K-shell vacancies carried by swift O and Si ions inside ferromagnetic hosts

Lokesh C. Tribedi, K.G. Prasad, and P.N. Tandon
Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005, India
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The single and double K-shell vacancy fractions for swift O and Si ions inside Fe and Gd foils have been measured using the probe layer technique. The measurements are carried out at velocities varying from 7.5 to $13.5v_0$ for Si ions and at a velocity of $7.8v_0$ for oxygen ions ($v_0 = \alpha c$ where α is the fine-structure constant and c is the speed of light). It is shown that all such available data for light ions fall on a smooth curve when plotted against the reduced velocity of the ion. These values are used along with the existing transient magnetic field data to derive the electron spin polarization acquired by the ions traveling inside ferromagnetic hosts. The degree of polarization is shown to decrease with the atomic number of the ions. This observation is, however, in disagreement with recent theoretical calculations.

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I. INTRODUCTION

When a highly charged energetic ion travels through a solid, because of the continuous electron capture and loss processes, the probability of having a vacancy in its K shell changes continuously until equilibrium charge distribution is attained. Additional features, however, are observed if the medium through which the ion travels is a polarized ferromagnet. A transfer of electron polarization from the ferromagnet to the moving ion has been observed, which, as a consequence of the oriented hyperfine interaction ultimately leads to the strong "positive" magnetic fields at the nuclei of the moving ion. These fields, known as the transient magnetic fields (TF), are of several thousands of Tesla in magnitude and atomic in origin. They are attributed to the polarization of the bound electrons of the moving ion [1–5]. In the case of light ions the observed TF arise predominantly from the polarization of unpaired K electrons and are shown to be directly correlated to the number of K-shell vacancies carried by the ions inside the ferromagnet [6]. The TF for hydrogenic ions, neglecting smaller contribution from higher atomic shells, can be expressed as [2–4]

$$B_{\mathrm{TF}} = B_{1s} q_{1s} p_{1s}, \tag{1}$$

where B_{1s} is the hyperfine field due to a $1s$ electron of the ion and q_{1s} the fraction of such ions carrying single K-shell vacancies. The quantity p_{1s} is the acquired degree of polarization in the K shell of the ion and can also be expressed as the fraction of unpaired K electrons of the ion which are spin polarized. The mechanism giving rise to polarization transfer is not yet understood although some models are proposed [4]. To develop a self-consistent quantitative theory for TF it is necessary to have systematic measurements of the polarization degree p_{1s} as a function of the velocity (v_1) and atomic number (Z_1) of the ions.

At ion velocities close to $Z_1 v_0$ (where $v_0 = c/137$), the quantity q_{1s} approaches a value of 0.5 and hence p_{1s} can be obtained reliably from the measured TF at these ions. Indeed, large values for p_{1s} in the range 10 to 30% have been derived in this way for some light ions at these high velocities in Fe and Gd hosts [2,5–9]. However, for obtaining p_{1s} values at lower ion velocities, it is absolutely essential to measure the q_{1s} value at that velocity. This has been recently stressed by us from q_{1s} measurements for S ions [10] in a Gd host where one observes q_{1s} to be substantially larger than the expected value. Using these measured values for q_{1s} it is now seen that p_{1s} decreases gradually with increasing atomic number of the ion [4, 5]. Several TF measurements for light ions at velocities considerably smaller than $Z_1 v_0$ have been reported; see, e.g., Ref. [11] for recent measurements on Si ions. It is therefore desirable to have q_{1s} measurements at these velocities to obtain reliable p_{1s} values. This would provide important information on the velocity dependence of p_{1s}. We have measured q_{1s} values for Si ions in ferromagnetic hosts like Fe and Gd at ion velocities varying between 7.5 and $13.5v_0$ and for O ions in Fe, Ni, and Gd hosts at $7.8v_0$ using the probe layer technique. The selection of ions and their approximate velocities were to some extent guided by the available TF data. The measured q_{1s} values were used to derive p_{1s} values. The main emphasis in the present investigation was therefore to deduce reliable values of p_{1s} at these ions and (making use of the existing data) to examine its variation with Z_1 and v_1. Any systematic trend would be very useful in developing a quantitative theory of TF. Dybdal and Rud [12] have also measured q_{1s} values for light ions at velocities lower than in the present measurements.

