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Alternative geometries for the determination of x-ray magneto-optical coefficients

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Abstract

Two alternative geometries are proposed for x-ray magneto-optical (MO) spectroscopy with linearly polarized light in photon-in/photon-out reflection experiments, without sophisticated polarization analysis of the reflected x-ray radiation. One of the geometries yields an MO effect that is odd in the magnetization M, i.e., to first order linear in $\langle M \rangle$. The other geometry yields a magneto-x-ray effect that is even in M, i.e., to lowest order proportional to $\langle M^2 \rangle$. This second MO effect is a promising tool for the x-ray reflection spectroscopy of antiferromagnets. The applicability of these spectroscopies is demonstrated by experimental results.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Magneto-optical (MO) spectroscopies sensitively probe those parts of the electronic structure that are modified by the appearance of magnetism. In addition to this, core-level MO spectroscopy carried out in the x-ray regime permits the examination of magnetic properties on an element-selective level. For these reasons magneto-x-ray spectroscopies have in recent years developed into highly-appreciated tools for the study of fundamental and applied magnetism [1, 2].

A meaningful distinction for contemporary magneto-x-ray spectroscopies is according to the detection mode adopted to measure the MO effect. The detection of MO effects can be achieved in a photon-in/photon-out experiment or, alternatively, in x-ray absorption using a total yield mode. In the latter mode, secondary excitation processes such as fluorescence or the creation of secondary photoelectrons are exploited, the occurrence of which events is roughly proportional to that of the primary excitation [3, 4]. The detection of secondary electrons has proven to be particularly fruitful for applications in electron microscopy, where only the contrast matters and not the absolute intensities (see, for example, [5–8]). On the other hand,

the detection of photons in a photon-in/photon-out experiment provides a worthwhile approach when absolute spectroscopic values are to be obtained. Also, while the electron yield mode is a mostly surface sensitive technique due to the small escape depth of the secondary electrons, photon-in/photon-out spectroscopies probe the bulk material [9]. Thus, both detection modes have specific merits of their own. Here we concentrate on magneto-x-ray spectroscopies employing the photons-only mode. X-ray spectroscopies of this kind have become increasingly popular and powerful during recent years (see, for example, [10]).

There exist several ways to classify the various photon-based magneto-x-ray spectroscopies. The distinctive characteristics are

(1) whether the effect is odd or even in the magnetization,
(2) whether a plain intensity measurement or a polarization state analysis is made of the light after its interaction with the material,
(3) whether the effect is measured in reflection or in transmission, and
(4) whether linearly or circularly polarized synchrotron radiation is employed.

The most decisive characteristic is the parity of the measured effect with respect to the magnetization. The vast majority of all x-ray MO spectroscopies performed until today are odd in the magnetization, i.e., to lowest order linear in M. Among these spectroscopies are the x-ray circular dichroism (XMCD) measured in transmission [11, 12], reflection [10, 13] or, more frequently, absorption (see, for example, [14, 15]). Other magnetic spectroscopies of this kind are the x-ray Faraday effect [16–20], the x-ray resonant magnetic scattering (XRMS) [21–23], the transversal MO Kerr effect (T-MOKE) [10, 24, 25], and the longitudinal MO Kerr effect (L-MOKE) [26]. Only two spectroscopies exist so far that are sensitive to $\langle M^2 \rangle$. These are the x-ray linear magnetic dichroism (XMLD), measured in transmission [9] or mostly in absorption (see, for example, [27–33]) and the recently discovered x-ray Voigt effect measured in transmission [34]. The XMLD in transmission requires an intensity measurement, whereas the x-ray Voigt effect requires a polarization state analysis. Compared to the x-ray MO spectroscopies that are odd in M, the size of the magnetic response observed in the even-in-M spectroscopies is much smaller. Microscopically, this was recently explained to stem from the exchange splitting of the core levels, which is tiny, yet it is the decisive quantity for the even-in-M MO response [34, 35]. The smallness is one of the reasons that up to now only a relatively small number of XMLD experiments and the first x-ray Voigt experiment [34] have been reported. However, x-ray spectroscopies that are even in M hold great potential for the investigation of the magnetism in antiferromagnetic materials on an element-selective level. Such investigation is plainly impossible using an MO effect that is odd in the magnetization. In spite of the prospects that even-in-M magneto-x-ray effects have for the study of antiferromagnets, so far only a small number of antiferromagnetic materials could be investigated thereby either spectroscopically or electron-microscopically. A particularly clear XMLD spectrum has been observed by electron-yield techniques at the Fe L-edge of antiferromagnetic Fe_2O_3 [28, 32]. A somewhat different measurement technique that has also been named XMLD, in which a total electron yield detection is employed to measure the absorption while varying the angle of incidence [36], was previously applied to the antiferromagnets NiO [7, 8, 31, 36] and $LaFeO_3$ [5, 6].

