Transient-field strengths for high-velocity light ions and applications to g-factor measurements on fast exotic beams

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The experimental data concerning transient-field strengths for ions with $6 \leqslant Z \leqslant 16$ moving in Fe and Gd hosts are summarized for ion velocities greater than $\frac{1}{2}Zv_0$. Based on model expectations, a parametrization of the field strength is proposed. For both Fe and Gd hosts the form is $B_{\mathrm{tf}}(v,Z)=AZ^P(v/Zv_0)^2e^{-(v/Zv_0)^4/2}$, where A and P are determined by fitting data. The implications of the parameter values for understanding the physics of the transient field are discussed along with applications to the measurement of excited-state g factors in exotic nuclei produced by intermediate-energy fragmentation reactions.

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I. INTRODUCTION

The transient hyperfine magnetic field has been used extensively to measure the gyromagnetic ratios of short-lived states in stable nuclei populated by Coulomb excitation [1,2]. Whether the experiments use projectile excitation [2,3] or more conventional kinematics [1,4,5], most g-factor measurements so far have been performed under conditions where the nuclei of interest move through the ferromagnetic medium as ions that have a velocity well below the velocity of the electrons carried in the K shell. For an ion with atomic number Z, this velocity is $v_K=Zv_0$, where $v_0=c/137$ is the Bohr velocity of an electron in the K shell of the hydrogen atom. The transient field in this low-velocity regime ($v_{\mathrm{ion}} \ll Zv_0$) cannot be calculated from first principles, so experimenters have come to rely on empirical parametrizations of the field strength [6–9].

The advent of accelerators that produce radioactive ion beams by intermediate-energy fragmentation reactions make it necessary to develop the transient-field technique for ions moving much more rapidly. As a starting point, the transient-field strength must be studied and parametrized for ion velocities that extend well beyond Zv_0. The purpose of the present paper is to summarize existing data [2,10–28] for light ions ($6 \leqslant Z \leqslant 16$) and propose a model-based parametrization of the field applicable for ion velocities above about $v_L=\frac{1}{2}Zv_0$ (the L-shell electron velocity). The data and the parametrization are presented in Sec. II.

Insights into the physics of the transient field, gained by distilling the experimental data into a simple parametrization of the field strength, are discussed in Sec. III. Although there are few data in the velocity region above Zv_0, which makes further experimental work essential, the proposed parametrization is useful for planning experiments on radioactive isotopes produced by intermediate-energy fragmentation reactions. This aspect is discussed in Sec. IV.

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II. SUMMARY AND PARAMETRIZATION OF HIGH-VELOCITY TRANSIENT-FIELD DATA

The transient-field data for ions between carbon and sulfur traversing Fe and Gd hosts at velocities above approximately $\frac{1}{2}Zv_0$ are summarized in Tables I and II. There has been some debate about the absolute strength of the field for C in Fe, where there is a conflict between experiments using ^{12}C [10,11] and ^{13}C [12] probes; however, the velocity-dependent trends evident from the more precise data for ^{12}C have never been disputed and, as the following analysis will show, the observed velocity dependence conforms with model-based expectations.

For ions moving in a ferromagnetic host with a velocity that exceeds v_L, the transient-field strength is expected to arise predominantly from the hyperfine interactions of the K-shell, or 1s, electron bound to the moving nucleus. The contact field at the nucleus is given by (see, e.g., Refs. [1,2]) $B_{1s}=16.7Z^3R(Z)$ T, where the relativistic correction factor $R(Z)\simeq[1+(Z/84)^{2.5}]$ is very near unity for all cases of present interest. In general, the transient-field strength for ion velocities near Zv_0 in a specified host is related to B_{1s} by an expression of the form [1,2,6,29,30]

$$B_{\mathrm{tf}}(v,Z) = \xi_{1s}(v,Z)F_{1s}^1(v,Z)B_{1s}(Z), \tag{1}$$

where $F_{1s}^1(v,Z_1,Z_2)$ is the fraction of ions that carry a single K-shell electron, and $\xi_{1s}(v,Z)$ is the polarization of these single K-shell electrons bound to the ion. In principle F_{1s}^1 and ξ_{1s} vary with ion velocity and Z. However, in order to proceed the assumption will be made that the polarization is insensitive to the ion velocity, as has generally been found in previous studies [2,22,29–31], i.e., $\xi_{1s}(v,Z)=\xi_{1s}(Z)$. A simple parametrization of the Z dependence of ξ_{1s} will be sought, $\xi_{1s}=A_\xi Z^{P_\xi}$, where A_ξ and P_ξ are parameters.

