Quantitative analysis of L-edge white line intensities: the influence of saturation and transverse coherence

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We have performed x-ray absorption spectroscopy at the Fe, Ni, and Co $L_{2,3}$ edges of in situ grown thin magnetic films. We compare electron yield measurements performed at SSRL and BESSY-I. Differences in the $L_{2,3}$ white line intensities are found for all three elements, comparing data from the two facilities. We propose a correlation between spectral intensities and the degree of spatial coherence of the exciting radiation. The electron yield saturation effects are stronger for light with a higher degree of spatial coherence. Therefore the observed, coherence related, intensity variations are due to an increase in the absorption coefficient, and not to secondary channel related effects.

Due to its high brilliance and energy tunability synchrotron radiation has become an important tool for studying electronic and magnetic properties of matter. One property of the light that for long was not taken into account, the degree of transverse coherence, has recently evoked interest in various fields. Ferromagnetic films have been studied extensively by means of x-ray magnetic circular dichroism in order to obtain element specific magnetic information of spin and orbital magnetic moments by applying magneto-optic sum rules (Carra *et al.*, 1993). In this X-ray Absorption Spectroscopy (XAS) study we focus on in situ grown thin ferromagnetic films of Fe, Co, and Ni, and on how the $L_{2,3}$ edge white lines vary in intensity versus the degree of transverse coherence of the exciting radiation. We find that a higher degree of transverse coherence gives rise to an enhancement of white line intensities. We show this to be due to an increase in the absorption coefficient itself. The enhancement of the $L_{2,3}$ white lines of Fe films (Hunter Dunn *et al.*, 2000*b*) has earlier been reported and linked with the different degree of transverse source coherence of the exciting radiation.

The measurements were performed at beam line 5.2 at the Stanford Synchrotron Radiation Laboratory (SSRL) and at the BESSY-I synchrotron facility in Berlin using SX700 beamlines (Arvanitis *et al.*, 1996). At BESSY-I bending magnet radiation was used while at the SSRL the radiation was produced by the Elliptically Polarized Undulator (EPU). The EPU enables varying the polarization state of the light by changing the row phase of the undulator. Radiation from a bending magnet enables for circular light when viewing the source from below or above the plane of the electron beam. The energy resolution at BESSY-I and the SSRL was characterized from measurements of the M4,5 edges of La in a $LaAl_2$ standard. Exit slit openings of 50m at BESSY-I and 20m at SSRL give a resolution of 1.5eV at 780eV which corresponds to a longitudinal coherence length of $\approx 1\mu m$ $(\lambda^2/\delta\lambda)$. The samples were all prepared and measured in situ in ultra high vacuum. The film preparation technique is based on electron beam evaporation and has been reported earlier in detail (Hunter Dunn *et al.*, 1995). In addition to a structural check with Low Energy Electron Diffraction the films were also checked for cleanness using Auger Electron Spectroscopy and XAS at the C and O K-edges. Magnetic properties, as they are structurally sensitive, constitute a further proof of the reproducibility of the film quality.

The XAS spectra were recorded by measuring both the samples electron yield and the photocurrent simultaneously. After normalization the two channels agree almost perfectly. The thickness was calibrated by means of the edge jump ratio (Arvanitis *et al.*, 1996). The samples were remanently magnetized using a pulse from an electromagnet and measured with a degree of circular polarization of 0.45 at BESSY-I (Hunter Dunn *et al.*, 1995) and 0.95 at the SSRL (Hunter Dunn *et al.*, 2000*b*).

In Figure 1 the L edge spectra are shown with bcc Fe as the lowermost, fct Co in the middle, and fct Ni at the top. The solid line spectra were taken at SSRL whereas the dotted line spectra were taken at BESSY-I. For comparison we use a standard normalization procedure (Chen *et al.*, 1995; Idzerda *et al.*, 1995) to normalize the spectra to a 0-100 edge jump ratio. In order to isolate, mostly, the d-state final states transitions, we use a 2:1 double step function with inflection points at the peak positions. Here we use different slopes in pre-, and post-edge region than previously used (Hunter Dunn *et al.*, 1995). The spectra of Fig 1 were taken at normal x-ray incidence. Fe and Co show no dichroism at this geometry whereas

