}$$

where μ_B is the Bohr magneton, N is the atom density, and δ is the number of polarized electrons per atom. This field is about 20 kG in saturated iron and is much too small to significantly precess an excited nucleus in 10^{-12} sec.

A large transient magnetic field arises from a polarized electron density enhancement at the moving ion nucleus due to the Coulomb scattering of *oppositely* charged particles. The scattered polarized electrons give rise to a magnetization density proportional to the polarized electron probability density, resulting in a magnetic field at the scattering center via the Fermi contact interaction. The density enhancement factor χ is calculated by considering the electron being scattered by an unscreened Coulomb potential with the result:

$$\chi = \frac{2\pi Z_1 V_0}{V_r}, \tag{2}$$

where V_0 is the Bohr velocity $(e^2/\hbar)$, V_r is the relative velocity between the ion and the electron, and Z_1 is the atomic number of the ion. Equation (2) is an approximation valid under the condition $Z_1 V_0 / V_r \geq \frac{1}{2}$. The factor χ is on the order of 300 for Fe in Fe yielding a magnetic field on the order of 6 MG. The relative velocity of interest is between the moving ion and the polarized electrons in Fe. If $\vec{V}_i$ is the velocity of a polarized electron and $\vec{V}$ the ion velocity, then $V_r = |\vec{V} - \vec{V}_i|$. Averaging over the randomly oriented vector $\vec{V}_i$ yields

$$\begin{aligned} \overline{V}_r &\cong V \quad \text{for } V > V_i, \\ \overline{V} &\cong V_i \quad \text{for } V < V_i. \end{aligned} \tag{3}$$

The polarized electrons are further defined to have an effective velocity $V_p \cong \langle V_i \rangle$, which should be a good approximation since most of the magnetization in iron is carried by the $3d$ electrons. From Eqs. (2) and (3) and the effective polarized electron velocity approximation, the enhancement factor becomes:

$$\chi = 2\pi Z_1 \frac{V_0}{V_p} f(V), \quad f(V) = V_p/V \text{ for } V > V_p, \quad = 1 \text{ for } V < V_p. \tag{4}$$

Another contribution to the enhancement factor comes from relativistic effects when the electron is close to the nucleus. A calculation yields the approximate formula[4]

$$R \cong \left[1 + \left(\frac{Z_1}{84} \right)^{2.5} \right]. \tag{5}$$

The probability of encountering polarized electrons will decrease at very low relative velocities until the ion is unable to penetrate the electron shells of the atom. This effect is accounted for with a relative probability factor $P(E)$ of scattering with a polarized electron. $P(E)$ is 1 at high energies and goes to 0 at very low ion energies. The choice of the function $P(E)$ will be discussed in the next section.

A possible polarized electron density enhancement arising from resonance and atomic binding effects involving both the host atoms and the recoiling ion at low E_R has been discussed previously[4] and is described in terms of a parameter C, where $C = C_{\text{ATOM}} C_{\text{ION}}$. The magnitude of C is believed to be ~1.[4]

We therefore take $C = 1$. The total enhancement factor Q is

$$Q = \chi R P C \tag{6}$$

and the magnetic field at the nucleus is

$$B(V) = \frac{8\pi}{3} \mu_B N \delta Q. \tag{7}$$

The transient field is effective for the slowing down time of the ion which is approximately 1 psec for most cases of experimental interest. The nuclear moment is precessed by the average field with the Larmor precession frequency $\omega = -g(\mu_N B)/\hbar$, where μ_N is the nuclear magneton. The total angular shift φ, through which the nucleus rotates in a time t', is

$$\varphi = \int_0^{t'} \omega(t) dt. \tag{8}$$

The expression for the total transient-field angular shift φ may be derived from Eqs. (7) and (8) with the result:

$$\varphi = \frac{16}{9} \left(\frac{e^2}{\hbar c} \right)^2 \left(\frac{m}{M} \right)^{1/2} q R g \delta \left(\frac{V_0}{V_p} \right) I(V), \tag{9a}$$

$$q = \left(\frac{Z_1 Z (A_1 + A_2)^3}{Z_2 A_1 A_2} \right)^{1/2}, \quad Z = (Z_1^{2/3} + Z_2^{2/3})^{3/2}, \tag{9b}$$

$$I(V) = \int_\epsilon^0 \frac{d(\epsilon^{1/2}) f(\epsilon^{1/2}) P(\epsilon)}{d\epsilon / d\rho}. \tag{9c}$$

The subscripts 1 and 2 refer to the ion and host, respectively. In Eq. (9a), $e^2/\hbar c$ is the fine-structure constant, m is the electron mass, and M is the nuclear mass. In Eq. (9c), ϵ is the Lindhard, Scharff, and Schiøtt (LSS) dimensionless energy variable defined in Ref. 5 and $d\epsilon/d\rho$ arises from the transformation of Eq. (8) from a time differential to a velocity differential.

The transient-field equations (9a)–(9c) predict the observed increase in the transient field with increasing Z_1, as well as the magnitude of the effect providing that the parameter V_p is chosen properly.

B. Experimental determination of V_p in iron

The transient field was calibrated for the particular case of iron in iron by determining V_p from experimental data on the angular shift of the 10.0-psec 847-keV (2^+) state of ^{56}Fe as a function of initial recoil energy.[6] A least-squares method of analysis was used to fit these data to the parameters V_p and g using Eq. (10) for the total angular shift $\Delta\theta$:

$$\Delta\theta = -g\left((\mu_N/\hbar)B_0\tau e^{-t_s/\tau} - \frac{\varphi(V_p)}{g}\right). \qquad (10)$$

B_0 is the effective field on iron in iron at rest and $e^{-t_s/\tau}$ corrects for decays in flight, as discussed below. The data and best fit are shown in Fig. 1.