It remains to parametrize the single K-vacancy fraction F_{1s}^1. The velocity dependence of F_{1s}^1 at high velocities is expected to resemble that of the hydrogen-like charge fraction for ions emerging into vacuum, but shifted to a lower energy so that the peak value of $F_{1s}^1=0.5$ occurs when v

TABLE I. Transient-field data for high-velocity light ions in Fe hosts.

Ion	$\langle v/v_0 \rangle$	$\langle B_{tf} \rangle$(T)	Reference
$^{12}_{6}$C	4.1	452(74)	[11]
	6.0	500(88)[a]	[11,16]
	7.4	378(96)	[11]
	7.9	144(176)	[11]
	9.7	90(207)	[11]
$^{13}_{6}$C	4.7	197(148)[b]	[12]
	7.4	188(159)[b]	[12]
$^{16}_{8}$O	5.9	397(37)	[14]
	6.9	509(77)	[14]
	7.35	694(318)	[25]
$^{20}_{10}$Ne	6.53	675(165)[b]	[27]
	6.8	1087(265)	[15]
	6.87	686(252)	[27]
$^{24}_{12}$Mg	5.74	852(277)[b]	[27]
	6.13	900(200)	[11]
	6.21	830(100)	[13]
	6.44	782(310)[b]	[27]
	6.76	450(280)	[11]
	6.77	910(190)	[13]
	7.26	1310(360)	[13]
$^{28}_{14}$Si	7.4	1310(240)	[24]
	7.6	1800(300)	[28]
	9.0	1770(320)	[24]
	10.8	3500(1100)	[20]
$^{32}_{16}$S	7.9	1760(200)	[18]

[a]The data for ^{12}C from Ref. [11] are normalized to this value as given in Ref. [16].
[b]Velocity-differential data obtained by subtracting thick-foil data.

TABLE II. Transient-field data for high velocity light ions in Gd hosts.

Ion	$\langle v/v_0 \rangle$	$\langle B_{tf} \rangle$(T)	Reference
$^{12}_{6}$C	4.1	338(60)[a]	[11]
	6.0	498(89)	[16]
$^{16}_{8}$O	6.45	963(52)	[14,19]
	6.75	1250(390)	[19]
	7.4	1080(130)	[14]
$^{20}_{10}$Ne	6.8	1300(300)	[15,26]
	12.5	1900(800)	[21]
$^{28}_{14}$Si	7.5	1100(200)	[28]
	11	2900(600)	[20]
$^{32}_{16}$S	6.3	1400(300)	[23]
	8.1	1380(270)	[17]
	16	3300(1100)	[23]

[a]Precession data from Ref. [11] normalized to be consistent with fields given in Ref. [16].

$=Zv_0$. This condition is required on the basis of electron capture and loss arguments [30] and is confirmed by experiment [30,32,33].

The single-electron charge fractions for several of the ions of interest emerging from Fe and Gd into vacuum were calculated as a function of energy with the code LISE [34], which offers three alternative formulations to evaluate the charge-state distributions. Whichever formulation was chosen, the H-like charge fraction was usually well fitted by a function of the form $f(x)=axe^{-bx^2}$, where $x=E/A$ is the energy per nucleon. Converting from energy/nucleon to ion velocity and requiring that the single vacancy fraction has a peak value of 0.5 at Zv_0 gives

$$F^1_{1s} = \frac{1}{2}\sqrt{e}(v/Zv_0)^2 e^{-(v/Zv_0)^4/2}. \qquad (2)$$

The transient-field parametrization proposed for light ions at high velocity is therefore

$$B_{tf}(v,Z) = AZ^P (v/Zv_0)^2 e^{-(v/Zv_0)^4/2}, \qquad (3)$$

where, if required, AZ^P can be separated into the contributing factors: $AZ^P=13.8Z^P\xi^{+3}$ T. Note that this form specifies the dependence of the field on the ion velocity, leaving only the overall magnitude and the Z dependence as free parameters.

The data in Tables I and II were fitted separately for Fe and Gd hosts under several assumptions. Although the parameters A and P can be strongly correlated, if they are both allowed to vary, the best fit values of P are close to, and consistent with, integer values in all cases. It is reasonable therefore to fix P to an integer value and obtain the best fit to A. Thus a fit to the Fe-host data in Table I having $Z>6$ gives $A=1.82\pm0.05$ T for $P=3$, with a χ^2 per degree of freedom, $\chi^2_\nu=0.60$. For Gd hosts a fit to the data in Table II gives $A=26.7\pm1.1$ T for $P=2$ and $\chi^2_\nu=1.09$.

