Evidence for Spin-Polarized Electrons of Highly Stripped Fluorine Ions Emerging from Thin Ferromagnetic Layers

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Spin polarization of 1s electrons has been observed for single-electron F ions on emergence from magnetized thin Fe layers into vacuum by use of the perturbed-angular-correlation technique on the isomeric ^{19}F$(5/2^+)$ state as a probe. The mean degree of polarization observed, $p_{1s}=0.10(3)$, is consistent with values relevant to measurements of transient magnetic fields.

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When energetic ions travel through magnetized ferromagnetic layers electrons of inner-shell vacancies become polarized, giving rise to strong oriented hyperfine fields at the nucleus.[1]

Nuclear-spin precessions following the hyperfine interaction (HFI) in these transient magnetic fields (TF) have been most effectively used for measurements of magnetic moments of short-lived nuclear states, thus contributing to the understanding of their particular structure.[2]

A systematic study of the polarization of 1s electrons in TF measurements for light ions has provided reliable data which for the first time allow to explore specific polarization mechanisms.[3] Values obtained for the degree of polarization vary between 0.14 and 0.28 for Fe and having a rather constant value of 0.24 for Gd host. These data have been well explained with spin-exchange scattering as the most likely polarization mechanism. This interpretation has now gained more importance by recent results of refined calculations of the relevant spin-flip cross sections.[4]

In view of the appreciable polarization which the ions receive while they move inside the ferromagnet, one would expect comparable values after their emergence into vacuum, unless depolarizing interactions at the surface destroy the effect. Several attempts have been made in the past to search for electron polarization after traversal of the ions through a ferromagnet (see, e.g., Refs. 5 and 6). So far only one successful experiment has been reported[7] in which strong tensor polarization was observed for deuterium atoms after channeling through a magnetized monocrystalline Ni foil. No polarization, however, was found with use of a polycrystalline foil.

The present report describes a set of measurements which for the first time show clear evidence for substantial polarization of 1s electrons attached to F ions as they emerge at high velocity from magnetized thin polycrystalline Fe layers into vacuum. One should note that for simple probes like single-electron ions the formalism of perturbed γ-angular correlations allows reliable predictions of the observable effects. The situation is only slightly complicated by the presence of fully stripped and two-electron ion fractions.

The measurements employ the perturbed-γ-angular-correlation technique with the long-lived ^{19}F$(5/2^+)$ state ($\tau=129$ ns, $g=+1.442$) as a probe, where strong perturbations are associated with the HFI between the nuclear spin I and the electron spin J of the moving ion. To detect the electron polarization by this technique in the hard-core limits of perturbations, one requires the nuclear spin also to be polarized, which is achieved by Coulomb excitation. The probe state at 197 keV was populated by the scattering of a ^{19}F^{6+} beam of 75 MeV from a Au foil at angles $\vartheta_{\text{lab}}=\pm 57°$ relative to the beam axis. The scattered ions traverse a distance $d=4$ cm through vacuum with mean velocity of $v_{\text{ion}}\simeq 11v_0$ ($v_0=c/137$) which corresponds to a time of flight of $t_f\simeq 1.7$ ns. The ions were detected in two Si detectors. A thick contact layer of Ag was placed behind the detectors in order to stop the ions in an almost perturbation-free environment, while the 25-μm-thin Si wafers provided a time signal. Scattering angles were well defined through narrow channels in a thick shield of tungsten which served as an efficient absorber for background radiation (Fig. 1). The 197-keV γ rays emitted from the

