Direct evidence for enhanced transient fields on fast ^{56}Fe ions recoiling through thin iron

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Results of ion-implantation perturbed-angular-correlation measurements on ^{56}Fe ions recoiling through magnetized Fe at high recoil energy ($E_R \approx 56$ MeV) are reported. Angular shifts were measured using targets of various thicknesses for which the excited nuclei either stopped in or recoiled out of the iron. The results clearly establish the existence of enhanced transient fields acting on fast recoiling ions leaving the magnetized Fe foil and stopping in Cu. In such measurements the contributions from the static field and from the normal Lindhard-Winther field are eliminated. The possible use of this technique for measurements of magnetic moments of short-lived states is discussed. An experiment in which the ^{56}Fe ions recoiled into vacuum through the polarized foil was also carried out. In this case a strong attenuation of the angular correlation was observed; however, no excessive precession was seen, as would be observable if polarized hyperfine fields persisted in vacuum for a substantial part of the nuclear lifetime.

[NUCLEAR REACTION ^{56}Fe(^{32}S, $^{32}S'$)^{56}Fe*(2^+), $E = 64$ MeV, targets of various thickness; measured $W(\theta, H, \infty)$ in polarized iron. Deduced transient field of Fe*Fe* at $v/c \approx 0.045$. Demonstrated existence of enhanced transient fields.]

I. INTRODUCTION

The transient magnetic fields which act on nuclei moving in a magnetized ferromagnetic material have been utilized over the past few years for g-factor measurements of short-lived nuclear states.[1-3] For relatively slowly moving ions, these fields are well explained by the adjusted Lindhard-Winther (ALW) theory.[2-4] Hubler *et al.*,[2,5] for example, have studied thoroughly the precession of the 2^+ states of ^{54}Fe and ^{56}Fe nuclei recoiling into Fe at various recoil energies. For the case of the 2^+ first excited state of ^{56}Fe, the -330 kG static field for the Fe in *Fe* (Fe*Fe*) system and the ALW transient field approximately cancel, so that normal ion-implantation perturbed-angular-correlation IMPAC measurements should yield very small precession angles. At high recoil velocities, however, Hubler *et al.* measured rather large negative precession angles, which they attributed to radiation damage reducing the static field[5,6] so that the cancellation of the static and transient precessions is no longer complete. An enhancement of the (positive) transient field rather than a weakening of the (negative) static field could also explain Hubler's data.

The results of numerous recent IMPAC experiments for light ions ($6 < Z < 14$) recoiling into Fe at high recoil velocities ($v/c \approx 0.01-0.06$) have demonstrated the existence of transient fields which considerably exceed the ALW prediction.[7-11] The large fields observed in these experiments are believed to arise from capture (or loss) of polarized s electrons from the magnetized iron by the slowing-down ion. The present experiment was undertaken in order to extend the data of Hubler *et al.* to much higher recoil energies and to investigate the relative contributions of radiation damage and enhanced transient fields (ETF) to the large precession angles measured for the Fe*Fe* system at high recoil velocities.

The results of the present experiment show that by using thin Fe targets of varying thicknesses such that the recoiling ions spend only the fast-moving ($v/c > 0.01$) part of their slowing-down history in the polarized Fe, one can eliminate the contributions of both the static field and of the nonenhanced LW field, and thus directly establish the existence of enhanced transient fields for Fe in Fe at high recoil velocity. Similar procedures could be used to measure magnetic moments of short-lived nuclear levels in this region of the Periodic Table. A measurement with a thin polarized iron foil with no backing did not show evidence of prevailing electronic polarization for ions recoiling into vacuum through the polarized iron.

TABLE I. Summary of experimental conditions for the four targets used in this work.