The aim of the present paper is to propose and analyse two alternative geometries for magneto-x-ray spectroscopy in the soft-x-ray regime, on the basis of photons only. Guided by practical considerations, we impose two constraints on these geometries and the concomitant measurement technique. The first constraint is that the magneto-x-ray effect can be measured in reflection. Many samples of current technological importance are thin-film structures on substrates (e.g., spin-valve devices), which can be measured in reflection but not in

transmission. The second constraint is that the magneto-x-ray effect can be obtained from an intensity measurement rather than a polarization analysis. In itself the analysis of the polarization state gives more complete information on the magnetic response (it basically yields two quantities, phase and amplitude), but its determination is a more complicated task, in particular in the soft-x-ray range, where suitable polarizers and analysers are rare [19]. In the hard-x-ray regime the instrumental situation is different, because in this regime a polarization analysis is not as difficult to perform (see, for example, [18, 37]). An intensity determination is an easier task, but it yields only one quantity (the amplitude). Apart from these constraints, it is desirable that the effects are detectable with linearly polarized synchrotron radiation, which is currently still better available with a high polarization degree than circularly polarized radiation, although progress in insertion devices yielding a high degree of circular polarization has been made.

The geometries that we discuss here do fulfill these constraints. In addition, the MO effects pertaining to these geometries can be obtained at any angle of incidence between 0° and 90°. The first geometry yields an odd-in-M MO effect for a ferro- or ferrimagnet, with either polar or longitudinal magnetization direction. The existence of such an MO effect was recognized recently for the longitudinal magnetization by Berger and Pufall [38]. Apart from the analytical description of this MO effect, we also present measured x-ray dichroic asymmetries using this effect. The second geometry leads to an MO effect that is even in M; it should thus exist for ferromagnets as well as antiferromagnets. Recently we showed that this magneto-x-ray spectroscopy, which could be called 'XMLD-in-reflection' is indeed an efficient, viable tool for the study of antiferromagnets [39].

2. Derivation of x-ray MO effects

To start with, it is instructive to consider first the form of the dielectric tensor $\boldsymbol{\epsilon}$ for a cubic ferromagnetic material with the magnetization parallel to the x axis,

$$\boldsymbol{\epsilon} = \begin{pmatrix} \epsilon_{\parallel} & 0 & 0 \\ 0 & \epsilon_{\perp} & \epsilon_{yz} \\ 0 & -\epsilon_{yz} & \epsilon_{\perp} \end{pmatrix}. \tag{1}$$

