SPIN-POLARIZED TWO-ELECTRON SPECTROSCOPY OF SURFACES

Two electrons resulting of a scattering of a single incident electron from a surface are detected, their momenta are measured. This technique allows studying electron scattering dynamics, electronic structure and correlations at surfaces.

Experiment

Vacuum: 10^{-11} Torr range.

Incident electron beam:
- polarisation 60-70%
- electron energy 20 - 50 eV
- pulse width 1 ns
- repetition rate 2.5.10 6 s^{-1}
- average current 10 - 13 A

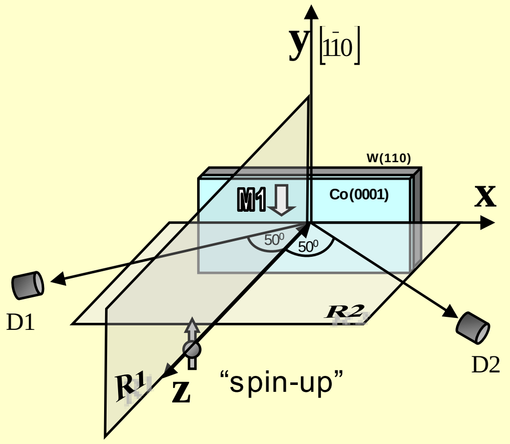
Samples: W(110); Fe, Co, Ni layers.

Detectors:
- position sensitive MCP- based
- acceptance angles ± 13°
- distance from the sample 126 mm

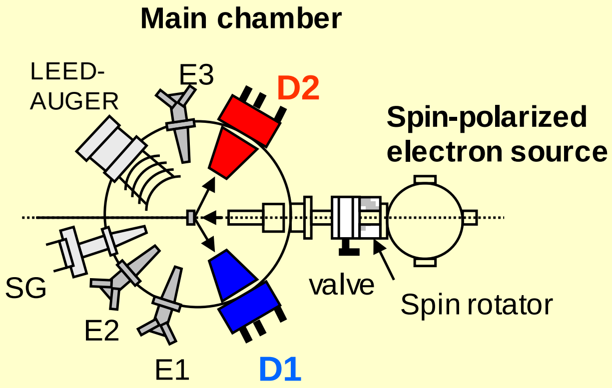
Time-of-flight energy analysis:
- "in parallel" detection of electrons with various energies
- "in parallel" angular distribution measurement

Coincidence count rate: 2 - 5 events per second

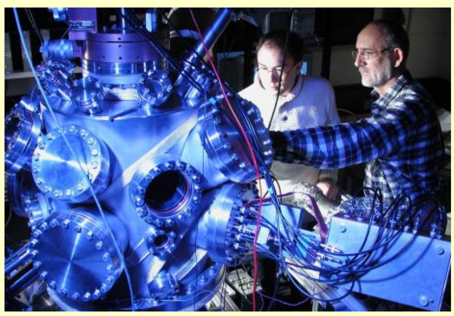
Auxiliary techniques:
- Auger Electron Spectroscopy
- Spin-polarized Electron Energy Loss Spectroscopy
- Low Energy Electron Diffraction
- Ion Sputtering Gun
- Quartz microbalance
- Mass spectroscopy



Scattering geometry



Experimental set up



Examples of application of spin-polarized spectroscopies for surface study.

Spin-polarized two-electron spectroscopy.

In spin-polarized two-electron spectroscopy we compared two very different geometrical arrangements: i) symmetric, with normal incidence of polarized electrons and symmetric detection of emitted electrons, and ii) asymmetric, with 57° of incidence and asymmetric detection of emitted electrons (Fig.1 and Fig. 2)).