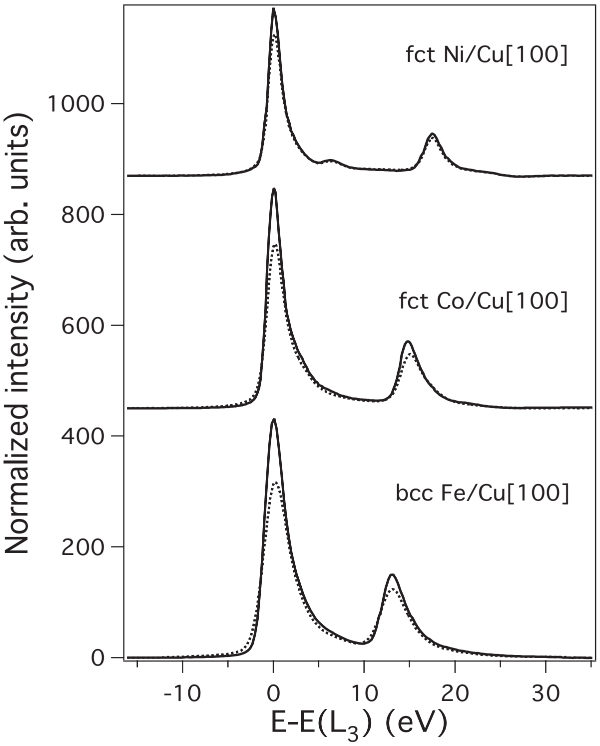

Figure 1
The figure shows bcc Fe, fct Co, and fct Ni films on Cu(100), 20 ML thick. The solid and dotted lines represent spectra taken at BL 5.2 of the SSRL and SX 700 beamlines of BESSY - I, respectively. The spectra were normalized to a 0 – 100 edge jump ratio. A 2:1 continuum step function is subtracted to obtain, mostly, 3d final states.

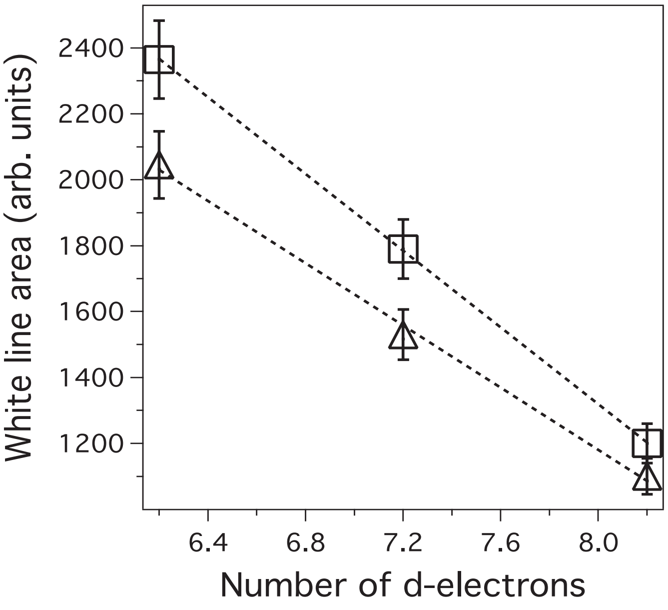

Figure 2
L_3 and L_2 white line area versus number of d-electrons from theory. Squares and triangles represent results from the SSRL and BESSY-I, respectively. The data are fitted with straight lines.

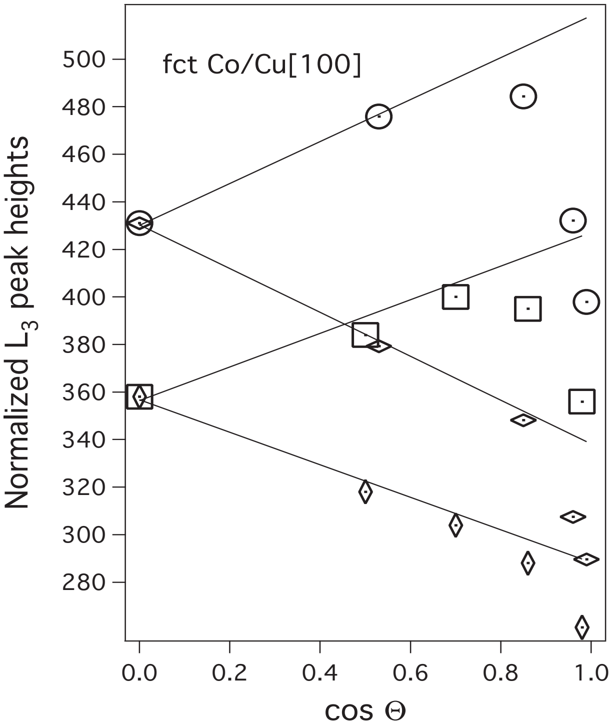

Figure 3
Measured L_3 peak heights taken at maximum intensity. The deviations from the solid lines are due to saturation effects in the electron yield. Circles (minority peaks) and horizontal diamonds (majority peaks) represent data taken at the SSRL. Squares (minority peaks) and vertical diamonds (majority peaks) represent data taken at BESSY-I.