For the first 2^+ state of ^{56}Fe, the static-field term and the transient-field term are both about 8 mrad for high initial recoil energies. However, they are opposite in sign, so that the two angular shifts cancel. As the initial recoil energy decreases, the transient-field term decreases and goes to zero at zero recoil energy. Therefore, the curve in Fig. 1 increases with decreasing initial recoil energy since the static angular shift remains nearly constant.

The results of the least-squares analysis described above give a best-fit value for the parameter V_p/c of 0.28×10^{-2} and a g factor for the 847-keV (2^+) state of ^{56}Fe of +0.60(0.10). The g factor, including a 15% uncertainty in the transient-field analysis, agrees well with the average of radioactivity experiments in the literature, g = +0.57(0.12).[7,8] Also, the velocity V_p is comparable with the Fe $3d$ electron average velocity calculated from the binding energy.

C. Transient-field calculations for heavy nuclei and short lifetimes

For excited states with short lifetimes, corrections to the transient-field and static-hyperfine-field angular shifts must be made for decays in flight. The correction to the transient-field shift is accomplished by inserting the electromagnetic decay probability $e^{-t/\tau}$ into Eq. (9c). The integral $I(V)$ becomes

$$I(V) = \int_0^{\epsilon} \frac{d(\epsilon^{1/2})f(\epsilon^{1/2})P(\epsilon)e^{-t(\epsilon)/\tau}}{d\epsilon/d\rho} \qquad (11)$$

and

$$t(\epsilon) = \frac{0.00782}{s}\left(\frac{A_2(A_1+A_2)^3Z^3}{A_1Z_1Z_2}\right)^{1/2} \times \int_{\epsilon_0}^{\epsilon} d\epsilon\, \frac{1}{\epsilon^{1/2}d\epsilon/d\rho}\ (10^{-13}\ \text{sec}),$$

where s is the density of the host material. The slowing down time expression can be evaluated from LSS theory. Similarly, the effect of decays in flight on the static-field angular shift $\omega_0\tau = -g\mu_N(B_0/\hbar)\tau$ may be accounted for (when $\omega_0\tau+\varphi \ll 1$) by inserting the factor $e^{-t_s/\tau}$, where t_s is the slowing down time. Implicit in this treatment is the assumption that B_0 becomes effective for the stopped nucleus in a time much less than τ.

A computer program was written to numerically integrate Eq. (11). The LSS theory for specific energy loss $d\epsilon/d\rho$ is used. As determined from the iron in iron analysis, V_p/c is chosen as 0.0028. Also, the factor $P(E)$ is taken as unity for $E>5$ keV and 0 for $E<5$ keV. This choice for P is quite reasonable as the ion, in effect, encounters a free electron gas when its kinetic energy is much greater than electronic binding energies. In the region of a few keV of energy, however, the electron binding becomes important and the scattering probability drops to zero. In any case, the total angular shift is relatively insensitive to the actual choice of cutoff energy.

Figure 2 shows the magnitude of the calculated transient-field angular shift versus Z_1 for different excited state lifetimes. The curves are for an iron host ($Z_2=26$, $\delta=2.2$),[9] and the values of φ/g are for the recoil energy (E_r) which yields the maximum effect. Figure 2 shows that the sensitivity increases rapidly with Z_1. The maximum sensitivity calculated is for $Z_1=92$ where a 15-mrad shift is expected for a 0.1-psec mean life state with a g factor of 1.0. Figure 3 is a plot of φ/g versus E_r for $Z_1=44$ showing the dependence of the transient-field shift on the initial recoil energy for different mean lifetimes. The rapid

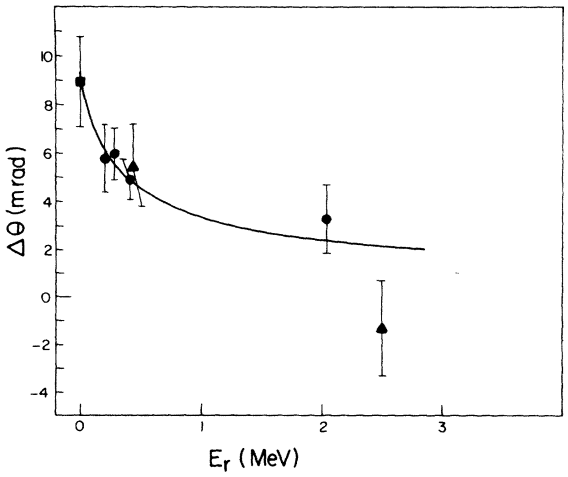

FIG. 1. Angular shifts for ^{56}Fe first 2^+ state implanted into Fe vs ^{56}Fe initial recoil energy. ■, radioactivity; ●, Heestand *et al.*; ▲, this work.