Recently, quantum beat measurements on spin polarized electrons in swift oxygen ions emerging from magnetized Fe, Ni, and Gd layers have been carried out [13, 14]. These measurements exhibit predominantly the hyperfine interaction frequencies corresponding to the $1s$ electron configuration and thus also provide direct information about the fraction of ions with single K vacancies after coming out of the ferromagnetic layers into vacuum. This enables one to have a comparison of the electronic configuration inside and outside the solid. We have also attempted to examine in the present studies how the q_{1s} values measured inside the ferromagnet differ from those

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outside the foils in vacuum using the available data on equilibrium charge distributions.

II. MEASURING TECHNIQUE AND EXPERIMENTAL DETAILS

The experimental setup, measuring technique, and data analysis have been discussed elsewhere [10] and hence only the necessary details are provided here.

It has been shown by Hopkins [15] that the target K x-ray yield rises dramatically when incident projectiles carry vacancies in their K shell. This has been explained in terms of the direct transfer of the target K electrons into the vacant K shell of the projectile. This feature of the ion-atom collision has been exploited in the probe layer technique to obtain the projectile K vacancies inside the target. In these measurements, therefore, the projectile, towards the end of its path in the target material, is made to encounter a thin probe layer. The incident K-shell vacancy configuration, in the swift ion, changes continuously inside the target material due to electron capture and loss processes. The residual K vacancies on the projectile at the end of the target get transferred efficiently to the probe atoms giving rise to probe K x rays. The resulting probe K x rays thus provide direct information on the vacancies carried by the projectile inside the target.

The probe material is generally chosen such that it is highly sensitive to projectile K vacancies, i.e., having a large K-K transfer cross section. The average probe sensitivity is characterized by parameters $\overline{\alpha}$ and $\overline{\beta}$, defined by

$$\overline{\alpha} = \overline{\sigma}_{K1}/\overline{\sigma}_{K0} \text{ and } \overline{\beta} = \overline{\sigma}_{K2}/\overline{\sigma}_{K0} \ , \tag{2}$$

where $\overline{\sigma}_{Ki}$, with i=0, 1, and 2, are the average probe K x-ray production cross sections with incident projectile having i K-shell vacancies. The average probe x-ray yield per atom, when the projectile traverses a thickness x of the target before encountering the probe, is represented, in a three-component model [16], by

$$\overline{\sigma}^i_K(x) = \overline{\sigma}_{K0}\left[1 + (\overline{\alpha} - 1)F^i_1(x) + (\overline{\beta} - 1)F^i_2(x)\right] , \tag{3}$$

where $F^i_1(x)$ and $F^i_2(x)$ are the fractions of ions having single and double K-shell vacancies created at the projectile when it has traversed a target of thickness x. These quantities are functions of the cross sections σ_{jf} ($j, f = 0, 1, 2$) which describe for $j < f$ the vacancy creation and for $j > f$ the quenching cross sections for transitions from a state with j K vacancies to a state with f K vacancies on the projectile [16]. The quantities σ_{K0}, α, and β were obtained from a study of the probe K x-ray intensities with projectiles carrying 0, 1, and 2 initial vacancies in their K shell [see Eq. (2)] and were used as frozen parameters in the fitting procedure. The quantity $\overline{\sigma}^i_K(x)$ is measured for various thicknesses of the target with a thin probe layer (composite targets) with projectiles carrying 0, 1, and 2 initial vacancies in their K shell. The quantities σ_{jf} are then obtained from fits to Eq. (3).

The equilibrium single and double K-shell vacancy fractions, $F_1(\infty)$ [same as q_{1s} in Eq. (1)] and $F_2(\infty)$, respectively, are then obtained using the following equations which are derived under the approximations [10,12] as discussed in Sec. III,

$$F_1(\infty) = \frac{2(\sigma_{12}/\sigma_{10})}{(1 + \sigma_{12}/\sigma_{10})^2} \text{ and } F_2(\infty) = \frac{(\sigma_{12}/\sigma_{10})^2}{(1 + \sigma_{12}/\sigma_{10})^2}. \tag{4}$$

The target K x-ray yield is also sensitive to the presence of a vacancy in the K shell of the ion and is given by

$$\sigma^i_K = \frac{\sigma_{K0}}{x}\int_0^x \left[1 + (\alpha - 1)F^i_1(x) + (\beta - 1)F^i_2(x)\right] dx. \tag{5}$$

This is an integral method and has also been used in some cases to derive the $F_1(\infty)$ and $F_2(\infty)$. In this case σ_{K0} and the sensitivity parameters α ($= \sigma_{K1}/\sigma_{K0}$) and β ($= \sigma_{K2}/\sigma_{K0}$) correspond to the values in the limit of zero target thickness and are used as the fitting parameters.