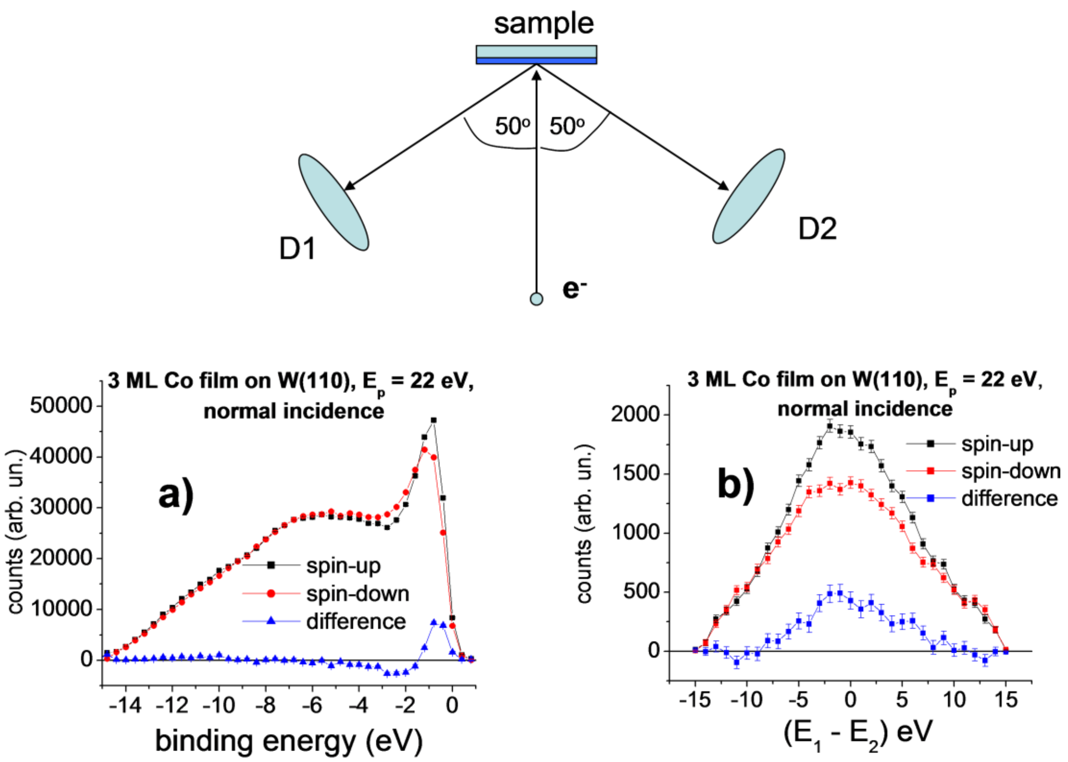


Fig. 1. Binding energy spectrum (a) and energy sharing distribution (b) measured on 3 ML cobalt film on W(110) with 22 eV spin-polarized primary electrons. Normal incidence, symmetric detection of electrons.

At normal incidence the largest effect of exchange scattering is observed at equal energy sharing, where $E_1 = E_2$ (see Fig. 3b). In binding energy spectrum the difference between spin-up and spin-down spectra changes sign: it is positive just below the Fermi energy, changes sign at about -1.5 eV and becomes zero at about -4 eV.

In contrast, at grazing incidence the energy sharing distributions become asymmetric with respect to the point $E_1 = E_2$ and the difference between spin-up and spin-down spectra has different structure compared to symmetric case. The difference between spin-up and spin-down binding energy spectra does not change the sign in case of grazing incidence in contrast to the normal incidence although the spin asymmetry of spectral density function does change the sign in this binding energy range.