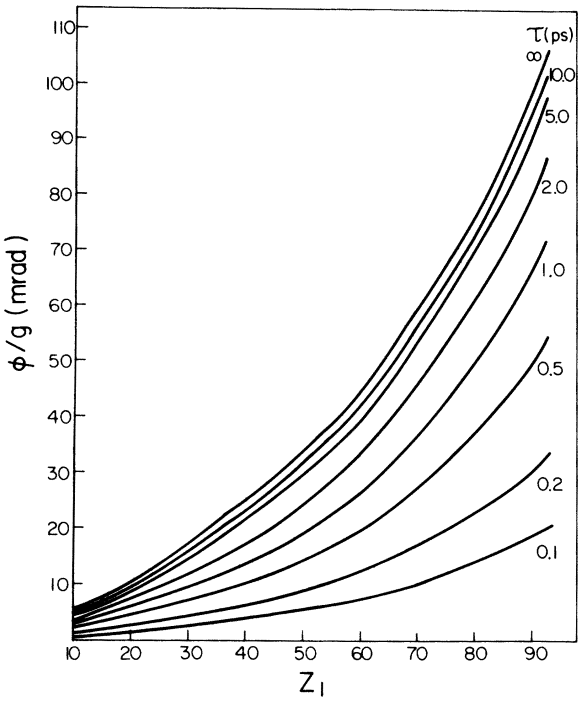

FIG. 2. Reduced transient-field angular shift vs Z_1 for several excited state lifetimes.

increase in the transient field with increasing initial recoil energy is the result of the transient field being largest at low energies, hence, a large fraction of the total effect is picked up at quite small initial recoil energies. The decrease in the transient field at high initial energies for mean lives of a psec or less is due to a large fraction of decays in flight before a full transient field is experienced. This effect becomes more severe, the shorter the mean life.

D. Compaison of transient-field theory with experiment

As indicated by Eq. (10), in any real experiment φ/g must be determined from a measured angular shift by first subtracting the static-field component. This is often difficult or uncertain as g factors and effective hyperfine fields are not always *a priori* known. Figure 4 is a plot of derived φ/g vs Z_1 from all available experimental transient-field data in iron. The solid line is the calculated curve from this work, which reproduces the trend and magnitude of the data very well. Three of the data points (Te, Pd, Ru) have been redetermined from the experimental angular shifts quoted by Heestand *et al.*[6, 10, 11] φ/g for Pd was extracted from the data displayed in Fig. 5. The line drawn through the points is a linear least-squares fit to Eq. (10), neglecting decays in flight, which are negligible in this case. The slope of this line is $-g(\mu_N/\hbar)B_0$ and the y intercept is φ, the transient-field shift. To obtain the reduced transient-field shift φ/g from the y intercept, one must know the average g factor of the four isotopes. As nuclear hydrodynamical models and systematics predict the g factors of the four Pd isotopes to be nearly equal, a measurement of g for one isotope should give the approximate g factor of all four of the isotopes. The g factor of the first 2^+ state of ^{106}Pd has been measured by perturbed angular correlation (PAC) to be 0.36(0.02),[12, 13] and the internal hyperfine field of Pd in iron has been measured by spin-echo nuclear magnetic resonance (NMR) as −594(12) kG[14] and by PAC as −554(38) kG[13] (both measurements are for $T = 4.2$ K). These data allow a good comparison to be made between the hyperfine magnetic field measured by the above two techniques and the IMPAC technique.

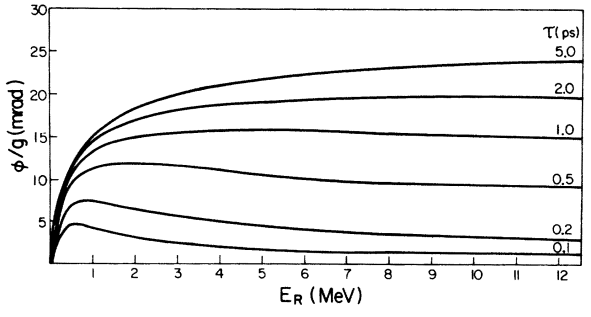

FIG. 3. Reduced transient-field angular shift vs initial recoil energy for several excited state lifetimes and a Z_1 of 44.

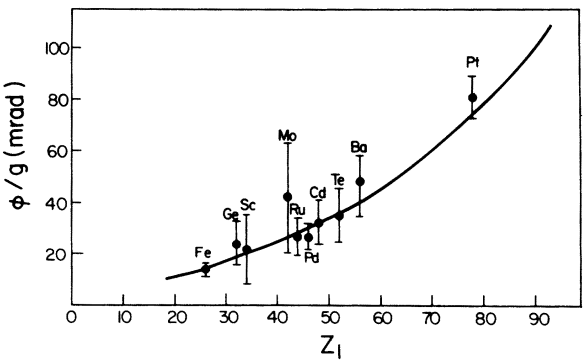

FIG. 4. Experimental and theoretical reduced transient-field angular shifts in Fe vs Z_1. ●, experiment; —, theory.

Using the slope optained from the fit in Fig. 5 and the PAC g-factor value, we obtain B_{Fe}(Pd) = −409(36) kG. An alternate method for extracting B is to take the angular shift for the ^{106}Pd point [3.8(1.2) mrad], and add to it the transient field shift (y intercept) of φ_{fit} = −9.3(1.4) mrad. The sum, 13.1(1.8) mrad, is the total rotation that would be caused by the internal magnetic field in the absence of recoil. The hyperfine field is then calculated from the first term in Eq. (10) to be B_0 = −413(68) kG.

The agreement between the hyperfine fields measured by IMPAC, and the spin-echo and PAC techniques, is poor. The g factors quoted in Ref. 11, however, were calculated assuming −594-kG hyperfine field resulting in an average g factor for the four isotopes of g = 0.25. A transient-field point for Pd was also calculated using this g factor. However, when the PAC g factor is used to calculate the transient field, one obtains φ/g = 26 in much better agreement with the transient-field theory. A similar reanalysis of the Ru and Te data (to be discussed later) also lowers the originally quoted transient-field points into agreement with the theory.