Target number	Fe thickness (mg cm^{-2})	Backing	Exit energy (MeV)	Exit v/c (%)	Time in foil (ps)
1	12	None	0	0	0.95 ± 0.02
2	2.6	Copper	19 ± 2	2.6 ± 0.1	0.31 ± 0.06
3	1.6	Copper	33 ± 2	3.5 ± 0.1	0.15 ± 0.04
4	1.6	None	33 ± 2	3.5 ± 0.1	0.15 ± 0.04

II. EXPERIMENT

The first excited 2^+ state of ^{56}Fe ($E_{2+} = 0.847$ MeV, $\tau = 10$ ps, $g = 0.55 \pm 0.1$) was Coulomb excited by a 7^+, 64 MeV sulfur beam from the Rutgers-Bell tandem Van de Graaff. Backscattered sulfur ions were detected in an annular surface barrier detector subtending an angular range of 167°–177°. This experimental setup corresponds to an average energy of about 56 MeV for the forward-recoiling ^{56}Fe ions. Deexcitation γ rays from the 2^+ state were detected in coincidence with the backscattered sulfur ions by four 7.6 cm × 7.6 cm NaI(Tl) crystals placed at 10 cm from the target. Random coincidences were also recorded and were subsequently subtracted in the off-line analysis of the data.

Four different target arrangements were used in order to investigate the enhanced transient fields in different velocity domains. One target consisted of an Fe foil of sufficient thickness (12 mg cm^{-2}) to stop the recoiling ions. Two targets consisted of 2.6 mg cm^{-2} and 1.6 mg cm^{-2} of iron backed with copper. The thicknesses of the iron layers were chosen so that the recoiling ions slowed down in the Fe layer but stopped in the copper backing, which provides a perturbation-free environment. The fourth target was 1.6 mg cm^{-2} of Fe with no backing so that the excited ions traversed the target and recoiled into vacuum. The effective thickness of the Fe layer (regarding the Coulomb excitation process) was 0.8 mg/cm^2 for all four targets. This thickness is the maximum depth from which low-energy backscattered S ions can escape the target foil and be counted by the particle detector within the defined energy window (1–5 MeV).

Table I summarizes the characteristics of the four targets used in this experiment, and gives relevant quantities related to the recoil history of the excited nuclei. The energy that the excited nuclei have upon exit from the target and their velocity at that point are given in columns 4 and 5 of the table. The times spent by the recoiling Fe ions inside the iron layer are given in column 6. The stated uncertainties reflect the spread in initial and final velocities due to the finite effective target thickness.

The iron layer of the targets was magnetized in a direction perpendicular to the plane defined by the four NaI(Tl) counters by an external magnetic field of 1 kG. This field was shown in an off-line magnetometer measurement to be sufficient to saturate the iron, but was still small enough to keep beam-bending effects negligible (<1 mrad).

III. RESULTS

The angular correlation for targets 1–3, for which the recoiling Fe ions stopped and decayed inside solid material, and the angular correlation for target 4, for which the Fe ions recoiled into vacuum, were measured. The result for the recoil-stopped targets (1–3) was found to be

$$W_{1\text{-}3}(\theta) = 1 + (0.58 \pm 0.04)P_2(\cos\theta) - (1.18 \pm 0.05)P_4(\cos\theta)\,,$$

in agreement (after correcting for finite solid angles) with a pure $m=0$, $2 \to 0$ correlation.

For the recoil-into-vacuum target, the angular correlation was found to be strongly attenuated, presumably due to the presence of large magnetic hyperfine fields at the nuclei acting for an appreciable fraction of the lifetime of the 2^+ state (see below). The correlation for this case was found to be

$$W_4(\theta) = 1 + (0.50 \pm 0.04)P_2(\cos\theta) - (0\ 65 \pm 0.05)P_4(\cos\theta)\,.$$

[The angles and solid angles of the NaI(Tl) crystals have been corrected for the center-of-mass motion.] The two angular correlations are shown in Fig. 1.