In view of the disparity in reported field strengths for C in Fe, these data were excluded from the global fit for Fe hosts. The adopted fit for $Z>6$ happens to agree rather well with the data for ^{13}C in Fe (see Fig. 1). This agreement may be fortuitous, however, because the ^{12}C data have been checked in subsequent experiments [16], but the ^{13}C measurements have yet to be confirmed. As shown in Fig. 1, the velocity dependence prescribed by the parametrization gives a good description of the velocity dependence of the ^{12}C data, which is quite well determined experimentally.

As a point of comparison, the data included in the fits to Eq. (3) were also fitted to the empirical linear parametrization, $B_{tf}=aZ(v/v_0)$ [6]. The results are $a_{Fe}=10.9\pm0.6$ T ($\chi^2_\nu=1.8$) for Fe hosts and $a_{Gd}=16\pm1$ T ($\chi^2_\nu=2.9$) for Gd. These parameters are very close to the previously adopted values [24]. Note that the quality of the fit is considerably worse than that obtained with the model-based parametrization, Eq. (3). The fits are compared with each other and the data in Figs. 2 and 3.

The present analysis indicates that the transient fields for Fe and Gd hosts have a different Z dependence. In the linear velocity region below Zv_0 a better description of the data for Fe hosts results ($\chi^2_\nu=0.74$) if the transient field is assumed to vary with Z^2: $B_{tf}(v,Z,\mathrm{Fe})=(0.99\pm0.03)Z^2(v/v_0)$T. This fit is also shown in Fig. 2.

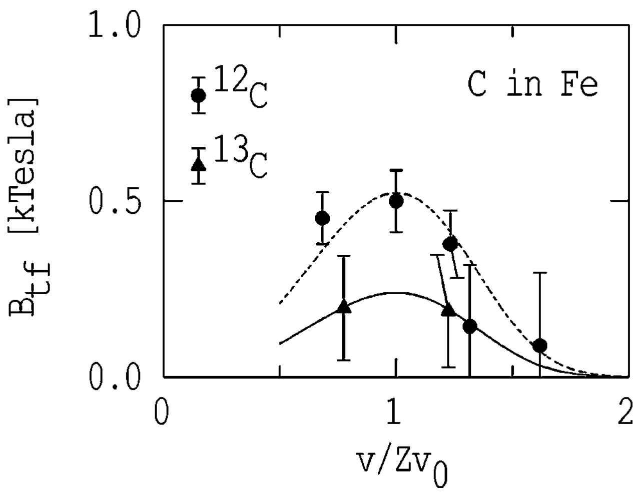

FIG. 1. Experimental transient-field strengths for C in Fe compared with the model-based parametrization in which the velocity dependence is fixed. The solid line indicates the adopted fit for high-velocity light ions with $8 \leqslant Z \leqslant 16$. The broken line is a rescaled fit to the ^{12}C data.

III. PROPERTIES OF THE TRANSIENT FIELD

According to the model on which the present parametrization is based, the transient fields for Fe and Gd hosts have a different Z dependence due to a difference in the behavior of the K-shell polarization. Thus for Fe hosts, the adopted parametrization implies that $\xi_{1s}(\mathrm{Fe}) = 0.133 \pm 0.004$, independent of $Z \geqslant 8$, which is close to the degree of polarization of the outer shells of the host, $2.2/16 = 0.14$ [30]. For Gd hosts the polarization varies inversely with Z: $\xi_{1s}(\mathrm{Gd}) = (1.94 \pm 0.08)/Z$. This also is close to the degree of polarization of the outer shells of the host, $7.2/36 = 0.20$ [30]; for example $\xi_{1s} = 0.24$ for O in Gd, falling to $\xi_{1s} = 0.12$ for S in Gd. It is reasonable to expect a difference between the Z