Oxygen and silicon ions at various energies were obtained from the BARC-TIFR 14UD pelletron accelerator at Bombay. A post accelerator foil stripper was used to obtain the incoming beam in different charge states [17]. A 1–2-μg/cm^2 probe layer of SiO and Ti for measurements with O and Si ions, respectively, was evaporated on the carbon backing (10–20 μg/cm^2). The targets of Fe, Ni, and Gd, of varying thicknesses (1–30 μg/cm^2) were then evaporated on the probe layer. In each composite target the probe layer was sandwiched between the ferromagnetic target and the carbon backing, and the ferromagnetic layer faced the incident beam. For measuring vacancies inside the Gd host Ti was used as a probe material for both the ions. The probe thickness was kept the same for all the composite targets of a given kind. The thickness of the ferromagnetic and the probe layers were measured to an accuracy of 5–10 % from the Rutherford scattered particles detected in a Si surface barrier detector placed at 60° with respect to the beam direction. For normalization purpose, the charge was collected from the entire chamber which was electrically isolated. In addition, the Rutherford scattered particles from a Au foil placed 6 cm downstream (from the target) were detected at 120° to the beam and this was used to provide a check on the charge normalization. Both the procedures gave identical results to within about 5%. Two x-ray detectors having resolution of 170 eV at 5.9 keV and whose efficiencies were measured earlier using PIXE and calibrated radioactive sources [18], were mounted face to face at 90° to the beam direction. The detectors were inside the vacuum chamber for measurements with the SiO probe and outside the chamber, isolated with a 25-μm Be window, for measurements using the Ti probe. The count rate in the detectors was restricted to less than 500 counts/sec using suitable absorbers to cut down the Si projectile x rays. All four spectra, two from the x-ray detectors and two from the particle detectors, were recorded simultaneously on a PC-based data acquisition system.

III. DATA ANALYSIS AND RESULTS

Typical x-ray spectra obtained using 25-MeV O ions with composite targets and targets having only the probe are shown in Fig. 1. Similar quality of spectra were also obtained with Si ions. The x-ray peak from the thin probe layer is very clean with very little background in each of the spectra. At some energies the radiative electron capture (REC) photopeak interferes with the probe K x-ray lines. This intensity was negligibly small and was taken into account in the final analysis. The intensity of the probe x ray was obtained by integrating the counts under the K x-ray peak ($K\alpha$ in the case of Ti) after subtracting the general background obtained by using a C target at the same bombarding energy of the ion. A Gaussian peak fitting procedure with linear background subtraction was adopted.

The quantities $\overline{\sigma}_{Ki}$ for the probe were determined using targets having only the probe layers. The sensitivity parameters $\overline{\alpha}$ and $\overline{\beta}$ were determined from these studies and are shown in Fig. 2 for O and Si ions. The target thickness dependence of the average probe x-ray cross sections $\overline{\sigma}^{i}_{K}(x)$, obtained from the normalized intensities using composite targets, are shown in Fig. 3. These data were fitted to Eq. (3). For fitting of the probe and composite target data it was assumed that σ_{20} and σ_{02} can be neglected in comparison to σ_{01}, σ_{10}, σ_{12}, and σ_{21}, and