Precession measurements for all four targets were then carried out with the γ detectors set at ±112.5° and ±67.5°, at which angles the angular correlation exhibits a large slope. The magnetization direction of the iron foil was reversed periodically under computer control and the coincidence γ-ray spectra routed accordingly. Integrated photopeak intensities were used to form double ratios, defined as

$$\rho_{ij} = \left[\frac{N(\theta_i)\uparrow}{N(\theta_i)\downarrow}\,\frac{N(\theta_j)\downarrow}{N(\theta_j)\uparrow}\right]^{1/2}, \quad i,j = 1,2,3,4,$$

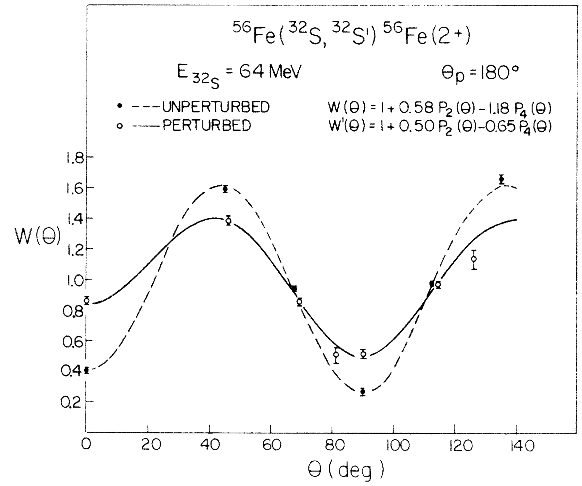

FIG. 1. Angular correlations for the recoil-into-copper (dotted line) and recoil-into-vacuum (solid line) measurements. The plotted lines represent least-square fits to the data.

where $\theta_{1(4)} = \pm 112.5°$, $\theta_{2(3)} = \pm 67.5°$; $N(\theta_i)\uparrow$ represents, for example, the peak sum for the ith detector with the magnetic field up.

The double ratios reflecting the angular precession are the symmetric-angle ratios ρ_{14} and ρ_{23}. The average double ratio $\rho = (\rho_{23}/\rho_{14})^{1/2}$ is free of systematic errors and is related to the observed angular shift $\Delta\theta$ by

$$\Delta\theta = \frac{1}{S}\frac{\rho - 1}{\rho + 1}; \quad S = \frac{1}{W(\theta)}\left.\frac{dW(\theta)}{d\theta}\right|_{\theta = 67.5°}$$

The double ratios ρ_{13} and ρ_{24} show no effect, as expected, and serve as a consistency check of the data.

Table II lists the measured angular shifts for each target along with the relevant experimental information.

IV. DISCUSSION

A. Thick target

The measured angular shift for 56 MeV Fe ions recoiling and stopping in the thick magnetized target ($\Delta\theta = -13$ mrad) is the sum of three contributions: (1) the nonenhanced ALW transient field; (2) the static magnetic field for Fe*Fe* (possibly reduced by radiation damage); (3) the enhanced transient field (if present), presumably acting only at high recoil velocities. As the angular shifts due to the static magnetic field and the ALW field are of opposite sign and of approximately equal magnitude,[2] a measured large negative net shift could indicate a reduction of the static field (radiation damage, according to Hubler *et al.*), the presence of enhanced transient fields,[10] or both of these effects.

The present result agrees qualitatively well with the general trend of previous results for Fe ions recoiling and stopping in thick magnetized Fe (Fig. 2). However, the extraction of information regarding the relative contribution of any of the three possible fields listed above to the total precession angle is practically impossible. The static field contribution, for instance, may depend strongly on experimental conditions such as type of incident beam, beam current, thermal contact of the target foil to the target frame, etc. It is, therefore, difficult to analyze confidently the results of a single thick-target IMPAC experiment, and even more so to compare different such experiments. The above considerations seriously limit the possibility of reliably calibrating the hf fields in thick-target IMPAC experiments in order to utilize them for magnetic moment measurements of very short-lived nuclear states. The second part of the present work was undertaken in order to study only the enhanced transient fields, thus overcoming these difficulties.