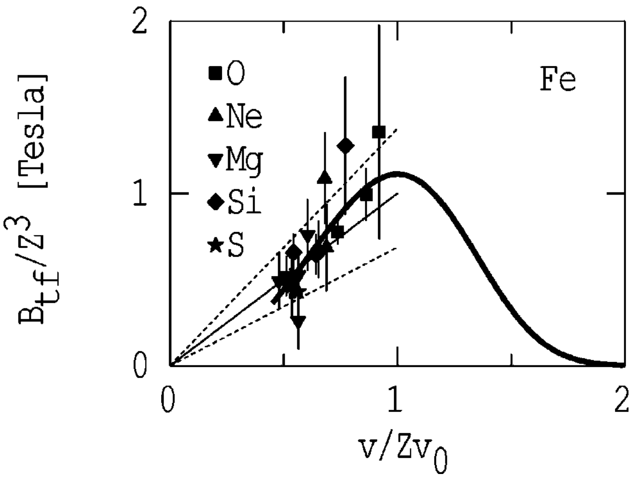

FIG. 2. Fits to transient-field data for high-velocity light ions, $8 \leqslant Z \leqslant 16$, in Fe hosts. Bold line: $B_{\mathrm{tf}}(v,Z,\mathrm{Fe}) = 1.82 Z^3 (v/Zv_0)^2 e^{-(v/Zv_0)^4/2}$ T. Solid line: $B_{\mathrm{tf}}(v,Z,\mathrm{Fe}) = 0.99 Z^2 (v/v_0)$ T. Dotted lines: $B_{\mathrm{tf}}(v,Z,\mathrm{Fe}) = 10.9 Z (v/v_0)$ T, plotted for $Z=8$ (upper) and $Z=16$ (lower).

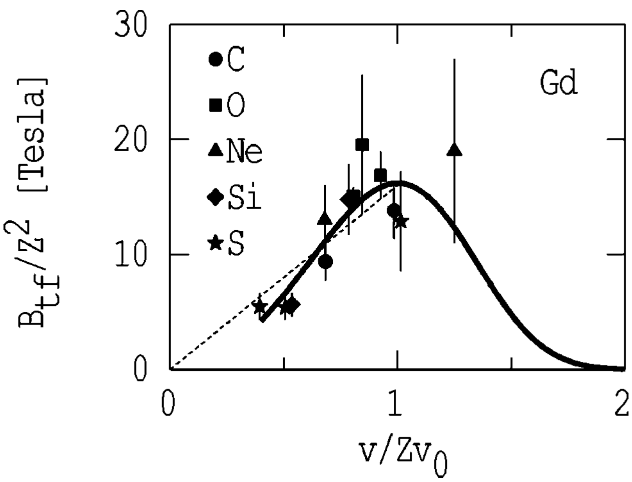

FIG. 3. Fits to transient-field strengths for high-velocity light ions, $6 \leqslant Z \leqslant 16$, in Gd hosts. Bold line: $B_{\mathrm{tf}}(v,Z,\mathrm{Gd}) = 26.7 Z^2 (v/Zv_0)^2 e^{-(v/Zv_0)^4/2}$ T. Dotted line: $B_{\mathrm{tf}}(v,Z,\mathrm{Gd}) = 16 Z (v/v_0)$ T.

dependencies of the transient fields for Fe and Gd hosts due to the polarization-transfer mechanism. Polarization transfer to the K shell is determined by the ratio of the cross section for polarizing K vacancies to the cross section for quenching K vacancies. For ion velocities near Zv_0 and $Z=8$ the electron capture cross sections for Fe and Gd hosts, which can be assumed to dominate the vacancy quenching process, are about equal according to the Brinkman-Kramers (BK) formula [35]. However as Z increases, the BK cross sections at Zv_0 for Gd hosts become significantly larger than for Fe hosts. This difference implies a relative reduction in polarization for Gd hosts at higher Z values in accordance with the adopted parametrizations of the data.

These conclusions concerning the Z dependence of ξ_{1s} largely concur with those drawn in previous work [2,22,31]. However, the present analysis favors a smooth Z dependence for high-velocity $8 < Z < 16$ ions in Fe, whereas an irregular Z dependence has been suggested previously [22].