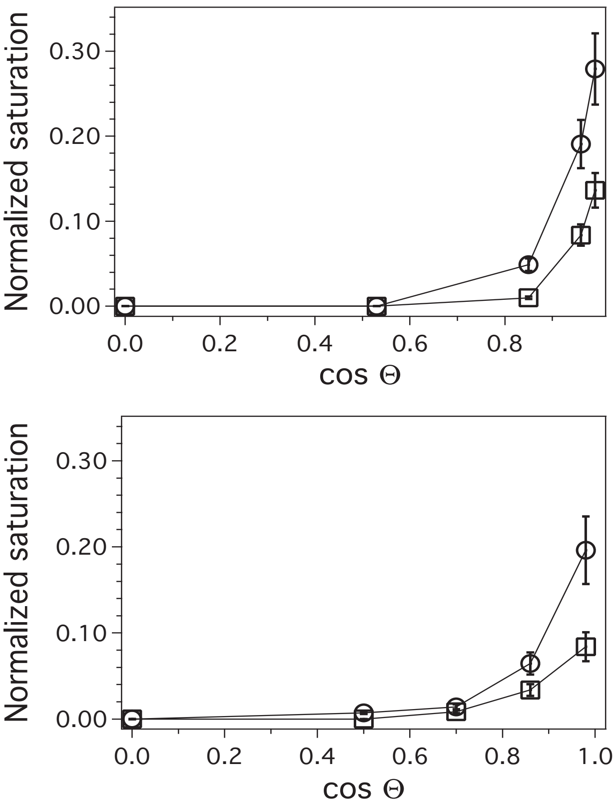

Figure 4
The saturation effects are shown for the SSRL (upper figure) and BESSY-I (lower figure). The intensity losses due to saturation are shown normalized to the peak heights at normal x-ray incidence ($\cos\theta = 0$).

Ni, with the easy direction perpendicular to the surface, shows full dichroism. For the Ni spectra in the figure we took the half sum of a minority-, and majority spectra. In Figure 2 the areas for the three elements, by integrating the spectra from Figure 1, are shown versus the theoretical number of ground state d-electrons (Söderlind *et al.*, 1992). For Fe and Co the enhancement of the total area is 16%, whereas for Ni only 8%. Results similar to SSRL have been recorded at Elettra, a high brilliance synchrotron source, where the source parameters imply a high degree of spatial coherence. On the other hand, data measured at SRS ,Daresbury, and MAX-I ,Lund, (medium brilliance machines, with a lower degree of spatial coherence), generates white line intensities nearly identical to BESSY-I (Hunter Dunn *et al.*, 2000*a*).

Figure 3 show how the L_3 peak intensity for the Co film varies versus the angle of x-ray incidence. The circles and the squares represent, respectively, the L_3 peak heights at the SSRL and BESSY-I, before correcting for the saturation effects. The solid lines show the linear $\cos\theta$ dependence of the L_3 minority peak heights after the saturation correction. The diamonds show the similar effect for the L_3 majority peaks. From simple geometrical considerations, assuming only E1 transitions, one expects the dichroic intensity to scale linearly versus $\cos\theta$, where θ is the angle measured relative to the surface plane. In the case of a cobalt film, with the easy magnetization direction in the surface plane, the maximum intensity should be expected at grazing x-ray incidence. However the experiment shows a weaker intensity at grazing than at normal x-ray incidence for both the BESSY-I and SSRL data.

For maximum x-ray absorption the photon penetration depth reduces and becomes comparable to the electron escape depth leading to an artificial damping of the resonant edges. As a consequence mostly the topmost atom layers contribute to the electron yield leading to saturation effects in this channel. When applying the saturation correction (van der Laan & Thole, 1988), the data are rescaled to recover the case where all potential ”donor” atoms contribute to the electron yield spectrum. The relative saturation effect (Figure 4) scaled to the L_3 intensity for normal x-ray incidence is bigger for the data taken at SSRL. This is an indication, that the enhancement of the areas for the SSRL data is not just due to coherence effects of the secondary channels in the yield but is due to a true enhancement of the absorption coefficient itself. Thus a higher value of the absorption would indeed lead to even less contributing ”donor” atoms for grazing incidence. In conclusion, we have presented data showing how different radiation sources show intensity variations for the L-edge white lines in Fe, Co, and Ni. We attribute these variations to the different degrees of transverse source coherence. The study of saturation effects further suggests that the observed, coherence related, intensity variations are related to an increase in the absorption coefficient itself, and are not due to secondary channel related effects only.

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