B. Thin targets

Thin foils of 2.6 mg cm^{-2} and 1.6 mg cm^{-2} of iron on thick copper backings were used in the second part of the present work. The Coulomb excitation process takes place within the first 0.8 mg cm^{-2} layer of iron and the recoiling Fe ions leave the iron foil with sufficient energy (Table I) to be implanted and consequently stopped (after about 0.5 ps) well inside the Cu backing. The energy of the Fe

TABLE II. Measured angular shifts. $\Delta\theta/g$ (net) represents the experimental angular shift after correcting for a small (≤ 1 mrad) beam-bending shift.

Target	Energy out (MeV)	ρ_{14}	ρ_{23}	ρ_{13}	ρ_{24}	S	$\frac{\Delta\theta}{g}$ (net) (mrad)
1	0	0.927(11)	1.080(11)	1.006(11)	0.997(11)	−2.90(8)	−22 ± 3
2	19 ± 2	0.947(13)	1.051(13)	1.006(13)	0.991(13)	−2.90(8)	−15 ± 3
3	33 ± 2	0.976(11)	1.040(11)	1.010(11)	0.986(11)	−2.90(8)	−9 ± 2
4	33 ± 2	0.981(16)	1.001(16)	0.984(16)	1.005(16)	−1.84(6)	−5 ± 6

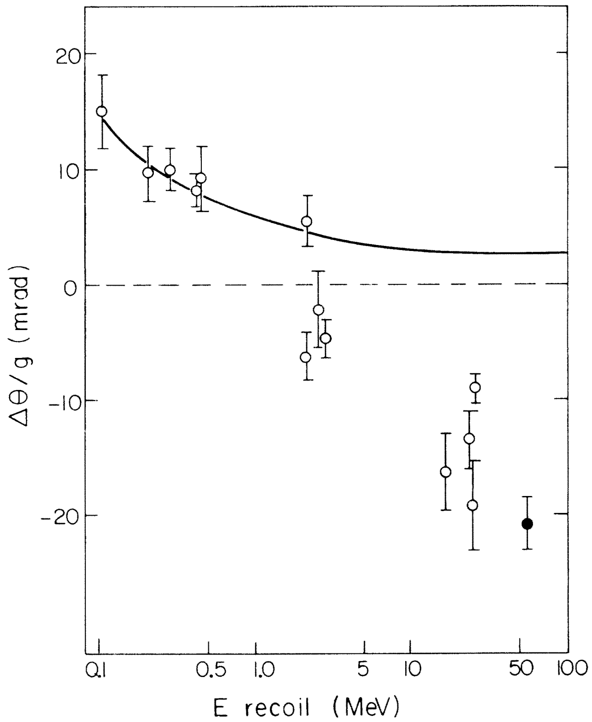

FIG. 2. Results of thick-target transient field measurements for Fe*Fe* at various recoil energies. The 56 MeV point is the result of the present experiment. The other points are taken from Hubler *et al*. (Refs. 2 and 5). The solid line is an ALW calculation.

ions leaving the iron foils ($E_{out}>16$ MeV) is high enough to justify neglecting the ALW contribution. Also, as all magnetic interactions (quadrupole interactions can be neglected) are switched off very shortly after entering the Cu, there will be no contribution from any static magnetic field. The measured angular precession, therefore, yields directly the integrated enhanced transient field effect from the initial 56 MeV recoil energy down to E_{out}.

The results presented in Table II and Fig. 3 clearly demonstrate the existence of enhanced transient fields for Fe recoiling through Fe at high recoil velocities. Figure 3 also shows calculated angular shifts using the phenomenological expression of Eberhardt *et al.*,[10] in which the enhanced transient fields are calculated using a magnetic field proportional to the atomic number z and to the velocity of the recoiling nuclei

$$B=az(v/v_0)^P\,, \tag{1}$$

where v_0 is the Bohr velocity, and $a=(12.5\pm1.7)\times10^4$ G, and $p=1.05\pm0.25$ have been fitted to experimental data. The empirical expression of Eq. (1) is to be contrasted with the ALW theory, where the field is inversely proportional to the velocity.