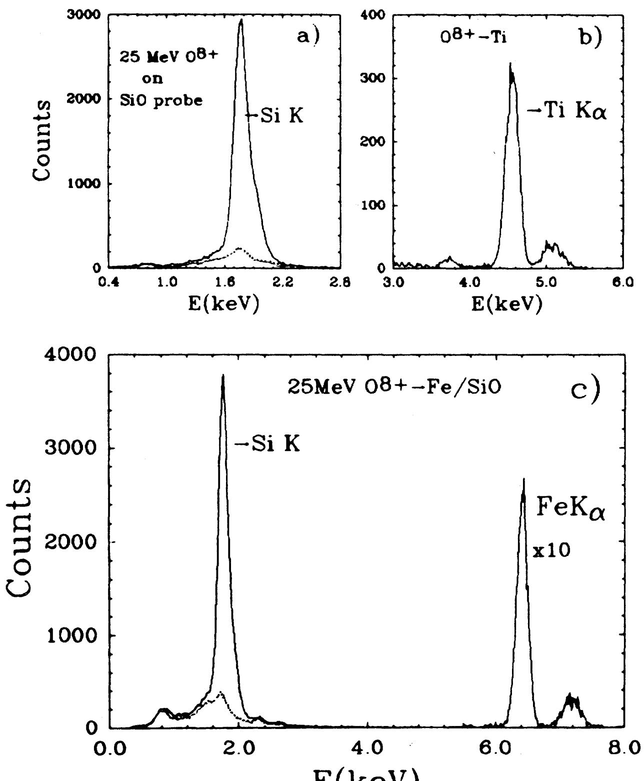

FIG. 1. (a) A part of the x-ray spectra obtained by bombarding 25-MeV $O^{8}+$ ions on a 1.5-μg/cm^2 SiO probe layer on a carbon backing. The dashed curve shows the background spectrum using a self-supporting C target of similar thickness. Apart from the REC x rays the background counts between 1.2 to 2.2 keV also consist of characteristic x rays of the impurity element like Si present in the C foil. (b) Similar spectra using a 1.5-μg/cm^2 Ti probe on a carbon backing, and (c) using a composite target consisting of Fe+SiO on a carbon backing. The dashed curve shows the spectrum without the probe layer.

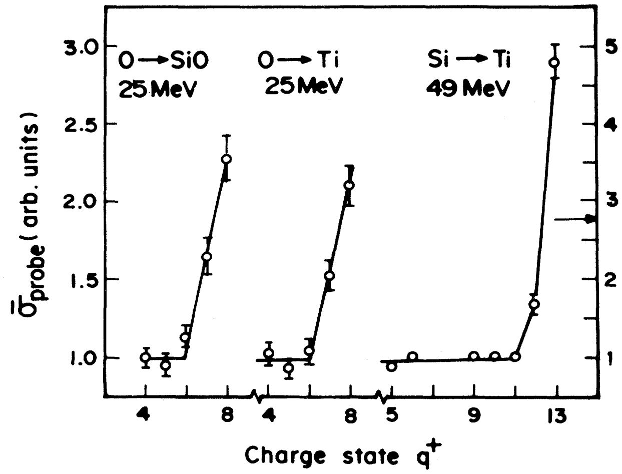

FIG. 2. The charge state dependence of the probe x ray yields for 25-MeV oxygen beam bombarding on a 1.5-μg/cm^2 (a) SiO probe, (b) Ti probe, and (c) for 49-MeV Si ions on a Ti probe.

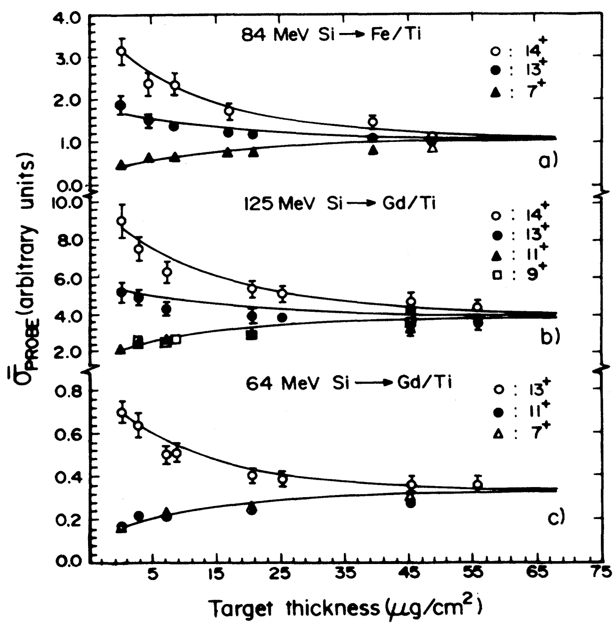

FIG. 3. Target (Gd or Fe) thickness dependence of the average probe K x-ray production cross sections obtained from the composite targets bombarded with ^{28}Si projectiles with different initial charge states. The figure shows the data at 64, 84, and 125 MeV along with the fits (solid line) to the three-component model (see text).