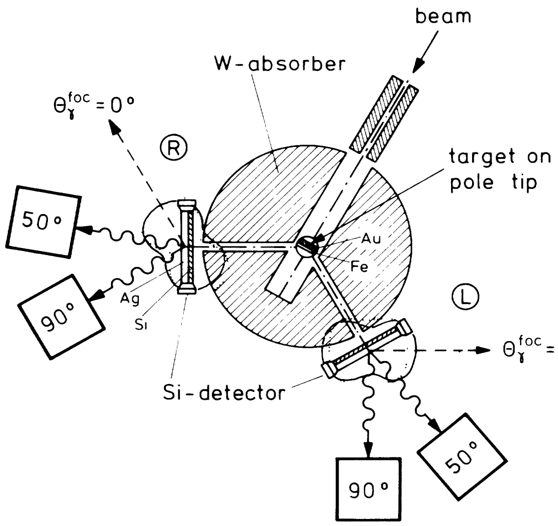

FIG. 1. Schematic view of the experimental setup with γ and ion detectors at specific angles of the focal coordinate system of the right (R) and left (L) scattering hemispheres of the Coulomb excitation process. For illustration the expected changes in the angular correlation in the presence of electron polarization (for an arbitrary value of $p_{1s} > 0$, dotted line) and without it (solid line) are displayed.

Ag layers of the ion detectors were measured with Ge(Li) [and NaI(Tl)] counters in coincidence with the registered ions. The detection angles Θ_γ^{foc} refer to the focal coordinate system in the center-of-mass frame (see below).

Two types of targets were used: One consisted of a 2-mg/cm^2-thick Au foil and the other of a Au foil of the same thickness with a 100-μg/cm^2-thick Fe layer added on one side. The latter could be magnetized to saturation by an external field of 0.01 T as found by magnetometer measurements. The surface magnetization was independently examined via the magneto-optical Kerr effect[8] and showed the same saturation behavior as the bulk. The targets were exposed to external magnetic fields of $\lesssim 0.05$ T provided by a small electromagnet perpendicular to the scattering plane. The field decreased from its maximum at the target position to negligible small values at the ion detectors.

For the measurements, a vacuum pressure of less than 10^{-7} mbar was accomplished with a cryopump connected directly to the target chamber. In addition, the massive tungsten absorber surrounding the target was cooled to liquid-nitrogen temperature while the target was kept through heating at room temperature. By these precautions no change of the target surfaces by the beam was found even after continuous bombardment for several days.

The experimental procedure consisted of the following measurements: (i) γ anisotropy or detailed angular correlations on both sides of the two scattering hemispheres (R,L) without external magnetic fields; (ii) atomic spin precessions which the scattered ions experience during their flight in vacuum in the transverse magnetic stray fields; (iii) perturbations of the angular correlations with the γ detectors at angles sensitive to the polarization of the emerging ions (see below and Fig. 1). Measurements (i) and (ii) provide equivalent information on the nature and abundance of the specific electron configurations formed on emergence of the ions from the targets. These data indeed were obtained with use of the measured charge state fractions of 22% (7^+), 50% (8^+), and 28% (9^+) at the given ion velocity for Au and Fe foils.[9]

During the flight of the ions in vacuum the strong HFI associated with single-electron and excited two-electron charge states lead to attenuations of the γ anisotropy which are determined by their hard-core values.[10] There was an additional small attenuation arising from perturbations in the Ag stopper. The measured anisotropies were

$$A^{\exp} \equiv W_{R(L)}(\Theta_\gamma^{foc} = 45°)/W_{R(L)}(\Theta_\gamma^{foc} = 90°) = 1.61(2).$$

The atomic spin precessions due to the Larmor precession of the total angular momentum $\mathbf{F} = \mathbf{I} + \mathbf{J}$ in the magnetic stray field cause rotations of the angular correlations, which were observed in terms of normalized counting rate ratios

$$R_{R(L)} \equiv [W_{R(L)}(\Theta_\gamma^{foc})\uparrow / W_{R(L)}(\Theta_\gamma^{foc})\downarrow]^2 - 1\,, \qquad (1)$$

for field "up" and "down" directions at angles $\Theta_\gamma^{foc} = 50°$. For normalization, the particle rates of the two detectors in the R,L hemispheres were recorded separately for each field direction. The different sign of the two ratios R_R and R_L is consistent with a well-defined rotation of the γ-angular correlations (see Figs. 1 and 2). Contributions from TF precessions in the thin Fe layer with an effective transit time of $\simeq 10$ fs for the ions were negligible. For a quantitative analysis the magnetic stray field was accurately mapped along the flight path of the ions. Data obtained for the two types of targets in both scattering hemispheres are displayed in Fig. 2. It should be noted that at $\Theta_\gamma^{foc} = 50°$ the effect of electron polarization on the observed ratio is negligible as a result of its highly reduced sensitivity [see Fig. 1 and Eq. (3)].