Here x is assumed to be an axis of at least threefold symmetry. From the form of the tensor it can be recognized that there exist only two basic MO coefficients. The first one is the so-called Voigt parameter [40] defined as $Q^{(x)} = \mathrm{i}\epsilon_{yz}/\epsilon_{\perp}$ for $M \parallel x$. Similar definitions can be made for $Q^{(y)}$ and $Q^{(z)}$ in the case of general magnetization directions. The other MO coefficient is related to the difference between $\epsilon_{\parallel}$ and $\epsilon_{\perp}$, which in a cubic or isotropic material only is present due to the magnetization-related symmetry breaking. This parameter has no name; we may define it as $D = (\epsilon_{\parallel} - \epsilon_{\perp})/\bar{\epsilon}$, where $\bar{\epsilon}$ is an averaged diagonal element, $\bar{\epsilon} = \frac{1}{2}(\epsilon_{\parallel} + \epsilon_{\perp})$. On account of the Onsager relations it can be shown that Q is odd in the magnetization, whereas D is even in the magnetization (see, for example, [34]). All MO effects mentioned in section 1 that are odd in M can be shown to be linear in Q. Thus, those types of spectroscopies all determine Q. The MO effects that are even in M (i.e., proportional to $\langle M^2 \rangle$) can be shown to be linear in D, but also terms of order Q^2 (in lowest order proportional to $\langle M \rangle^2$) can occur. This is, for example, the case for the Voigt effect that is expressed by [34]

$$\theta_{\mathrm{V}} - \mathrm{i}\varepsilon_{\mathrm{V}} = \frac{\omega d \bar{n}}{4\mathrm{i}c}[D + Q^2], \tag{2}$$

where θ_{V} and ε_{V} are the Voigt rotation and ellipticity, respectively, and d is the thickness of the transmitted film. $\bar{n} = \sqrt{\bar{\epsilon}}$ is an averaged refractive index. The term Q^2 is in the x-ray regime much smaller than D, and can thus safely be neglected [34]. In the visible range, however,

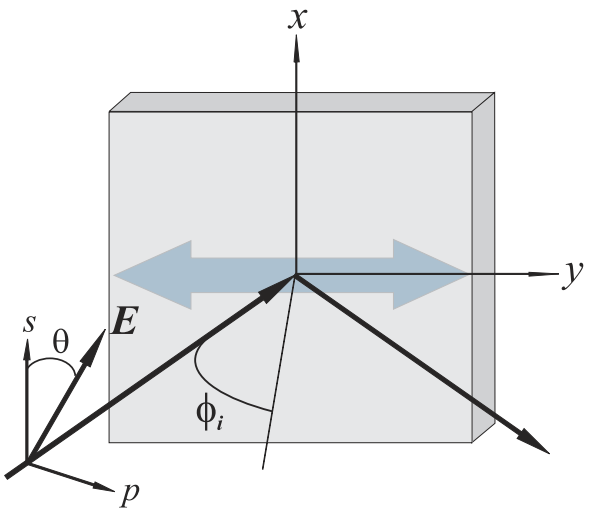

Figure 1. The geometry employed for detecting the MO effect that is sensitive to $\langle M \rangle$ in the reflection of linearly polarized light. The longitudinal magnetization M lies in the plane of refraction along y.

this is not the case. In this range the term Q^2 may even dominate the MO response (see, for example, [41]).

2.1. Odd-in-M magneto-x-ray effect

The first MO effect discussed here can be observed for a ferromagnet with either longitudinal or polar magnetization orientation. In the longitudinal geometry the existence of the MO effect was found recently [38]. We shall derive expressions for this effect in the longitudinal M configuration in more detail; the derivation for the polar configuration is analogous. The considered reflection geometry is depicted in figure 1. The incident linearly polarized light contains both s and p components, i.e., $\boldsymbol{E}^{\mathrm{i}} = (E_{\mathrm{s}}^{\mathrm{i}}, E_{\mathrm{p}}^{\mathrm{i}}) = (E^{\mathrm{i}} \cos\theta, E^{\mathrm{i}} \sin\theta)$, see figure 1. The intensity of the reflected light follows from the Fresnel reflection coefficients describing the reflectance at a dielectric/magnetic interface. For the MO effect in the present geometry the difference between $\epsilon_{\parallel}$ and $\epsilon_{\perp}$ can be neglected; i.e., we assume magnetic isotropy within the film plane. The Fresnel reflection coefficients for the longitudinal magnetization are then given by [42, 43]