that $\sigma_{01} = 2\sigma_{12}$ and $\sigma_{21} = 2\sigma_{10}$ (see Refs. [10, 19] for detailed fitting procedure). The data at a given beam energy and corresponding to different charge states were fitted simultaneously to the same set of parameters. In each case the fitting was also performed by allowing a small variation in the values of $\overline{\sigma}_{K0}$, $\overline{\alpha}$, and $\overline{\beta}$ around the corresponding values for the probe itself. The values of the fitted parameters σ_{10} and σ_{12} thus obtained were used to evaluate the equilibrated K-shell vacancy fractions using Eq. (4). These values are shown in Table I. For low-velocity Si ions, where double vacancies are negligibly small, the data were fitted using a two-component model. It should be mentioned here that there could be some systematic errors in the quantities σ_{01} and σ_{12} since they are obtained as the fitting parameters. These are also quite sensitive to the choice of the probe parameters. However, the ratios of these cross sections were found not to be very sensitive to the choice of the fitting parameters as well as the fitting procedure and thus resulting in more accurate values for the vacancy fractions [see Eq. (4)]. The q_{1s} values were also deduced from the thickness variation of the target K x-ray yield. The values obtained were in good agreement with those obtained using the probe layers technique.

The q_{1s} values for Si in Fe-Gd have also been measured by Dybdal *et al.* [12] at some velocities and their values are in good agreement with our results.

IV. DISCUSSION

The q_{1s} fractions are dependent on the vacancy creation and quenching cross sections σ_{01} and σ_{10}, respectively, which in turn depend on the ion velocity. At low ion velocities these cross sections are known to be affected by the promotion of electrons to continuum states via the formation of molecular orbitals (MO's). Indeed, extremely large values for q_{1s} reported for oxygen ions at velocities between 2 and $5v_0$ inside Fe hosts [12], are attributed to the MO effects. These results were confirmed by the observation of large TF associated with the K shell of oxygen ions in an Fe host (see, e.g., Ref. [6] and references therein). In order to see systematic trends in q_{1s} values for any projectile-host combinations we have shown in Fig. 4 the variation of the measured q_{1s} values as a function of the reduced ion velocity v_1/Z_1v_0. We have excluded the data for oxygen ions below $4v_o$ as they are affected by MO effects. For completeness all the measured values of q_{1s} in the hosts Fe, Co, Ni, and Gd are taken including our earlier data on S ions [10,12]. We have shown the data using $3d$ magnetic hosts and Gd separately in Figs. 4(a) and 4(b), respectively, because of their widely different atomic numbers. Two prominent features are apparent from these plots, namely, the nearly smooth variation of q_{1s} as a function of the reduced ion velocity irrespective of Z_1, and slightly lower values for q_{1s} for Gd host at a given reduced velocity as compared to the $3d$ ferromagnet data. Though we have data only up to S ions, we expect the vacancy fractions for still heavier ions also to fall on this line provided they are unaffected due to MO effects. This smooth variation with q_{1s} will therefore enable one to deduce reliable values for p_{1s} [Eq. (1)] from the available TF data at reduced velocities between 0.5 and 1 (see below). The lines drawn through the data points are linear fits to a limited set of data lying between reduced velocities of 0.4 and 0.8. The variation of the measured q_{1s} values with those derived using the fitted line is not more than 10% in most cases. To make use of these curves one has to ascertain that the measured TF values are only from the K-shell vacancies at the ion. We have used this curve for the q_{1s} value at a given reduced velocity to obtain p_{1s} from the available TF data for light ions which are known to arise from the K shell of the ions.

We have also shown in Fig. 4, the H-like equilibrium charge state fractions for O, F, Si, and S ions emerging out in vacuum through thin foils of Fe, Ni, and Sm. The data are taken from Refs. [20,21]. Assuming that these ions are in their respective ground states, this fraction

TABLE I. Equilibrium values of the single and double K-shell vacancy fractions for Si and O ions at various ion velocities inside Fe, Ni, and Gd hosts. The total capture σ_c ($=2\sigma_{10}$) and loss cross sections σ_l ($=2\sigma_{12}$) are also shown. The errors in the cross sections are about 20–25 %.