Figure 6 is a plot of the data obtained by Heestand *et al.*[10] and Kugel, Borchers, and Kalish[15] on angular shifts of ^{196}Pt in Fe as a function of initial recoil velocity. The solid line is the theoretical prediction of this work. The points obtained with an ^{16}O beam are in reasonable agreement with theory, while the points obtained with a ^{32}S beam lie above the theoretical curve. A possible explanation of the discrepancy in the ^{32}S points is that the hyperfine field is attenuated, resulting in an overestimate of the transient field. The apparent reduced internal fields as measured by IMPAC in several cases will be discussed elsewhere.[16]

Lindhard and Winther have proposed moderate oscillations in the transient-field shift as a function of Z_1 near closed chemical shells due to the appearance of bound polarized s electrons on the ion.[4] Another possible source of oscillations is the well-established oscillation in the stopping power as a function of Z_1 which increase in amplitude as the ion velocity decreases,[17] Recalling Eq. (9c) for the transient-field shift, one sees that there is a dE/dx in the denominator. Furthermore, the low-velocity region where the oscillations in dE/dx are largest is where the transient field has its maximum value. Therefore, even though the oscillations occur at very low velocities, they can lead to a relatively large effect in the transient field. Oscillations of 10% modulation have been calculated assuming the amplitude of the oscillations in Ref. 17 continue at high Z_1. The transient-field data available are not precise enough to determine if the oscillations predicted by Lindhard and Winther or the oscillations due to variations in dE/dx exist.

E. Estimates of error in transient-field calculations

The largest source of error appearing in the framework of the Lindhard and Winther model comes from uncertainties in stopping power equations. To minimize these errors, the electronic stopping power constant k_e was varied to produce agreement between the calculated range and the available data. There is very little experimental data, however, on the range of heavy ions (Z > 26) in high-Z elemental solids. Cohn *et al.*[18] have measured the range of the ^{150}Sm ions in Cu with an IMPAC experiment. It was found that an electronic stopping constant of $0.9k_e$ reproduced Cohn's results to within 5%. A stopping constant of $0.9k_e$ in this range of Z is also consistent with

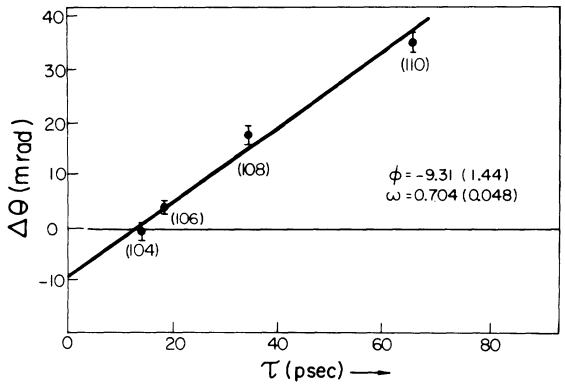

FIG. 5. Angular shifts vs mean life for Pd isotopes implanted into Fe (from Ref. 11).

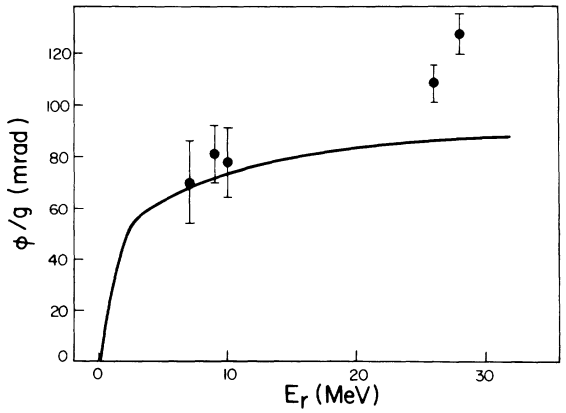

FIG. 6. Experimental and theoretical reduced transient-field angular shifts for ^{196}Pt in Fe vs initial recoil energy. ●, experiment; —, theory (from Refs. 10 and 15).

the tabulations of Northcliffe and Schilling[19] to within 7%.

The plot of φ/g vs Z_1 shows that Mo is the only case where the difference between experiment and theory is greater than 20%. The Mo point is taken from Ref. 11 where only two experimental points were used for a straight line fit to the angular shift data. The transient-field shift obtained from the y intercept of this line is not very reliable as indicated by the large error bars. Therefore, a conservative estimate of error of ~20% may be assigned to the transient-field calculations. This ~20% error seems to successfully encompass the errors in dE/dx, possible oscillations, and any inadequacies of the theory.

Below about 1 MeV of recoil energy, the error in calculated values becomes much larger, however. When fitting the ^{56}Fe data it was found that the actual saturation value of the transient-field shift was quite insensitive to large excursions in the parameter V_p. The reason for this can be seen from Figs. 7(a) and 7(b). Figure 7(b) shows that changing V_p varies the effective field only at low energies. Therefore, the integral of B suffers the largest relative change at low energies. Figure 7(a) illustrates this effect. For a 46% increase in V_p, from 0.26×10^{-2} to 0.38×10^{-2}, the value of φ/g for a 200-keV initial recoil energy decreases 32%, while at 3.4-MeV recoil energy φ/g decreases only 16%. Thus, for low initial recoil energies, the transient-field calculation may be in error by more than 20%, due to an uncertainty in the effective polarized electron velocity V_p.