$$\begin{aligned} r_{\mathrm{ss}} &= \frac{n_0 \cos\phi_{\mathrm{i}} - \bar{n} \cos\phi_{\mathrm{t}}}{n_0 \cos\phi_{\mathrm{i}} + \bar{n} \cos\phi_{\mathrm{t}}}, \\ r_{\mathrm{pp}} &= \frac{\bar{n} \cos\phi_{\mathrm{i}} - n_0 \cos\phi_{\mathrm{t}}}{\bar{n} \cos\phi_{\mathrm{i}} + n_0 \cos\phi_{\mathrm{t}}}, \\ r_{\mathrm{ps}} &= \frac{-\mathrm{i} n_0 \bar{n} Q \cos\phi_{\mathrm{i}} \sin\phi_{\mathrm{t}}}{(\bar{n} \cos\phi_{\mathrm{t}} + n_0 \cos\phi_{\mathrm{i}})(\bar{n} \cos\phi_{\mathrm{i}} + n_0 \cos\phi_{\mathrm{t}}) \cos\phi_{\mathrm{t}}}, \\ r_{\mathrm{sp}} &= -r_{\mathrm{ps}}. \end{aligned} \tag{3}$$

Here ϕ_{i} and ϕ_{t} are the angles of incidence and refraction, respectively, and n_0 is the refractive index of the dielectric medium. r_{sp} describes the coupling of an incident p linearly polarized wave to an out-going s polarized wave at the interface.

The reflectance of the light is defined by $R_\theta = I_\theta / I_0$, where I_θ is the reflected intensity and $I_0 (\equiv |E^{\mathrm{i}}|^2)$ the incident intensity. The reflectance for a fixed, saturated magnetization can

be expressed as

$$R_\theta = (|E_s^r|^2 + |E_p^r|^2)/I_0 = |r_{ss}\cos\theta + r_{sp}\sin\theta|^2 + |r_{pp}\sin\theta + r_{ps}\cos\theta|^2. \quad (4)$$

To obtain a magnetic signal in this geometry the reflectance has to be measured twice for two antiparallel directions of the magnetization. Under magnetization reversal, r_{ss} and r_{pp} are invariant, but r_{sp} and r_{ps} reverse sign, on account of the odd magnetization dependence of Q. The magnetic asymmetry in the reflected intensity becomes

$$\begin{aligned} R_\theta(+M) - R_\theta(-M) &= [r_{ss}r_{sp}^* + r_{ss}^*r_{sp} + r_{pp}r_{ps}^* + r_{pp}^*r_{ps}]\sin 2\theta \\ &= 2\,\mathrm{Re}[r_{ss}r_{sp}^* + r_{pp}r_{ps}^*]\sin 2\theta \\ &= 2\,\mathrm{Re}[(r_{ss} - r_{pp})r_{sp}^*]\sin 2\theta. \end{aligned} \quad (5)$$

This MO signal is linear in Q, analogous to the conventional L-MOKE signal, that requires a polarization state analysis, however. Conventional L-MOKE measurements are performed with either s or p linearly polarized light [43], but the present MO effect would *disappear* when either purely s or p linearly polarized light is used (corresponding to $\theta = 0$ or $\pi/2$). A maximum is expected for equal parts of s and p polarization, i.e., for $\theta = \pi/4$.

A normalized dichroic asymmetry can be defined by $A_L = [R_\theta(+M) - R_\theta(-M)]/[R_\theta(+M) + R_\theta(-M)]$. The final expression for this MO effect becomes

$$A_L \approx \frac{\mathrm{Re}[(r_{ss} - r_{pp})r_{sp}^*]\sin 2\theta}{|r_{ss}|^2\cos^2\theta + |r_{pp}|^2\sin^2\theta}. \quad (6)$$

The exact equation for the denominator would contain a term $|r_{ps}|^2$, which would lead to a higher-order term Q^3, that can safely be neglected.