In the measurement (iii) the calculable strong nuclear polarization from the Coulomb scattering was utilized for detecting the electron polarization. The orientations of the nuclear spin are opposite for the two hemispheres with the spin pointing out of plane (z direction) for the right side (R).

The electron polarization expressed by

$$p_{1s} \equiv \langle S_z \rangle / [S(S+1)]^{1/2}, \text{ with } p_{1s}^{\max} = 0.58\,, \qquad (2)$$

causes an increase or decrease of the γ anisotropy depending on whether the nuclear and the electron spins are parallel or antiparallel. The orientation of the elec-

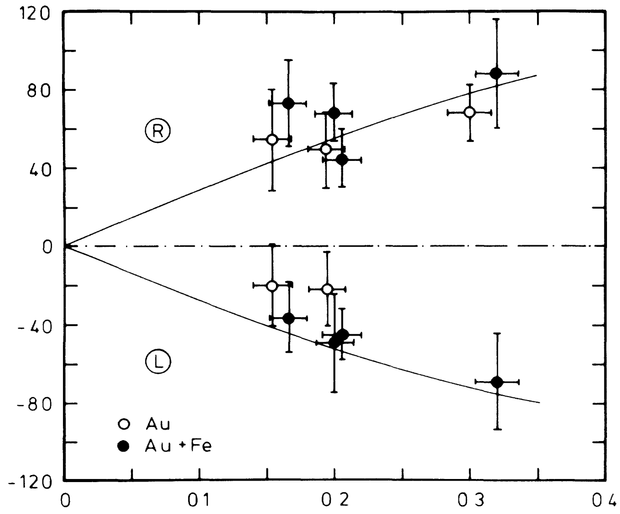

FIG. 2. Atomic spin precession data as functions of the magnetic field path integral over the flight distance of the ions scattered from Au and Au+Fe targets to the (R,L) hemispheres. Curves have been calculated with Eq. (3) with use of well determined parameters.

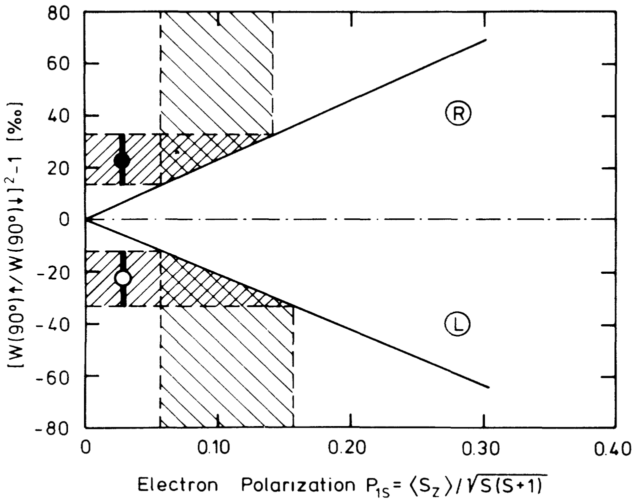

FIG. 3. Average values of field "up"/"down" ratios for polarized ions emerging from Au+Fe targets as observed on the (R,L) hemispheres. Solid lines represent calculations [Eq. (3)] of the ratio as functions of the electron polarization with use of the same parameters as used for describing the other measured quantities. Hatched areas refer to the 1 standard deviation limits of the data from the two separate measurements.

tron spin is determined by the direction of the magnetizing field implying $p_{1s} < 0$ for field up. It is evident that an increase of the anisotropy on one side is corrected with a decrease on the other side and vice versa. The change in anisotropy was determined in terms of normalized counting-rate ratios for field up and down [Eq. (1)] on both scattering hemispheres at angles $\Theta_\gamma^{\rm foc} = 90°$ where the atomic spin precessions yield null effects because of a vanishing slope of the angular correlation. Figure 3 shows average values from several runs and targets. It should be noted that in all these measurements atomic spin precessions were also observed simultaneously.