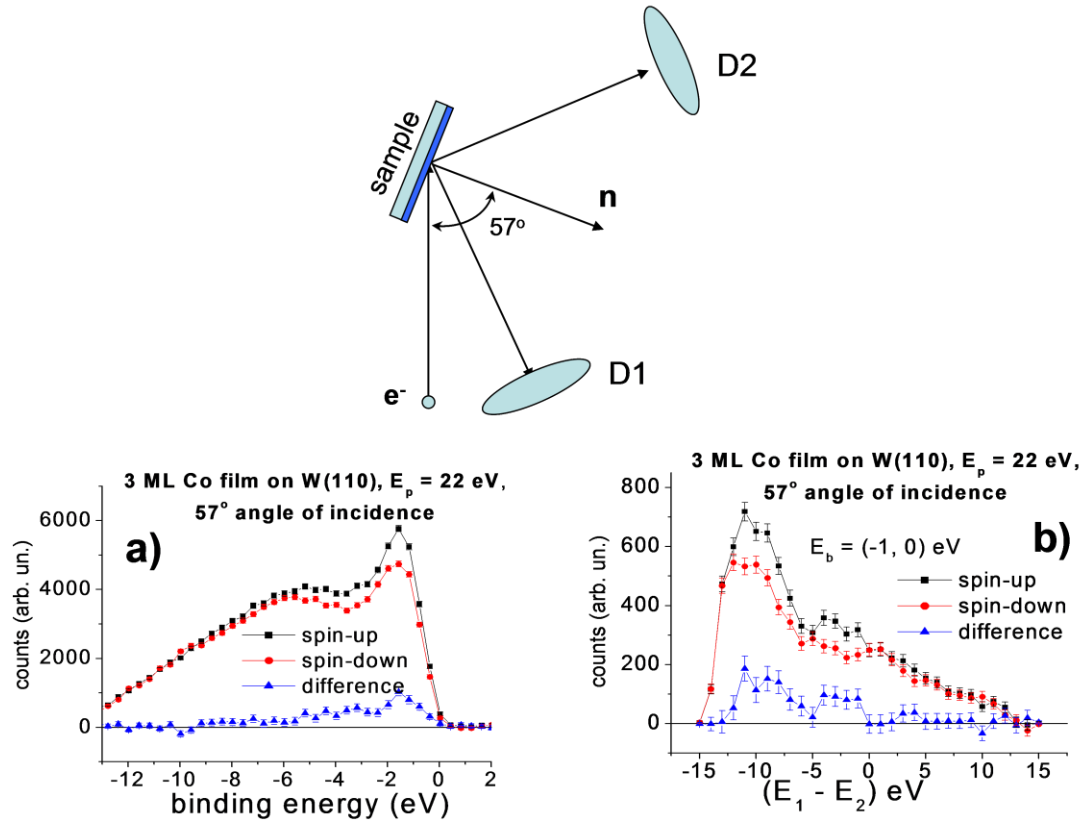


Fig. 2. Binding energy spectrum (a) and energy sharing distribution (b) measured on 3 ML cobalt film on W(110) with 22 eV spin-polarized primary electrons. Grazing incidence and asymmetric detection of electrons.

These results demonstrate that different geometrical arrangement of the electron scattering from a crystal surface allows unraveling various features of spin-dependent low-energy electron-surface interaction. The role of dynamics and kinematics in these reactions is still to be analyzed.

Spin-dependent electron energy loss spectroscopy of thin Fe and oxygen covered Fe layer on W(110) at various kinematics.

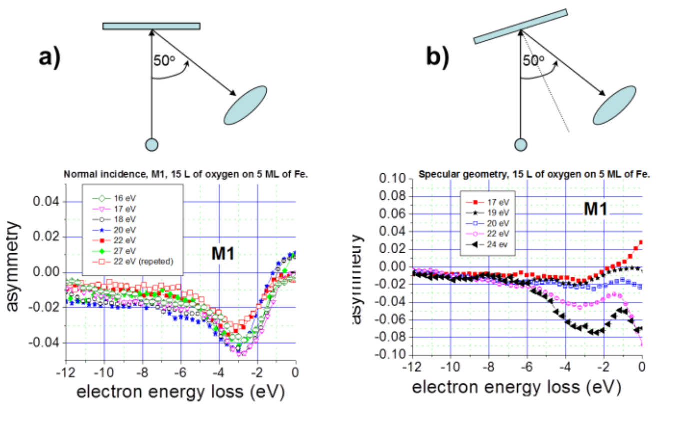


Fig. 3. Energy dependence of SPEELS asymmetry for two different geometries of the experiment.

The intensity asymmetry of the secondary emission spectra of ultrathin iron films on W(110) excited by spin-polarized electrons were measured at various geometrical arrangements and various primary energies. The magnitude and shape of the Stoner excitation asymmetry provide information on the spin (magnetic) state of the film. The geometrical structure of the film influences its magnetism and this is reflected in the asymmetry of the spin polarized electron energy loss spectra (SPEELS). Oxygen adsorption reduces the asymmetry of Stoner excitations, but not as dramatically as in studies of Ni surface. The kinematics of the scattering process influences the asymmetry of the spectra (Fig. 3) and should be taken into account while using SPEELS for studying surface magnetism. (Paper submitted).

Azimuthal dependence of spin-polarized electron scattering from nonmagnetic surface: W(110).