The above parameters were obtained using ^{28}Si data at high recoil velocity and were also used by Eberhardt *et al.* to explain data for Fe*Fe* obtained from thick target experiments. The agreement with the results of Hubler *et al.* is fair, assuming that the large precession angles are due only to ETF. However, as was mentioned above, part of the measured effect for the thick target experiments may be due to radiation damage. This will reduce the deduced ETF contribution and a smaller value of the proportionality parameter will be needed. Furthermore, a thick target experiment measures the integrated angular shift from the initial recoil velocity down to zero, and there is no reason to believe that the above expression for enhanced field is valid for low velocities. The present results, where only ETF contribute to the measured shift, yield (assuming $p=1$) $a=7.6\times10^4$ G (Fig. 3).

This phenomenological approach seems to reproduce the correct features of ETF. Much more experimental work is needed, however, in order to establish the quantitative validity of this method and to better determine the values of the relevant parameters.

A microscopic picture for the ETF in Fe*Fe* at this recoil velocity is much more difficult to ob-

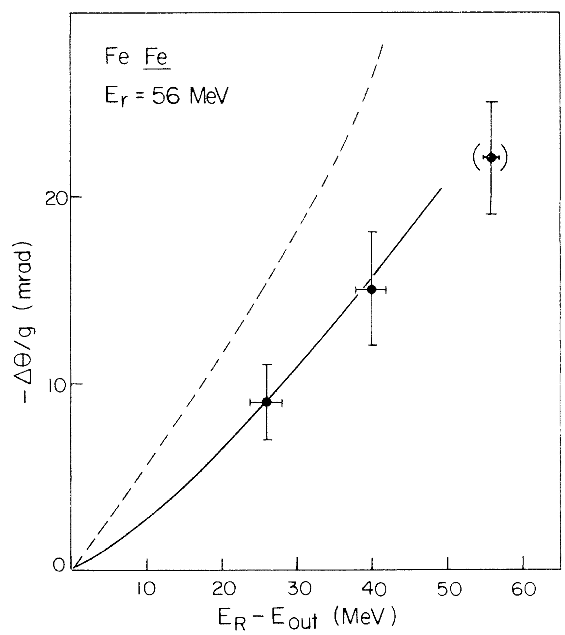

FIG. 3. Results of the present experiment using the copper-backed Fe targets. The 56 MeV point is the thick-target result. The dotted line is the calculated shift using phenomenological parameters of Eberhardt *et al*. (Ref. 10). The solid line represents a similar calculation using parameters chosen to fit our data (see text).

TABLE III. Charge states for Fe ions recoiling out of a solid target at 30 MeV.

Charge state	Ground-state configuration	Fraction
10^+	$(2p)^6(3s)^2 3p^4$	0.015
11^+	$(2p)^6(3s)^2 3p^3$	0.068
12^+	$(2p)^6(3s)^2 3p^2$	0.180
13^+	$(2p)^6(3s)^2 3p^1$	0.280
14^+	$(2p)^6(3s)^2$	0.259
15^+	$(2p)^6(3s)^1$	0.141
16^+	$(2p)^6$	0.045

tain, and only qualitative arguments can be given at this stage to account for the measured enhanced fields. If one considers only fields induced by pure s-electron configurations, the relative contributions of $1s$, $2s$, and $3s$ polarized electrons to the total fields have to be considered. $4s$ electrons are likely to be completely ionized at the recoil velocities relevant to the present work (see Table III).