Ion	Host	Probe	v_1/v_0	$F_1(\infty)$%	$F_2(\infty)$%	σ_l(Mb)	σ_c(Mb)
Si	Gd	Ti	7.5	12(1)		1.9	38.6
			8.4	20(2)		3.4	28.0
			9.6	25(2)		4.8	27.0
			11.0	28(3)	2.9(3)	5.4	26.4
			13.4	40(4)	7.6(8)	7.6	20.0
Si	Fe	Ti	7.5	22(2)		.36	2.4
			8.4	27(3)	2.6(2)	2.3	12.0
			9.6	36(3)	5.6(6)	3.3	10.6
			11.0	38(3)	6.8(6)	2.6	7.4
			13.4	50(3)	23(2)	4.2	4.6
O	Gd	Ti	7.8	50(2)	25(1)	66.0	66.0
O	Fe	SiO	7.8	46(2)	12(1)	24.0	44.0
O	Ni	SiO	7.8	46(2)	12(1)	15.3	28.0

represents q_{1s} data for ions after emerging from a thin target into vacuum. These fractions are found to be much smaller than the measured values inside the ferromagnets over the entire range of velocity scale investigated (Fig. 4). The discrepancies are very large particularly at reduced velocities below 0.6 where one sees a large fraction of ions having vacant K shells inside the ferromagnet. These data suggest that the ions are predominantly in their excited states inside the solid, thereby increasing the q_{1s} fraction. This argument is further supported from quantum beat measurements (see below) as well as large TF originating from K shell at low ion velocities [6].

Detailed quantum beat measurements of the atomic $1s$ hyperfine levels have recently been performed for swift oxygen ions emerging through thin ferromagnetic layers of Fe, Ni, and Gd at velocities between 6.6 and $7.2v_0$.

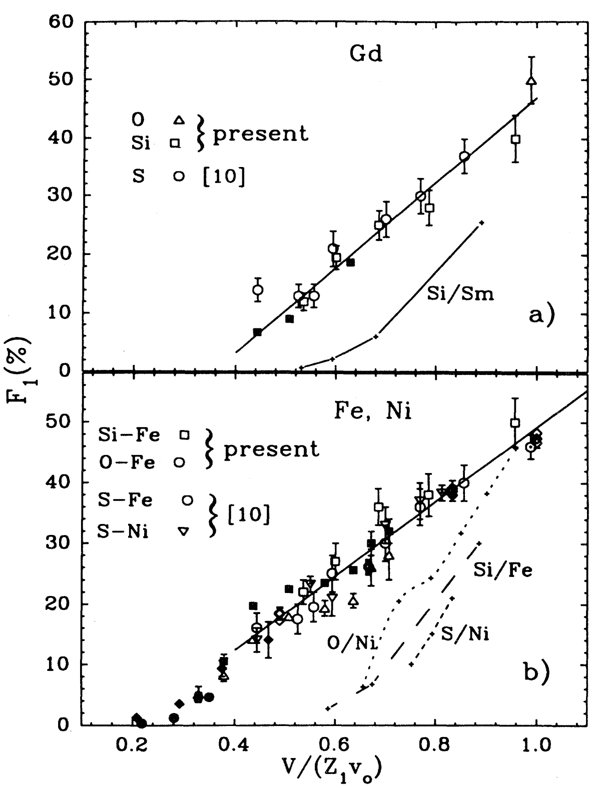

FIG. 4. The single K-shell vacancy fractions, $F_1(\infty)$ ($\equiv q_{1s}$), of swift light ions in Gd (a) and Fe (b) hosts against the reduced velocity v_1/Z_1v_0 of the ions. Along with the new data (indicated in the figure) all the other existing data are taken from Refs. [10] and [12]. In (a) the filled squares (S) and in (b) the filled circles (S) and squares (Si), the open (F) and filled (Mg) diamonds, and the open triangles (Si) and the dotted inverted triangles (O) are taken from Ref. [12]. The solid line denotes a linear fit to the data in the reduced velocity range of 0.4 to 0.8. The + and × symbols denote the H-like equilibrium charge state fraction after the ions emerge out in vacuum through the indicated foil materials. The lines are drawn to guide the eye. These data are taken from Refs. [20] and [21].