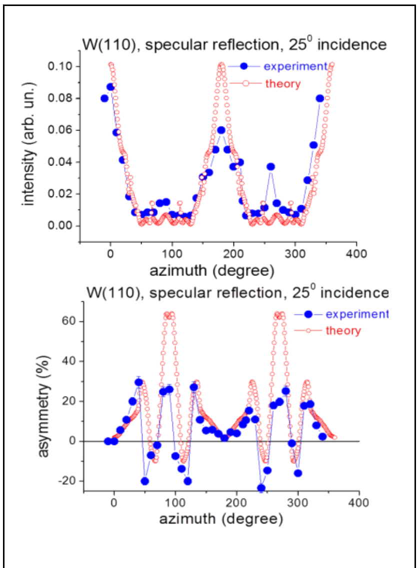


Fig. 4. W(110), azimuthal dependence of intensity (top panel) and asymmetry (bottom panel) of elastic electron scattering at specular geometry.

Azimuthal dependence of intensity and spin asymmetry of elastic spin-polarized electron scattering from W(110) at specular geometry shows strong influence of the crystal symmetry. Fig. 4 represents intensity (top panel) and asymmetry defined as $A = (I^{up}-I^{dow})/ (I^{up}+I^{dow})$ (bottom panel) of elastic scattering as a function of the azimuthal position of the sample at 25^0 of the polar angle (angle of incidence) and specular detection. The primary energy is 22 eV. Zero on the "X" axis corresponds to the orientation of the sample when the $[1\bar{1}0]$ direction is perpendicular to the scattering plane. One can see that the highest value of the intensity on the angular distribution corresponds to a minimum value of the asymmetry (see Fig. 4). Theoretical calculations by Prof. R. Feder at al. reproduce very well the experimental curves (see Fig. 4). (Paper in preparation).

Azimuthal dependence of spin-polarized electron scattering from magnetic surface: thin iron film on W(110).

Influence of the mutual orientation of the incident electron spin polarization vector and the magnetization vector of the sample on the Stoner excitation asymmetry of the 5 ML Fe film has been studied using 22 eV primary energy. It turns out that the experimental curve (expected "cosine") deviates from cosine at the angles θ_i and $\theta_i + \pi$. These deviations are assigned to the existence of two sets of magnetic domains making angles θ_1 and θ_2 relative to the quantization axis (see Fig. 5). Zero angle on the "X" axis corresponds to the sample orientation when the $[1\bar{1}0]$ direction of the substrate (easy magnetization axis of the Fe film at this thickness) is perpendicular to the scattering plane and nominal magnetization vector is pointing up (majority spins are down). It is interesting to note that at the angle $\theta = \pi/2$ the asymmetry of Stoner excitations vanishes indicating that the incident polarized electron beam "does not see" magnetic moment of the sample. From the "sample view point" the incident beam is not polarized at this mutual orientation of the polarization vector and magnetization of the sample. This experimental procedure potentially can be used for studying domain structure of thin ferromagnetic layers and surfaces.

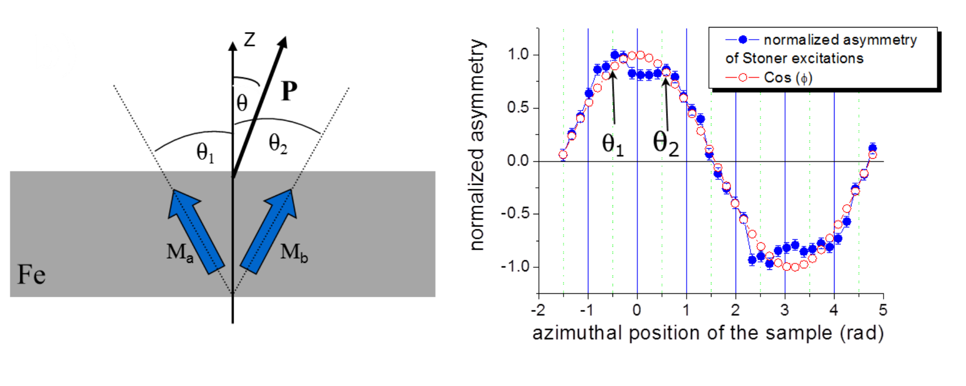


Fig. 5. Normalized asymmetry of Stoner excitations as a function of the angle θ (right panel) between polarization vector P and quantization axis "Z".

Plasmons excitation by spin-polarized electrons in Ag films on magnetic and non-magnetic substrates.