Various possible mechanisms for the preferential pickup, or loss, of polarized electrons have been discussed in connection with other enhanced field experiments (see in particular Ref. 10). Always, the two important considerations are how s-state vacancies are formed and how they might be preferentially polarized. For $1s$ vacancies in the Fe*Fe* system, quantitative cross sections may be reliably inferred by applying scaling laws[12] to solid target measurements of K-shell x-ray production in the nearby symmetric Ni-Ni collision system.[13] Within the molecular orbital description,[14] the dominant mechanism for formation of $1s$ vacancies is interpreted[13] to be a two-step process: first, one or more collisions produce a $2p$ vacancy in the moving ion, then promotion of this vacancy to the $1s$ orbit occurs in a later collision. With the extreme assumptions that all of the $2p$ vacancies are similarly promoted from the $3d$ shells only and that no polarization is lost at any step, then, for 56 MeV Fe ions, the estimated upper limits to the $1s$ contribution to ϕ/g are only -1.0 mrad if E_{out} is taken to be 33 MeV, and -1.5 mrad if the ion stops in the polarized foil. Therefore, as has already been concluded,[10] the main origin of the ETF in the Fe*Fe* system must be the $2s$ and $3s$ shells. How they pick up polarized electrons from the magnetized iron foil is a more complicated question since many less quantitatively understood multistep processes are likely to play a role.

An attempt at a microscopic description of $2s$ and $3s$ polarization in Fe*Fe* by balancing capture and loss cross sections has been made by Eberhardt *et al.*,[10] but this yielded fractions of polarized electrons much too small to explain the data. However, by postulating that indirect capture cross sections (capture to higher states followed by downward transitions) were 10% of the direct, these authors were able to match the data fairly well.

For purpose of illustration, taking 280 MG and 40 MG for the $2s$ and $3s$ fields respectively,[10] our present measurement of the precession angle ($E_{out}=33$ MeV) could be explained by an average of either ~2% $2s$ polarization or ~20% $3s$ polarization. The relative contribution of these fields can not be determined from the present experiment.

Much more theoretical and experimental atomic-physics information is needed in order to obtain a self-consistent picture of the processes giving rise to ETF and to give phenomenological fields a better microscopic basis.

C. Radiation damage

The combination of the thick-target and thin-target experiments allows one to obtain an indirect estimate of radiation damage effects on the static hf field. If we compare the measured angular shifts for the thick target and the 2.6 mg cm^{-2} target ($E_{out}\approx 19$ MeV), we can divide the contributions to the total precession angle according to the stage in the slowing-down process in which they have occurred, and write

$$\Delta\theta(56\to 0)=\Delta\theta(56\to 19)+\phi(19\to 0)+\Delta\theta_{sta}, \qquad (2)$$

where $\Delta\theta(56\to 0)$ is the experimentally determined angular shift for the thick target, $\Delta\theta(56\to 19)$ is the experimental shift for the 2.6 mg cm^{-2} target, $\phi(19\to 0)$ is the transient shift, integrated from 19 MeV down to zero, and $\Delta\theta_{sta}$ is the shift due to the static (possibly radiation-damaged) field.

The ALW theory for intermediate and heavy nuclei was derived using data for recoil velocities of about 10–12 MeV.[2] If we assume that $\phi(19\to 0)$ is given approximately by the ALW calculation for Fe*Fe* at 19 MeV ($\phi=-7.3\pm 1$ mrad), the only unknown in Eq. (2) is $\Delta\theta_{sta}$. We can write

$$\Delta\theta_{sta}=(-12.3\pm 1.3)-(-7.3\pm 1)-(-8.7\pm 1.6),$$

obtaining

$$\Delta\theta_{sta}=+(3.7\pm 2.3)\ \text{mrad}.$$

The angular shift due to the undamaged static field for Fe*Fe* is about +9 mrad.[15]

This qualitative analysis demonstrates the presence of radiation damage effects which substantially reduce the static magnetic field from its original value and is in qualitative agreement with estimates by Hubler.[5] As was already pointed out, the presence of such effects, which depend strongly on particular experimental conditions, complicates the use of thick-target, transient-field experiments for nuclear magnetic moment measurements in regions of the Periodic Table where static magnetic fields are substantial.