The 3^- nuclear state of ^{16}O at 6.13 MeV was used as the probe [13,14]. These measurements, which are sensitive to the electronic configuration of the recoiling ions, are carried out within a flight time of about 150 ps of the ions in vacuum. A predominant fraction of these ions are observed to be either in their ground state or in excited states having comparatively longer lifetimes. The total fraction of ions observed in the hydrogenlike ground-state configuration in these measurements, varying between 26% and 32% through Fe, Ni, and Gd layers [14], is in reasonably good agreement with the measured charge state distribution outside the foils [21] but lower than the measured K vacancy fractions inside the ferromagnet (see Fig. 4). Similar measurements were also carried out using ^{20}Ne and ^{24}Mg ions recoiling out in vacuum at a velocity of $8.2v_0$ through thin layers of carbon [22]. The fraction of H-like ground-state electron configuration in both the cases [26(8) and 16(2) for Ne and Mg, respectively] are consistent with the available charge state distribution data outside the foil. The measured K vacancy fractions inside the ferromagnet will also have a contribution from He-like ions having one electron in an excited state. This is also confirmed from the quantum beat measurements in all three cases of O, Ne, and Mg ions which indicate a sizable contribution from excited He-like ions. The larger K-shell vacancy fractions observed inside the ferromagnet are thus consistent with the electronic configuration deduced from quantum beat measurements at high ion velocities.

We have not made any attempts to quantitatively calculate the vacancy fractions $F_1(\infty)$ and $F_2(\infty)$ using theoretical estimates for σ_{01} and σ_{10} as one knows that there are large discrepancies between the theoretical and experimental results [10]. The capture cross section σ_c ($= 2\sigma_{10}$) includes the capture from target K, L, M,... shells, i.e., $\sigma_c = \sigma_{KK} + \sigma_{LK} + \sigma_{MK}$. It is known that the perturbative calculations such as the Oppenheimer-Brinkman-Kramers-Nikolaev (OBKN) or the perturbed-stationary-state (PSS) approaches do not give reliable cross sections. We have recently shown [19, 23] that the close-coupling calculations [24] can reproduce the K-K transfer data for near symmetric collision systems. But such calculations for L-K or M-K transfer are difficult and hence are not easily available. It is also shown [10] that the derived electron loss cross sections σ_l ($= 2\sigma_{01}$) can only be explained by the first-order Born calculations provided one includes some empirical factors. It is, therefore, desirable to have *ab initio* calculations in order to understand the capture and loss cross sections as well as the vacancy fractions measured in the present work. Furthermore, as discussed above, we expect the observed ratios, (σ_l/σ_c), and hence the q_{1s} values to be in better agreement with the calculations than the cross sections themselves.

Several TF measurements in Fe and Gd hosts have been reported at ion velocities varying between 7.5_{v_0} and $13.0v_0$ for Si ions (see Table II and Refs. [11,25–27] and between 2_{v_0} and $7.5v_0$ for O ions [6, 28, 29]. The data relevant to present measurements are summarized in Table II. It does not include high velocity Si ion data because of the inherent attenuations in TF due to heavier

TABLE II. Summary of the available TF data for O and Si ions in Fe and Gd hosts relevant to the present data. The values deduced for p_{1s} using the derived q_{1s} values from Fig. 4 are also given [$q_{1s} \equiv F_1(\infty)$]. The TF data at $13.4v_0$ for Si in Fe and Gd are not used because of the attenuations in TF [27,28].

Ion	Host	$\bar{v}/v_0$	B_{TF} (MG)	Ref.	$\bar{q}_{1s}$	p_{1s}
Si	Fe	11.0	35.0(11)	[26]	0.36	0.21(7)
Si	Fe	9.0	17.7(32)	[11]	0.27	0.14(3)
Si	Fe	7.6	18.0(30)	[25]		
Si	Fe	7.4	13.1(24)	[11]		
		average	15.0(19)		0.21	0.16(2)
Si	Gd	11.0	29.0(60)	[27]	0.31	0.20(4)
Si	Gd	7.5	11.0(20)	[25]	0.13	0.18(4)
O	Fe	6.9	5.09(77)	[6]	0.41	0.14(2)
O	Fe	5.9	3.97(37)	[6]		
O	Fe	5.5	4.43(107)	[6]		
		average	4.02(35)		0.32	0.15(2)
O	Gd	7.4	10.8(13)	[6]	0.41	0.31(5)
O	Gd	6.5	11.3(13)	[29]		
O	Gd	6.4	9.31(57)	[6]		
		average	9.63(52)		0.33	0.34(4)

ions used in the measurements [27]. All these TF measurements were carried out in velocity differential conditions where not very significant changes in the ion velocity and hence electronic configuration take place during the interaction time [2]. Because of the small interaction time chosen for the nuclear state inside the ferromagnet, these measurements are sensitive to the TF originating from a single vacancy in the K shell of the ion. Moreover, as the contribution from higher atomic shells of the ion decreases as $1/n^3$, where n is the principal quantum number of the atomic shell, one could neglect these small contributions and therefore assume that the TF are associated with single K-shell vacancy at the ion. The value of p_{1s} can therefore be deduced with the help of Eq. (1), if q_{1s} is known.