This MO effect should be observable for a polar magnetization orientation, too. The reflection coefficients for M normal to the surface are equal to those given for the longitudinal magnetization in equation (3), except that for the polar magnetization orientation [42, 43] one has $r_{ps} = r_{sp}$, which in this geometry becomes

$$r_{ps} = \frac{-in_0\bar{n}Q\cos\phi_i}{(\bar{n}\cos\phi_t + n_0\cos\phi_i)(\bar{n}\cos\phi_i + n_0\cos\phi_t)}. \quad (7)$$

The expression for the dichroic asymmetry A_P for the polar magnetization is similar to equation (6), but with $(r_{ss} + r_{pp})r_{sp}^*$ in the numerator, and r_{sp} as listed above (equation (7)). Implications and properties of this MO effect are discussed below in section 3.

2.2. Even-in-M magneto-x-ray effect

The second MO effect emerged from the consideration that no magneto-x-ray effect in reflection has been reported that is even in M. In the visible range there exists the Voigt effect in reflection, that was first observed by Schäfer and Hubert [44]. The detection of this MO effect requires a polarization analysis of light reflected at normal incidence, something that is currently not feasible in the soft-x-ray regime. A further guiding consideration is the search for an MO reflection spectroscopy applicable to antiferromagnetic materials.

Our theoretical consideration led to such a magneto-x-ray effect that we recently observed [39]. In the following we shall define the measurement geometry and derive the expression for the MO effect. We now consider the situation of an antiferromagnetic material with an in-plane quantization axis (i.e., spin axis); a generalization to ferromagnetic materials is formulated further below. The magnetic moments directed along the quantization axis are supposed to lie either within the plane of refraction (longitudinal orientation) or be perpendicular to the plane of refraction (transversal orientation). This geometry is shown

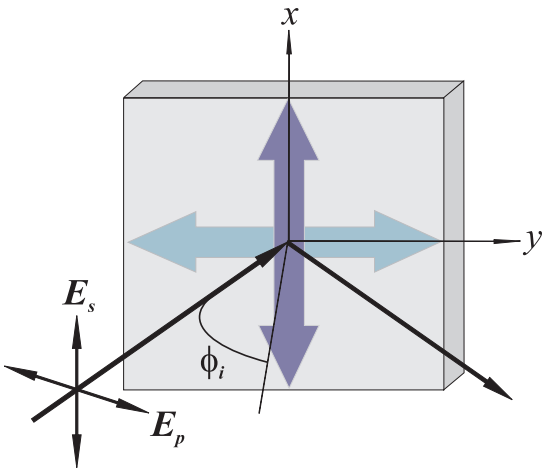

Figure 2. The geometry employed for the detection of the MO effect that is sensitive to $\langle M^2 \rangle$. The reflected intensity is determined for the quantization axis of the magnetic moments once perpendicular (i.e., transversal) and once parallel to the plane of refraction.

schematically in figure 2. Since the material is antiferromagnetic, Q is zero and the cross-reflection coefficients vanish, $r_{\rm sp} = r_{\rm ps} = 0$. The refraction index of the material depends—to lowest order in $\langle M^2 \rangle$—on the direction of the quantization axis. In principle we could work with Fresnel reflection coefficients $r_{\rm ss}$ and $r_{\rm pp}$ of the form (3), but now as well as the refractive index the angle of refraction also depends on the quantization axis. The material is birefringent on account of the spin axis, and thus two beams are present in the material. It is more convenient to use the Fresnel reflection coefficients for a birefringent crystal where the angles of refraction are eliminated by applying Snell's law. These adopt the form

$$r_{\rm ss} = \frac{n_0 \cos\phi_{\rm i} - (\varepsilon_{xx} - n_0^2 \sin\phi_{\rm i})^{1/2}}{n_0 \cos\phi_{\rm i} + (\varepsilon_{xx} - n_0^2 \sin\phi_{\rm i})^{1/2}}, \tag{8a}$$

$$r_{\rm pp} = \frac{(\varepsilon_{yy}\varepsilon_{zz})^{1/2} \cos\phi_{\rm i} - n_0(\varepsilon_{zz} - n_0^2 \sin\phi_{\rm i})^{1/2}}{(\varepsilon_{yy}\varepsilon_{zz})^{1/2} \cos\phi_{\rm i} + n_0(\varepsilon_{zz} - n_0^2 \sin\phi_{\rm i})^{1/2}}. \tag{8b}$$

The plane of refraction is the y–z plane (see figure 2), and the diagonal dielectric tensor elements ε_{ii} equal $\varepsilon_\parallel$ or $\varepsilon_\perp$, depending on the spin axis. The even-in-M MO effect can be detected with either s or p linearly polarized light. It follows from the reflectance difference $\Delta R = R_{\rm L} - R_{\rm T}$ between linearly polarized light reflected in the longitudinal ($R_{\rm L}$) and in the transversal ($R_{\rm T}$) geometry.