III. g-FACTOR EXPERIMENTS AND REANALYSIS OF PREVIOUS DATA

A. Technique

The g-factor measurements reported here were performed at the Rutgers-Bell tandem Van de Graaff accelerator facility using the IMPAC technique which has been adequately described elsewhere.[1-3] Two layer (impurity on iron) targets were held between the pole tips of an electromagnet which produced a polarizing field of 1.9 kG. Backscattered particles, detected in an annular silicon detector, were counted in coincidence with γ rays detected by one of four 7.62×7.62-cm NaI detectors placed in the plane perpendicular to the polarizing field direction. Fast-slow coincidence circuitry with a time resolution of about 5 nsec allowed real and random collection of γ-ray, particle, and time-to-amplitude counts with the Rutgers-Bell on-line computer system. The external magnetic field was automatically reversed every 2×10^5 counts in the particle window. All angular shifts were extracted using the difference over sum ratio of integrated photopeak areas accumulated for external field up and down. The γ detectors were placed at complementary angles of maximum slope in the angular correlation and were 10 cm from the target. The angular shifts were corrected for small beam-bending effects and angular correlations were fitted to the general angular-correlation function[20]

$$W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta). \tag{12}$$

B. Iron

As discussed in Sec. II B, the g factor for the 847-keV 2^+ state of ^{56}Fe was determined to be 0.60 ± 0.10 in agreement with previous results. In addition, the g factor of the 1.409-MeV 2^+ state of ^{54}Fe was determined to be $1.43+0.28$.[21] In this case, the 1.4-psec lifetime was short enough so that the static-field precession was only a small correction to the measured angular shift. For the ^{54}Fe experiment, angular shifts were obtained for each of five target and beam combinations. Each experimental point represents about 36 h of accelerator beam time. The angular shifts, corrected for small beam-bending effects, are listed in Table I.

Analyzing these data with the calibrated transient-field theory and assuming values of -330 kG[22] in iron and -364 kG[23] in the alloy for the static hyperfine field yields $g=1.53\pm0.32$. There is evidence that in the high-recoil-energy experiments there is radiation damage at the final site of the implanted iron, which reduces the static hyperfine field.[16] This amounts to a 12% correction to the ^{16}O points, lowering our final result to $g=+1.43\pm0.28$. The error includes a 15% error assigned to the transient-field theory.

This result is inconsistent with one interpretation of an early $(p,p'\gamma)$ perturbed-angular-correlation experiment of Murnick *et al.*[24] The

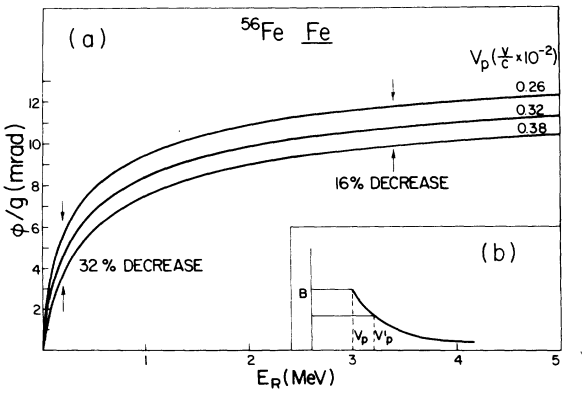

FIG. 7. Error in theoretical φ/g introduced by uncertainty in the parameter V_p. The decreases indicated refer to the nonlinear effect of V_p on φ/g.

original analysis of their experiment was based on a particular velocity dependence of the transient-field effect and was sensitive to the low-velocity behavior of the transient field. The present high-recoil-velocity experiments are independent of these problems.[25]

C. Palladium

A 36-MeV ^{16}O beam was used to Coulomb excite and implant targets of ^{104}Pd, ^{106}Pd, ^{108}Pd, and ^{110}Pd into an $Fe_{0.8}Co_{0.2}$ disordered alloy. The targets were nominally 400-$\mu g/cm^2$ Pd on 0.025-mm alloy. ^{106}Pd on natural iron was also run as a check with previous data.[11] Angular correlations of the first 2^+ states were obtained for all five targets and were found to be consistent with each other and with the theoretical A_2 and A_4. Consequently, the theoretical A_2 and A_4 were used to calculate the angular shifts. The angular shifts obtained are plotted in Fig. 8 versus the lifetimes of the excited states.

From the slopes of the straight line fits in Figs. 5 (data of Ref. 11) and 8, it is clear that the hyperfine fields of Pd in the two backings are equal to within the 9% uncertainty allowed by the errors in the fitted slopes. The measured fields are $B = -409(36)$ for Pd in Fe and $B = -409(31)$ for Pd in the alloy assuming $g_{ave.} = 0.36$. For the alloy backing, the number of polarized electrons per atom is larger than for pure iron ($\delta = 2.43$[26]) and the hyperfine field of Pd in the alloy was not known.

Assuming a hyperfine field of −409 kG effective on the Pd ions in iron and the alloy, g factors were extracted from both the iron data and the alloy data. The g factors were calculated by solving Eq. (10) for g using φ_{fit} for the transient-field contribution; the slowing down correction is negligible in this case. The results are shown in Table II. The ^{104}Pd angular shifts are consistent with zero. This could be caused by either a zero g factor or a cancellation of the hyperfine-field shift and transient-field shift. In the latter interpretation, the g factor is completely indeterminant from the one angular-shift measurement. Assuming, however, that the g factors of the four isotopes are nearly equal (which is the assumption that allows the angular shifts to be plotted versus lifetime in Figs. 5 and 8) a g factor may be extracted for ^{104}Pd. In the following section the g factors for ^{100}Ru and ^{102}Ru first 2^+ states have been calculated under the same assumption. The nearly equal g-factor assumption is in agreement with systematics and theoretical predictions for first 2^+ states in the Pd region.[11]

TABLE I. Summary of ^{54}Fe g-factor data. For the first three data points the beam was ^{16}O; for the last two points the beam was ^4He.