The p_{1s} values have been deduced for C, O, Ne, Mg, Si, and S ions in Fe and Gd hosts from the measured TF at velocities close to Z_1v_0 and also much below this velocity [3,5]. It has also been shown in the case of O and C ions, where TF data are available at a few velocities, that p_{1s} seems to be independent of the ion velocity [6]. The limited results for p_{1s} in the present analysis (see Table II) also agree with this observation. A decrease in p_{1s} with Z_1 was first indicated from our recent measurements on S ions [10]. Such a trend is also apparent considering all the light ion data in Fe and Gd hosts, though there is a considerable amount of scattering in the case of the Fe host [4,5]. In view of the presently established smooth variation of q_{1s} with the reduced velocity in Fe and Gd (Fig. 4), we have recalculated the p_{1s} values using the q_{1s} values from the linear fits shown in Fig. 4. These values are shown in Fig. 5 as a function of Z_1 in Fe and

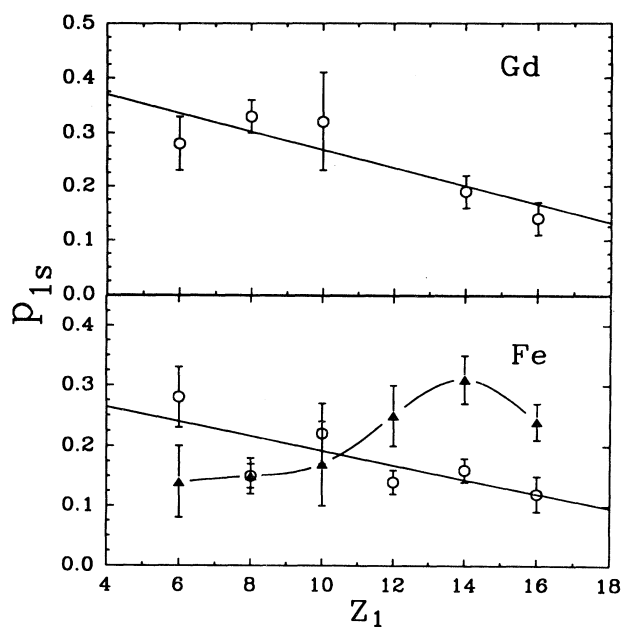

FIG. 5. The values of p_{1s} obtained using the q_{1s} values from Fig. 4 for Gd (upper panel) and Fe (lower panel). The lines drawn are to guide the eye. The calculated values of p_{1s} shown by the triangles joined by broken lines are taken from Ref. [4]. The errors in these calculations stem from the use of experimental capture and loss cross sections.

Gd hosts. We have taken the weighted average of the deduced value of p_{1s} wherever it is available at more than one velocity of the ion assuming p_{1s} to be velocity independent. There are small changes compared to the values deduced by Speidel [5] but the overall decreasing trend of p_{1s} with Z_1 persists. In fact, the scatter of the data in the case of the Fe host are very much reduced and a smooth decreasing trend can be observed.

Theoretical efforts to understand TF to arise from the scattering of quasifree spin polarized electrons of the ferromagnet by the ion probe led to underestimation of the TF [3]. However, recent refined calculations considering the electrons to be localized do explain the magnitude of the TF [4]. Though the magnitudes of the polarization effects are well accounted, however, the observed decreasing trend with Z_1 is in disagreement with these calculations (see Fig. 5).

V. CONCLUSIONS

The single and double K-shell vacancy fractions for Si and O ions in Fe and Gd hosts have been measured using the probe layer technique. These values, along with the earlier available data for light projectiles, are shown to fall on a smooth curve when plotted against the reduced velocity of the ion. It is thus possible to obtain the q_{1s} values for these ions at lower velocities much more reliably. Furthermore, a comparison of the measured q_{1s} values with similar data on hyperfine frequencies from quantum beat measurements suggest a large fraction of the ions to be in excited state inside the foil. The degree of spin polarization (p_{1s}), giving rise to strong transient magnetic fields, was calculated using these q_{1s} values along with the existing TF data. The derived values of p_{1s} show a decreasing trend with Z_1 for Fe and Gd hosts. These observations are in contradiction to the recent theoretical predictions.

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