For s polarized incident light, this reflectance difference is given by

$$\Delta R_{\rm s} = |r_{\rm ss}^{\rm L}|^2 - |r_{\rm ss}^{\rm T}|^2, \tag{9}$$

while $\varepsilon_{xx} = \varepsilon_\perp, \varepsilon_\parallel$, for the longitudinal, transversal geometry, respectively. After substitution of these expressions in (8a), $\Delta R_{\rm s}$ can be derived by an expansion to first order in the small quantity $\varepsilon_\parallel - \varepsilon_\perp$, which leads to

$$\Delta R_{\rm s} \approx 2R_{\rm s}^0 \,{\rm Re}\left[\frac{(\varepsilon_\parallel - \varepsilon_\perp) n_0 \cos\phi_{\rm i}}{(\bar{\varepsilon} - n_0^2 \sin^2\phi_{\rm i})^{1/2}(\bar{\varepsilon} - n_0^2)}\right]. \tag{10}$$

$R_{\rm s}^0$ is the s mode reflectance for the isotropic, non-magnetic material. For p polarized light we have $\varepsilon_{yy} = \varepsilon_{zz} = \varepsilon_\perp$, and $\varepsilon_{yy} = \varepsilon_\parallel$, $\varepsilon_{zz} = \varepsilon_\perp$, for the transversal and longitudinal geometry,

respectively. A similar derivation yields for ΔR_p

$$\Delta R_\mathrm{p} \approx 2R_\mathrm{p}^0 \,\mathrm{Re}\left[\frac{(\varepsilon_\parallel - \varepsilon_\perp) n_0 \cos\phi_\mathrm{i} (\bar{\varepsilon} - n_0^2 \sin^2\phi_\mathrm{i})^{1/2}}{\bar{\varepsilon}^2 \cos^2\phi_\mathrm{i} - n_0^2(\bar{\varepsilon} - n_0^2 \sin^2\phi_\mathrm{t})}\right]. \tag{11}$$

Equations (10) and (11) can both be brought into a similar form, using Snell's law for the isotropic material, $\bar{n}\sin\phi_\mathrm{t} = n_0 \sin\phi_\mathrm{i}$. The final expression for this MO effect reads

$$\Delta R_\mathrm{s,p} \approx 2R_\mathrm{s,p}^0 \,\mathrm{Re}\left[D\frac{n_0 \bar{n}\cos\phi_\mathrm{i}}{(\bar{n}^2 f_\mathrm{s,p} - n_0^2)\cos\phi_\mathrm{t}}\right], \tag{12}$$

where $f_\mathrm{s} = 1$, and $f_\mathrm{p} = \cos^2\phi_\mathrm{i}/\cos^2\phi_\mathrm{t}$.[4] A normalized quantity can be defined by $\Delta R/2R = (R_\mathrm{L} - R_\mathrm{T})/(R_\mathrm{L} + R_\mathrm{T})$, which is also given by equation (12), but without the factor $2R_\mathrm{s,p}^0$. At normal incidence the distinction between s and p polarization vanishes, and consistently the same expression follows from equation (12) for both s and p polarizations.