Target	E_r (MeV)	$\Delta\theta_{exp.}$ (mrad)	g
^{54}Fe on alloy	25.5	−12.3(2.2)	1.42(0.25)
^{54}Fe on nat. Fe	25.5	−18.9(4.8)	2.41(0.61)
^{54}Fe sep. iso.	25.5	−13.1(2.5)	1.69(0.33)
^{54}Fe sep. iso.	2.75	−6.60(2.49)	0.92(0.35)
^{54}Fe sep. iso.	2.10	−9.02(2.86)	1.30(0.41)

D. Reanalysis of published g-factor data

In Sec. III it was pointed out that the hyperfine fields at several nuclei in iron as measured by IMPAC and static techniques are not in agreement (Table III). In addition, when the lifetime of an excited state is less than ~10 psec, the decays in flight appreciably alter the static- and transient-field angular shifts. In Ref. 11, these two facts were not incorporated into the g-factor analysis of angular-shift data on isotopes of Ge, Ru, Cd, and Te in iron. These data have thus been reanalyzed with the inclusion of the reduced hyperfine fields and decays-in-flight corrections. The Se and Mo data of Ref. 11 are suspect, but were not reanalyzed for lack of enough data.

The results are listed in Table IV which contains the lifetimes and measured angular shifts of the isotopes in columns 2 and 3, the g factor quoted in Ref. 11 in column 4, the corrected g factor using a static field deduced from the data in column 5, and radioactivity determined g factors for comparison in column 6. Pd is also included where the values quoted are an average of the reanalyzed results of Ref. 11 and this work. The errors quoted on the g factors in column 5 in-

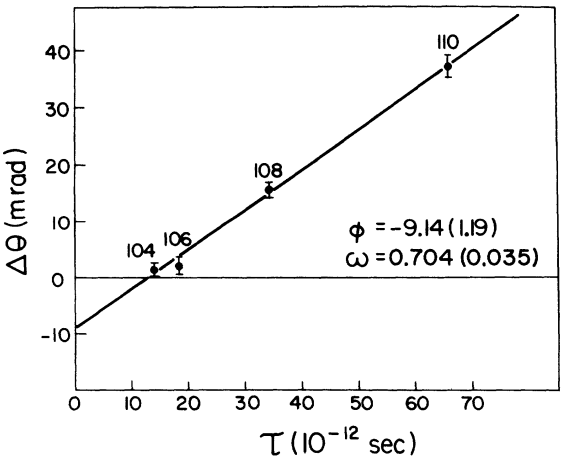

FIG. 8. Angular shifts vs mean life for Pd isotopes implanted into an $Fe_{0.8}Co_{0.2}$ alloy.

TABLE II. Summary of angular shifts and g factors for Pd isotopes implanted into Fe and $Fe_{0.8}Co_{0.2}$ alloy. (Column 2, Ref. 11; columns 3 and 5, this work).

Pd iso.	Fe $\Delta\theta$ (mrad)	Fe $\Delta\theta$ (mrad)	Fe g	Alloy $\Delta\theta$ (mrad)	Alloy g
104	−0.8(1.4)		0.31(0.08) [a]	1.3(1.2)	0.38(0.07) [a]
106	4.5(2.6)	3.5(1.4)	0.37(0.07)	2.0(1.5)	0.32(0.06)
108	17.5(1.6)		0.40(0.06)	15.6(1.2)	0.37(0.04)
110	35.0(2.3)		0.34(0.04)	36.9(1.8)	0.36(0.04)

[a] The value quoted assuming nearly equal g factor for all the first 2^+ states of the even Pd isotopes.

clude the error on the angular shifts, lifetimes, the transient-field theory φ/g when applicable, and the y intercept φ_{fit} where applicable.

$^{98, 100, 102, 104}$Ru g factors were calculated with the same method as the Pd g factors with the best fit parameters $\varphi_{fit} = -10.7(2.4)$ mrad and $B = -359(44)$ kG. The effective field was deduced from the slope of a least-squares fit straight line through the IMPAC angular-shift data of Table IV. The average g factor of 0.40(0.03) was taken from the weighted average of two radioactivity measurements.[28] The internal field deduced from a radioactivity measurement is −490(10) kG.[27]

TABLE III. Comparison of the average room temperature hyperfine field of solutes in Fe as measured by the IMPAC technique and the NMR or PAC methods.

Solute	IMPAC	Other methods
Pd	−409(36)	−573(20) [a]
Ru	−359(44)	−490(10) [b]
Cd	−238(131)	−348(10) [b]
Te	+342(163)	+606(20) [b]

[a] Reference 14.
[b] Reference 27.

The hyperfine field at Ge in Fe is only +70(3) kG.[27] This small field, coupled with the very short lifetimes of the Ge isotopes studied, results in the angular shifts being almost entirely due to the transient field. Because of the short lifetime for ^{70}Ge, decays-in-flight corrections are significant. The Ge g factors were determined by calculating $\Delta\theta/g$ from Eq. (10) and then calculating the g factor from the expression $g = \Delta\theta(\text{exp.})/\Delta\theta/g(\text{calc.})$. This procedure eliminates any dependence on a constant g-factor assumption. An internal field of +70 kG was used in the calculation of $\Delta\theta/g$.

TABLE IV. Summary of g-factor experimental results and reanalysis.