IV. APPLICATIONS TO *g*-FACTOR MEASUREMENTS ON FAST EXOTIC BEAMS

One of the motivations for the present work is to facilitate g-factor measurements on exotic nuclei produced as fragments in intermediate-energy reactions [36]. To this end, the predicted transient-field precessions were estimated for several exotic nuclei traversing Fe and Gd hosts under various conditions. The calculated transient-field precession angle per unit g factor is $\phi = \Delta\theta/g$, where g is the nuclear g factor and $\Delta\theta$ is the precession angle of the nuclear spin to be observed in an experiment. ϕ is related to the strength of the transient field by

$$\Delta\theta/g = \phi = -\frac{\mu_N}{\hbar}\int_0^{T_e} B_{\mathrm{tr}}(t) e^{-t/\tau}\, dt, \tag{4}$$

where T_e is the time at which the ion exits from the ferromagnetic foil. Examples of the predicted $\Delta\theta/g$ values for 10

TABLE III. Transient-field precessions predicted by the adopted parametrizations. $E_i(E_e)$ are the energies with which the ion enters into (exits from) the ferromagnetic host. Formulas for the evaluation of the average ion velocity, $\langle v/v_0\rangle$, the average transient-field strength, $\langle B_{\mathrm{tf}}\rangle$, and the effective interaction time, t_{eff}, may be found in Ref. [37].

Ion	τ(ps)	E_i(MeV)	E_e(MeV)	$\langle v/v_0\rangle$	$\langle B_{\mathrm{tf}}\rangle$(kT)	t_{eff}(ps)	$\Delta\theta/g$(mrad)
				Fe hosts			
$^{22}_{10}$Ne	3.6	220	50	15.9	0.33	1.38	22
$^{32}_{12}$Mg	20	320	80	15.7	1.14	1.71	93
$^{38}_{16}$S	5	380	100	15.8	4.06	1.13	220
$^{38}_{16}$S	5	760	200	22.9	2.00	2.02	193
				Gd hosts			
$^{22}_{10}$Ne	3.6	83	49	11.0	1.52	0.49	36[a]
$^{22}_{10}$Ne	3.6	220	50	16.0	0.47	1.82	41
$^{32}_{12}$Mg	20	320	80	15.7	1.39	2.43	161
$^{38}_{16}$S	5	380	100	15.9	3.70	1.55	275
$^{38}_{16}$S	5	760	200	23.0	1.77	2.57	217

[a]This example corresponds to experimental conditions described in Ref. [36].

and 20 MeV per nucleon beams of ^{22}Ne, ^{32}Mg, and ^{38}S entering magnetized Fe and Gd hosts are presented in Table III. Additional calculations were performed to ensure that the following conclusions are not critically dependent on the extrapolation into the region beyond Zv_0. To satisfy this requirement, it was found necessary to assume only that the transient field varies smoothly with ion velocity.

It is evident from Table III that appreciable transient-field precessions can be achieved for intermediate-energy ions using either Fe or Gd hosts, which strongly suggests the feasibility of transient-field g-factor measurements on rapidly moving excited exotic-nuclei. In order to achieve sufficiently large precessions, however, the ions *must* be slowed to velocities around Zv_0 where the magnitude of the transient field is maximal. Since the slowing process takes time, the nuclear excited-state lifetime must generally exceed several picoseconds—otherwise the states may decay before the highest fields are encountered.

As a point of comparison with measurements on stable isotopes, $\Delta\theta/g\sim 10$ mrad was observed for the $\tau=0.25$ ps, 2_1^+ state in ^{32}S traversing Fe with an effective interaction time $t_{\mathrm{eff}}=0.11$ ps [18]. The increase in the precession angles, by an order of magnitude for many of the examples in Table III, stems from the increase in t_{eff} that can be achieved with intermediate-energy secondary-fragment beams when the nuclear lifetime exceeds the time the ion spends within the ferromagnetic medium.

V. CONCLUDING REMARKS

The parametrizations of the transient-field strength presented here should be sufficiently accurate to plan g-factor measurements on exotic fragments near the "island of inversion" [38] around ^{32}Mg. However, extreme caution is required if these parametrizations are used outside the Z regime considered in the fit. For example, the observed transient field strength for Cr ions ($Z=24$) in Gd [39] is smaller by a factor of 5 than implied by an extrapolation of the present fit. This reduction can be attributed to an effect of the heavy beam on the magnetization of the host [20], but there may also be a contribution from changes in the effectiveness with which polarization is transferred from the ferromagnet to K vacancies of the swiftly moving ion.

Despite the considerable effort that has been invested already in studying the behavior of the transient field for light ions, the summary of data and the results of the present fits presented in Figs. 2 and 3 show that there remains a need for further precise transient-field data in the high-velocity regime, especially for ions moving with velocities beyond the K-electron velocity, Zv_0. The proposed parametrization uses the current understanding about the origin of the field to make a model-based extrapolation of the transient-field strength into this region where the experimental data are scant. Should major departures from the parametrization be exposed in future experimental studies, they will point to new or unanticipated phenomena in the mechanisms that give rise to the transient field.

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