For ferromagnets the situation is different. Now the cross-mode reflection coefficients are non-zero for the longitudinal magnetization, whereas for the transversal magnetization an additional contribution to r_pp occurs. This additional contribution and the cross-mode coefficients contain terms of order Q and Q^2. As a result, in the reflectance difference for s polarized light ΔR_s (equation (10)) an extra term of order Q^2 occurs. For p polarized light, additional contributions to ΔR_p both of order Q and Q^2 appear. The term linear in Q is large compared to D, and has to be eliminated. This can be done by measuring R_T twice, for two antiparallel magnetization directions, and by defining $\bar{R}_\mathrm{T} \equiv [R_\mathrm{T}(+M) + R_\mathrm{T}(-M)]/2$. Consequently, in the reflectance difference $\Delta R_\mathrm{p} = R_\mathrm{L} - \bar{R}_\mathrm{T}$ the term linear in Q drops out, but the Q^2 term remains. Both ΔR_s and ΔR_p then have only additional Q^2 terms. In the visible regime the Q^2 term would be substantial or even dominating, but in the soft-x-ray regime it is negligible against D and can therefore be omitted [34].

3. Discussion and conclusions

We consider first the features of the MO effect that is odd in M. Both A_L and A_P can be measured at an angle of incidence ϕ_i between 0° and 90°. At normal incidence ($\phi_\mathrm{i} = 0$) r_ss equals $-r_\mathrm{pp}$, and therefore the asymmetry A_P disappears, contrary to the conventional polar MOKE signal that becomes *maximal* at perpendicular incidence [43]. The asymmetry A_L vanishes at normal incidence, too, but in the longitudinal configuration this occurs because r_ps vanishes for $\phi_\mathrm{t} = 0$. The different dependence of A_L and A_P on the angle of incidence could be exploited to distinguish different magnetization directions.

In figure 3 we present the angular dependence of room-temperature dichroic asymmetries A_L that were measured utilizing linearly polarized light of the UE56/1 undulator beamline at BESSY [45]. The measurements were performed using the BESSY soft-x-ray polarimeter [46]. The asymmetry A_L was measured for two energies at the Fe L_3-edge of an Fe/C multilayer with period thickness $d = 3.11$ nm and 100 periods [10]. As can be seen in figure 3, the asymmetry A_L vanishes at angles θ that are multiples of $\pi/2$, consistent with the angular dependence predicted by equation (6). Due to the θ-dependence of the denominator in equation (6) the asymmetry A_L can adopt its maximum or minimum for an angle shifted from $\theta = \pi/4$ (modulo $\pi/2$).

Apart from the θ-dependence of the asymmetry A_L, we can explicitly prove that the effect is linear in the magnetization M by deploying it to measure magnetization loops. In figure 4 we show as an example a magnetization loop that was recorded using the MO effect from

[4] In [39] the last term of equation (1) should read +1 which then gives the same as equation (12).

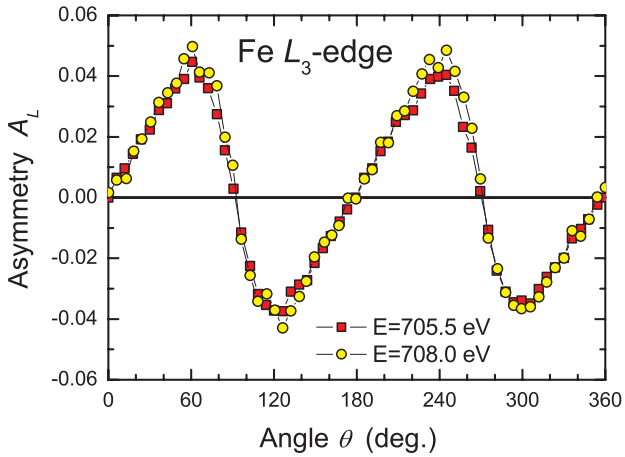

Figure 3. The measured dependence of the longitudinal dichroic asymmetry A_{L} on the angle θ between the polarization vector $\boldsymbol{E}$ and the s polarization direction. The asymmetry was measured on an Fe/C multilayer capped with 2.5 nm Al, for two photon energies near the Fe L_3-edge. The angle of incidence was $\phi_{\mathrm{i}} = 62°$.