Isotope	τ (psec)	$\Delta\theta$ (mrad)	g (Ref. 11)	g (IMPAC B)	$g_{rad.}$
^{70}Ge	1.92(0.20)	−11.2(1.5)	0.59(0.29)	0.88(0.21)	
^{72}Ge	4.54(0.50)	−9.9(1.7)	0.50(0.25)	0.58(0.14)	
^{74}Ge	17.2 (1.4)	−11.3(1.3)	0.46(0.23)	0.47(0.10)	
^{76}Ge	25.2 (2.6)	−9.9(1.5)	0.37(0.18)	0.36(0.08)	
^{98}Ru	8.5 (0.6)	−5.0(4.0)	0.30(0.17)	0.39(0.30)	
^{100}Ru	17.2 (1.2)	3.3(3.2)		0.47(0.15) [a]	0.42(0.03)
^{102}Ru	25.4 (1.8)	2.8(4.4)		0.31(0.12) [a]	0.34(0.06)
^{104}Ru	83.5 (6.0)	47.8(4.4)	0.29(0.04)	0.41(0.05)	
^{104}Pd	14.0 (1.0)			0.35(0.05) [a]	
^{106}Pd	18.4 (1.3)		0.29(0.17)	0.34(0.05)	0.36(0.02)
^{108}Pd	34.4 (2.4)		0.30(0.04)	0.38(0.03)	
^{110}Pd	66.0 (4.0)		0.25(0.03)	0.35(0.03)	
^{110}Cd	7.2 (0.7)	−10.7(3.8)	0.39(0.15)	0.50(0.22)	0.27(0.09)
^{112}Cd	8.9 (0.7)	−7.3(0.9)	0.30(0.06)	0.36(0.11)	
^{114}Cd	13.0 (1.1)	−5.2(2.5)	0.32(0.13)	0.31(0.19)	0.44(0.06)
^{116}Cd	19.8 (1.5)	−4.0(1.9)	0.71(0.38)	0.40(0.31)	
^{120}Te	13.4 (2.6)	−15.6(3.6)	0.21(0.06)	0.29(0.08)	
^{122}Te	11.0 (1.1)	−15.8(1.2)	0.24(0.06)	0.32(0.05)	0.38 [b]
^{124}Te	9.5 (0.5)	−12.9(0.9)	0.21(0.05)	0.27(0.04)	0.28 [b]
^{126}Te	6.37(0.70)	−13.1(2.5)	0.25(0.07)	0.31(0.08)	
^{128}Te	4.59(0.60)	−10.1(2.0)	0.21(0.06)	0.27(0.07)	
^{130}Te	2.87(0.30)	−10.6(2.2)	0.25(0.07)	0.32(0.09)	

[a] $-g$ is the value quoted assuming nearly equal g factors for all the first 2^+ states of the isotopes of a given element (see text).
[b] $-g$ is an unweighted average of several experimental values.

As no consistent independent g-factor measurements were available for the Te and Cd isotopes, the effective hyperfine field and average g factor were both determined from an analysis of the data with the following procedure. Solving Eq. (10) for $\omega\tau$ yields the angular shift that would result in the absence of recoil, i.e.,

$$\omega\tau = [\Delta\theta(\text{exp.}) - g\varphi/g(\text{calc.})]\, e^{t_s/\tau} . \qquad (13)$$

Fitting a straight line to the data points after modification by Eq. (13), and varying g until the line intersects the origin yields the average g factor and hyperfine field. With the hyperfine field thus determined, the individual g factors were then calculated as was done for the Ge isotopes. The average g factor, and effective hyperfine fields were determined to be $g_{\text{ave.}} = 0.36$, $B = -238(131)$ kG for Cd and $g_{\text{ave.}} = 0.30$, $B = +342(162)$ kG for Te.

The experimental reduced transient-field shift for Te in iron was obtained by the following procedure. The transient-field contribution to each angular shift was calculated with the equation $\varphi = \Delta\theta - \omega\tau e^{-t_s/\tau}$, where $g = 0.3$, $B = +342$ kG were used in the calculation of ω. The resulting transient-field shift φ was corrected for decays in flight relative to an infinite lifetime. The six corrected values for φ were averaged yielding a final result of $\varphi = 10.8$ mrad. The reduced transient-field shift plotted in Fig. 4 is $\varphi/g = 10.8/0.3 = 36$ mrad.

IV. DISCUSSION

The reanalysis of the g-factor data of Ref. 11 was included in this paper under the demonstrated hypothesis that the hyperfine field experienced by the implanted nuclei is reduced from the field seen in static measurements and the fact that decays in flight must be accounted for. Table IV shows that generally the g factors deduced using the IMPAC effective field are in better agreement with the radioactivity g factors and larger than those quoted in Ref. 11. The self-consistency of the data analysis techniques in this paper leads to a useful method for obtaining g factors from IMPAC angular-shift data.

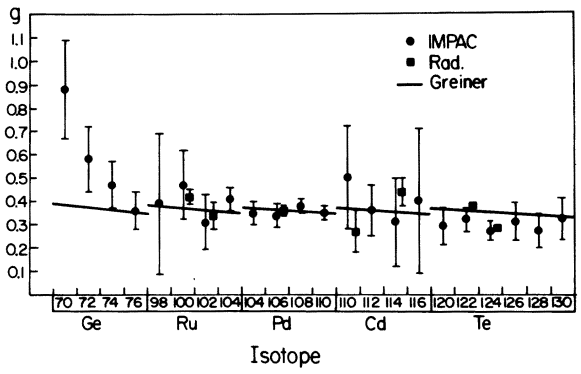

FIG. 9. Comparison of IMPAC and radioactivity g-factor measurements with the theory of Greiner.