Enhancement of an electromagnetic field in the vicinity of a "plasmonic" surface is used in photochemistry as well as in variety of spectroscopies: surface-enhanced infrared absorption; surface-enhanced Raman spectroscopy; surface-enhanced fluorescence; extraordinary optical transmission.

The possibility of tailoring parameters of plasmon excitations in nano-structures as well as a potential use of them in magneto-plasmonic devices generated a new wave of research in the field of surface plasmon excitation by electrons or photons in various structures. Silver is a particular material with respect to plasmon excitations. Its plasmon resonance frequency is situated in the near UV region (3.7 eV). It is observable by means of optical spectroscopy and electron energy loss spectroscopy and easy for use in potential applications.

We have studied plasmons excitation in thin Ag films deposited on W(110) surface and on Fe layers using Spin-Polarized Electron Energy Loss Spectroscopy (SPEELS). The aim of the study was to investigate an influence of a ferromagnetic substrate on the spin-dependent cross-section of plasmon excitation in a thin Ag film. Fig. 1 shows an example of energy loss spectrum of Ag and Fe films with plasmon loss at 3.7 eV in Ag and asymmetries of SPEELS.

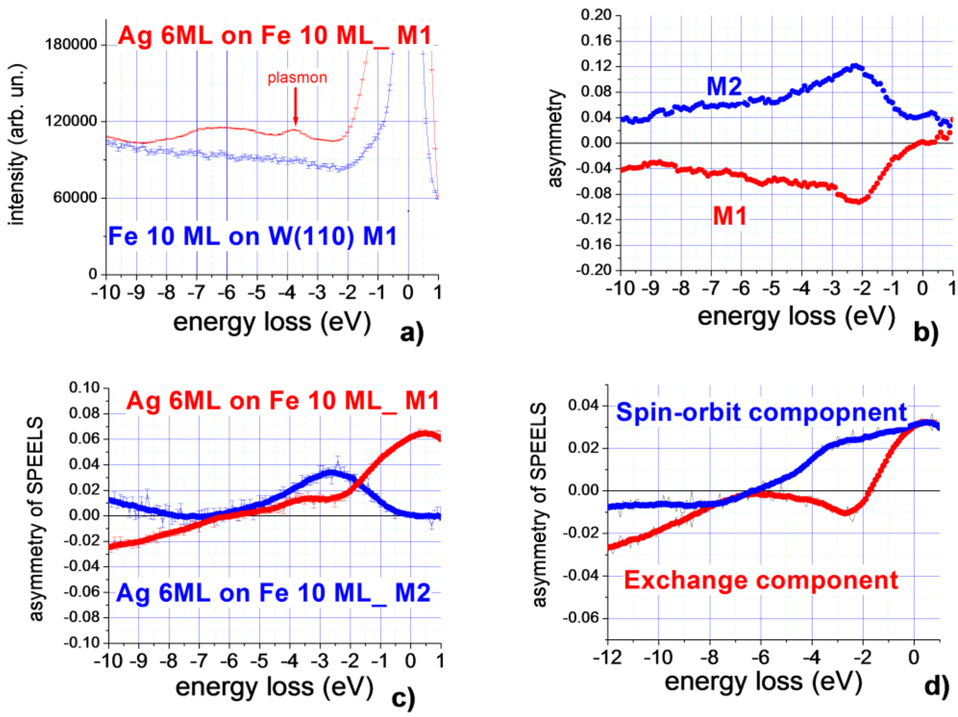


Fig. 1. a) Spin-polarized Electron Energy Loss Spectra (SPEELS) of 6 ML Ag film on 10ML Fe layer on W(110) excited by 17 eV primary electrons (red) and SPEELS of 10ML Fe layer (blue) on W(110); b) asymmetry of SPEELS of Fe layer; c) asymmetry of bi-layer structure for two magnetizations of Fe layer; d) spin-orbit and exchange component of SPEELS asymmetry.

These results indicate that in SPEELS of the Ag/Fe bi-layer system at specular geometry and 25^{o} of incidence there is a substantial spin-orbit and exchange contribution to the measured spin asymmetry. On the other hand we do not see any specific spin asymmetry feature at the plasmon energy loss (around 3.7 eV). It means that in this experimental set-up no spin dependence in the plasmon excitation cross section is detected.

Role of kinematics in spin-polarized electron spectroscopies.

Spin-polarized Electron Energy Loss Spectroscopy (SPEELS).