The same measurements were also performed with use of Au targets in otherwise identical conditions. In these runs, the atomic spin precessions were the same within the experimental errors as for Au+Fe targets, whereas the field up/down ratios at $\Theta_\gamma^{\rm foc} = 90°$ gave essentially zero values: $|\bar{R}_{R(L)}| = 0.001(5)$. These measurements were an important test on (a) the precision of the scattering geometry as, e.g., detector angles of the experimental setup; (b) the minor role of higher-order effects like reorientation in the Coulomb excitation process. Contributions from tilted foil effects[11] [the target was tilted relative to the direction of the emerging ions (Fig. 1)] are not expected because of their field independence and the s-electron configurations of the ions involved.

For the interpretation of the measured quantities we have used the angular correlation function as expressed in the focal coordinate system of the scattering plane $(\Phi = 90°)$[10]:

$$W(\Theta_\gamma^{\rm foc}) = \sum_{k,q} A_k G_{kk}^{\rm Ag} Q_k a_k^q(\vartheta,\xi) \sum_{J,F} f_J G_{kk}(J,F) Y_k^q(\Phi, \Theta_\gamma^{\rm foc} - \omega_F t_f) + 3 p_{1s} f_{1s} \sum_{k,k'=k\pm 1,q} A_k G_{kk'}^{\rm Ag} Q_k a_{k'}^q(\vartheta,\xi) \sum_F U_{kk'}^q(F) Y_k^q(\Phi, \Theta_\gamma^{\rm foc} - \omega_F t_f), \quad (3)$$

where the A_k are the angular correlation coefficients; $G_{kk}^{\rm Ag} Q_k = 0.85$ accounts for perturbations in the Ag stopper and solid angle effects of the detectors. The $a_k^q(\vartheta,\xi)$ are the statistical tensor elements describing the initial orientation of the nuclear state depending on the adiabaticity parameter ξ and scattering angle ϑ in the center-of-mass frame. The attenuation coefficients $G_k(J,F)$ are the hard-core values with normalized fractions f_J (f_{1s} for $J = \frac{1}{2}$) of the perturbing configurations ${}^2S_{1/2}$ and ${}^3S_1$. The Larmor frequency

$$\omega_F = -\frac{\mu_B g_F}{\hbar d} \int_0^d B_{\rm ext}(s)\, ds \quad (4)$$

determines the atomic spin precession in the external stray field, extending over the flight distance $d = v_{\rm ion} t_f$, with atomic g_F factor which is well determined for the configurations in question.

The second term of Eq. (3) accounts for the polarization of a 1s electron and consists of nonzero odd k' elements of a_k^q, provided that the nuclear state is polarized. The $U^q_{kk'}(F)$ coefficients are given explicitly in Ref. 10.

With the only exception of p_{1s} all parameters of Eq. (3) are well known. Hence, attenuations and atomic spin precessions were calculated for normalized ion fractions of 50% $^2S_{1/2}$, 5% $^3S_1$, and 45% $^1S_0$ with no HFI. The curves obtained are shown in Figs. 2 and 3. Thus the calculated anisotropy $A^{\mathrm{calc}}=1.63$ agrees very well with the measured value.

From the weighted average of the up/down ratios (R,L) a mean electron polarization of

$$p_{1s}=0.10(3)$$

was obtained which is consistent with values relevant to TF measurements. For comparison, with the TF measurements, however, the derived value has to be renormalized because of the different definitions of the degree of polarization in the two cases $[p_{1s}^{\max}(\text{atomic})=0.58$ and $p_{1s}^{\max}(\text{TF})=1.0]$ leading to a value of 0.17(5).[3]

It should be noted that this result does not exclude the possibility of contributions from the foil surface with which larger electron polarizations are associated as, for example, polarizations detected in diffraction measurements of polarized electron beams.[12]

In conclusion, we have shown by our measurements that substantial electron polarizations exist for F ions emerging from magnetized thin Fe layers. The HFI of the ion configurations in question are well explained in a consistent way. Applications to g-factor measurements and further experiments employing time-differential techniques are in progress.

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