D. Recoil into vacuum

The angular correlation for the recoil-into-vacuum experiment exhibits strong attenuation relative to the recoil-into-solid angular correlation (Fig. 1). This attenuation arises from strong hyperfine magnetic fields present in the recoiling ensemble and acting on the Fe nuclei for a substantial part of the lifetime of the 2^+ level. In spite of these strong magnetic fields, the angular shift for the 1.6 mg/cm^2 unbacked target does not show (within experimental errors) any excessive polarization effects over those measured for the same thickness Cu-backed target. Such effects could have arisen if some orientation of the fields responsible for the angular shift inside the iron foil were maintained in vacuum for an appreciable fraction of the nuclear lifetime. Several mechanisms could be considered to explain the present negative results. Among these are the magnetic properties of the outermost surface layers of the iron foil, or the short lifetime of the polarized atomic configurations which give rise to the enhanced fields. It is also possible, in view of the large observed attenuation, that the fields in vacuum may be very large and act for a long time, thus approaching the hard-core limit ($\omega\tau \gg 1$). In this case no apparent precession will be observed although polarized electrons with very strong magnetic fields still may exist in the recoiling ensemble. For the case of $\omega\tau > 1$, quantum effects due to the coupling of the atomic spin J to the nuclear spin I also have to be taken into account.[16] Nevertheless, the negative present result is consistent with other negative results[17,18] for lighter ions, like oxygen, recoiling into vacuum through a magnetized thin iron foil.

The comparison of the angular correlations of the recoil-into-vacuum and recoil-into-solid experiments yields integral attenuation coefficients of

$$G_2 = 0.86 \pm 0.08, \quad G_4 = 0.58 \pm 0.05 .$$

These values of G_2 and G_4 are consistent with the assumption of a static magnetic perturbation[19]:

$$\frac{1 - G_2}{1 - G_4} \sim \frac{K(K+1)|_{K=2}}{K(K+1)|_{K=4}} = 0.3 ,$$

while the measured values yield

$$\frac{1 - G_2}{1 - G_4} = \frac{0.14}{0.42} = 0.33 .$$

The charge state distribution for Fe ions recoiling out of a solid target at 30 MeV[20] is given in Table III. The active configurations in the charge state equilibrium process at this energy belong to the $n = 3$ shell. This situation can be compared to a previous experiment for oxygen ions recoiling at $v/c = 0.01$ where rather similar configurations of the $n = 2$ major shell are involved.[21] In the ^{16}O case, a statistical model for the static perturbation in the $n = 2$ shell was introduced and successfully employed in extracting nuclear information. Using the same ideas in the present experiment for the $n = 3$ shell yields attenuation coefficients in agreement with the measured G_2 and G_4. A quite similar procedure was also used by Jain *et al.*[22] in analyzing a decoupling measurement for ^{40}Ca of $v/c = 0.015$. In order to better understand the magnetic fields of the various configurations in the electronic ensemble, more experimental information is needed as can be obtained, for example, from decoupling and time-differential measurements. A combination of such experiments can serve as a powerful tool for magnetic moment measurements using multielectron electronic ensembles.

In conclusion, the present experiment demonstrates directly the existence of enhanced transient fields for Fe*Fe* at high recoil velocities. These polarized fields probably do not persist for an appreciable fraction of the nuclear lifetime after the ions recoil into vacuum, although strong perturbations for the recoil-into-vacuum case do exist. The enhanced transient magnetic fields, as well as the static magnetic fields of free ions in vacuum, can be used for future magnetic-moment experiments for similar systems.

Note added in proof. It has been recently pointed out[23] that the magnitude and velocity dependence of transient magnetic fields at high velocity could be explained in the framework of a dynamic screening theory by taking into account nonlinear effects governing the electron cloud response at the origin of the moving ion. This approach is markedly different from the picture of capture and loss of polarized s electrons presented here and in earlier related publications.

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