We have studied the influence of the kinematics on spin asymmetry of SPEELS from magnetic and non-magnetic surfaces. Spin-orbit asymmetry is known to depend strongly on electron energy and angles of scattering. Much less is known about exchange asymmetry in SPEELS from ferromagnetic surfaces. Fig. 2 represents two kinematical arrangements of SPEELS measurements on 3 ML Fe film on W(110) substrate: a) normal incidence and detection at 50^{o} from normal; b) specular scattering with the angle of incidence of 72^{o}. M1 and M2 denote magnetization of the sample (in opposite directions collinear with the polarization vector of the incident beam).

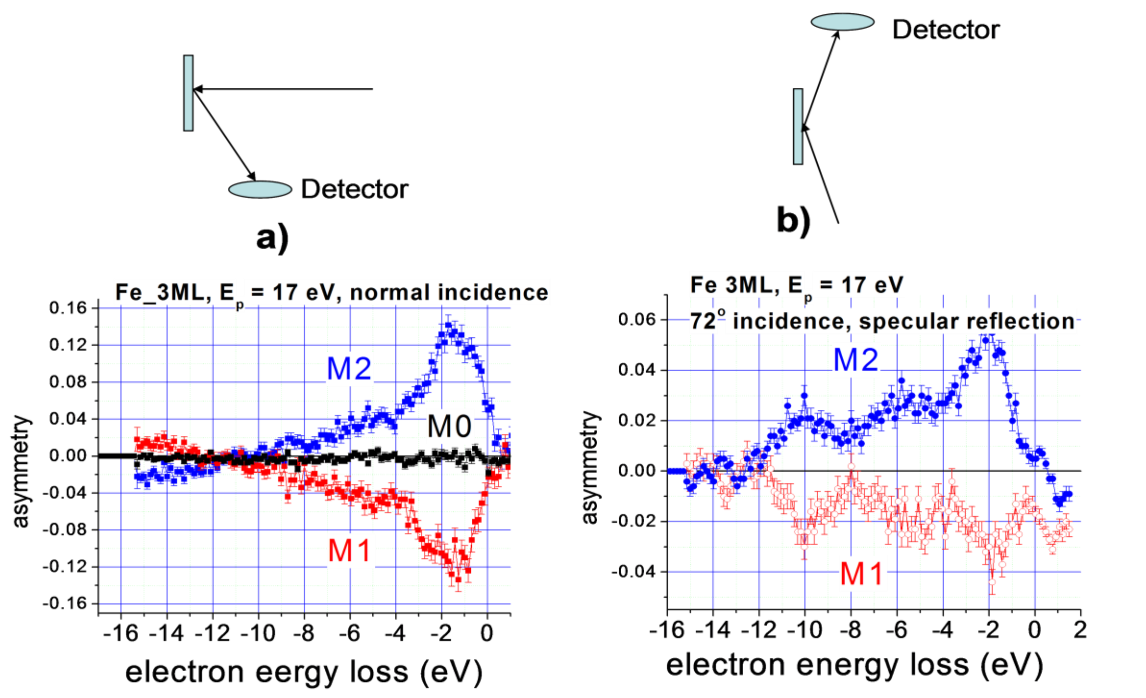


Fig. 2. Spin asymmetries of electron energy loss spectra from 3 ML Fe film on W(110) measured with 17 eV spin-polarized incident beam at two geometries: a) normal incidence, detection at 50°; b) 72° incidence, specular detection of electrons. M1 and M2 are two opposite magnetizations of the sample collinear with the polarization vector of the incident beam. M0 – magnetization of the sample perpendicular to the polarization vector of the beam.

M0 on Fig. 2a denotes the asymmetry of SPEELS when the magnetization of the sample is perpendicular to the polarization vector of the beam and it is zero as it should be. Curves M1 and M2 of Fig. 2a represent asymmetry of SPEELS for two opposite magnetizations of the sample. They are identified as Stoner excitations asymmetry with maximum at about 2 eV energy loss. This energy approximately represents an exchange splitting of spin-up and spin-down states in the Fe film. Both asymmetries on Fig. 2b for grazing incidence spectra show oscillatory behavior as a function of electron energy with a period of about 4 eV. They are clearly of magnetic origin because they change sign when magnetization changes sign. They might be a manifestation of spin-polarized quantum well states in the Fe film.