Except for the case of the Ge isotopes, the reanalyzed g factors display very regular behavior consistent in trend with a simple collective-model prediction Z/A. It is interesting to note that in the cases of Pd and Te which are most accurately determined, the g factors are constant to within 10% for Pd and 20% for Te.

In general the g factors are depressed from the Z/A collective-model values. Heestand *et al.* found that the g factors could best be described by a model proposed by Greiner[29] which predicts the quenching of these g factors and their smooth variation across the vibrational region. The results in Table IV reinforce this statement since the corrected g factors are in close agreement with this theory. Greiner uses the hydrodynamical-vibrational model along with the fact that the pairing force between protons is stronger than that between neutrons. Consequently, the neutrons on the average undergo a larger spatial deformation than the protons and participate more in the collective motion. Figure 9 compares the experimental and reanalyzed g factors from this work with the theory.

The corrected g factor of ^{70}Ge is surprisingly large, being about twice the Z/A value of 0.46. The g factors of the four Ge isotopes ($^{70, 72, 74, 76}$Ge) decrease sharply as neutrons are added. Since ^{70}Ge is on the edge of the vibrational region, this could be evidence for Ge isotopes undergoing a transition between single-particle-like behavior to collective-like behavior.

Our result for the ^{54}Fe 1.409-MeV (2^+) g factor, $g = 1.43(28)$, shows unambiguously that this state has a single-particle nature. This result overlaps the Schmidt limit and recent calculations of Zamick[30] and Talmi.[31] The error assigned to the g-factor measurement is too large to distinguish between the two calculations.

It is noteworthy that under the assumption of nearly equal g factors for isotopes of a given element, the hyperfine fields at Pd, Ru, Cd, and Te nuclei in iron as measured by IMPAC are all smaller than the fields measured by other techniques. Table III summarizes these results. In fact, this hyperfine-field discrepancy between IMPAC and other techniques is the rule rather than the exception when ^{16}O or heavier ions are used as the projectile. A possible mechanism for these reduced fields is radiation damage from Coulomb collisions between the primary beam and iron host atoms in the region of the host where

the heavier implanted atom comes to rest. The reduced fields will be discussed in a future publication.

Other approaches for measuring g factors of very short-lived states are the recoil-into-gas[32] and recoil-into-vacuum[33] techniques, which use the randomly oriented fluctuating hyperfine fields of highly stripped atoms to precess the nucleus. Both methods measure an attenuation of the angular correlation and extract a number proportional to the quantity $\omega^2\tau_c\tau$ where ω is the precession frequency, τ_c is the correlation or flipping time of the perturbing field, and τ is the mean life of the excited state. For the recoil-into-vacuum technique, the correlation time τ_c is governed exclusively by optical and Auger transitions in the highly excited atom. In the recoil-into-gas technique, collisions with gas atoms determine τ_c which can be varied by changing the gas pressure. The attenuation of the angular correlation in both methods arises from the loss of nuclear alignment caused by the interaction between the randomly oriented fluctuating fields and the nuclear dipole moment. The average magnetic hyperfine fields experienced by the recoiled nucleus in both techniques is typically on the order of 50 MG. These large fields make possible the measurement of g factors of very short-lived nuclear excited states.

Despite the fact that the effective fields are larger in the vacuum and gas methods than in the transient-field method, the sensitivity of the techniques are comparable. The alignment of the hyperfine-field with the transient-field recoil method allows the direct measurement of the precession of the nucleus. A 10-mrad shift is easily measurable for a highly anisotropic correlation. On the other hand, the random orientation of the effective fields in the gas and vacuum techniques allows only an attenuation of the angular correlation to be measured. A perturbation of $(\omega^2\tau_c\tau)^{1/2} \gtrsim 100$ mrad is needed to produce a measurable attenuation. In practice, the correlation time τ_c is such that the two methods have comparable sensitivity.

The hyperfine fields at nuclei recoiling into vacuum or gas are extremely difficult to calculate. The calculation of the field contribution from a single unpaired s electron in a stable electronic configuration is straightforward, but adding the complication of a highly excited atom and many different charge states makes the calculations formidable. For this reason, a statistical approach is used in which one hopes that a unique average randomly oriented hyperfine field describes the state of affairs. In this case an estimate of τ_c and the average field allows the extraction of g factors from angular-correlation attenuation coefficients. Presently the vacuum and gas techniques are limited to measuring ratios of gyromagnetic ratios of two levels of comparable lifetimes in similar nuclei, thus dividing out the unknowns τ_c and H in $\omega^2\tau_c\tau$. An exception to this statement occurs for light ions in well-defined atomic states for which the hyperfine fields are exactly calculable.[34] A great deal of work is being done with these recoil methods; they are of interest in both nuclear and atomic physics. If the present theoretical ambiguities are removed, the vacuum and gas techniques have promise of delivering precision absolute g-factor measurements of very short-lived states.

In contrast to the recoil-vacuum or -gas techniques, the transient-field recoil technique has a firm theoretical and experimental footing. The theory of Lindhard and Winther reproduces the experimental data to at least 20% accuracy from which absolute g-factor measurements may be made for very short-lived states. For lifetimes in the 10^{-12}-sec regime, the technique is quite insensitive to 20% changes in the lifetime and to the actual value of the internal hyperfine field. The latter effect is desirable since the effective value of B in IMPAC experiments is often uncertain.

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*Present address: Naval Research Laboratory, Washington, D.C. 20375.

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‡Associate of the Graduate Faculty, Rutgers University, New Brunswick, New Jersey.

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