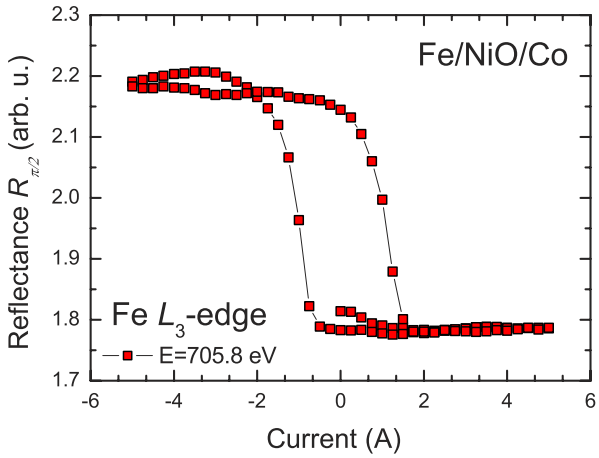

Figure 4. X-ray magnetization loop measured at the Fe L_3-edge of an Fe/NiO/Co trilayer, using the odd-in-M reflection effect. The angle θ (see figure 1) was 45°, while the angle of incidence was $\phi_{\mathrm{i}} = 70°$.

an Fe/NiO/Co trilayer (for details of the trilayer system, see [47]). The magnetization loop was measured at the Fe L_3-edge, for $\theta = 45°$, while the magnetic field is defined via the current in the coils. The magnetization loop shows element-selective magnetization reversal on Fe, yet due to the exchange coupling to the antiferromagnetic NiO layer the loop is not fully symmetric. A similar behaviour was previously reported for other exchange coupled ferromagnetic/antiferromagnetic layers [49].

As yet the conventional polar MO Kerr effect could not be observed in the soft-x-ray range. One of the reasons is that the absolute reflectance becomes quite small in the soft-x-ray range, and therefore a polarization analysis becomes unwieldy to be carried through. The MO effect discussed here could therefore be a practicable approach to investigate magnetic films with

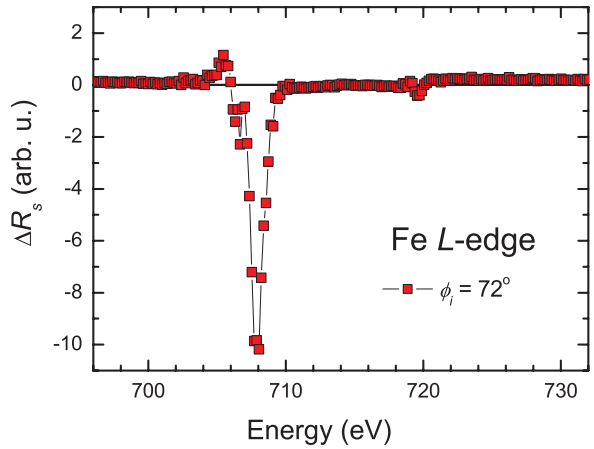

Figure 5. The XMLD-in-reflection spectrum measured with s polarized light at the Fe L-edge on a 30 nm Fe film, covered with 3 nm Al. Shown is the (unnormalized) signal $\Delta R_\mathrm{s} = R_\mathrm{L} - R_\mathrm{T}$.

perpendicular magnetization orientation even at grazing incidence where the reflected intensity is much larger. A minor drawback of the measurement geometry—as compared for example to the transversal geometry—is the polarization of the incoming light which is a mixture of s and p. Such polarization could for example be achieved by rotating the sample around the incoming light beam, or by modern insertion devices which rotate the polarization plane (see, for example, [48]).

Recent test measurements also unambiguously demonstrated the existence of this MO effect in the visible range [50]. In the polar geometry this MO effect could offer prospects in an appliance to read out magnetically stored information. As there is no need for the usual polarization analysis of the reflected light the read-out process could be simplified, so that the MO storage device can be simplified and possibly made more compact.

The XMLD-reflection-effect that is sensitive to $\langle M^2 \rangle$ has to be detected in somewhat different ways for ferromagnets and antiferromagnets. For ferromagnets an additional reflectivity measurement is required, yet the magnetization can simply be switched from longitudinal to transversal by applying a magnetic field. This is not possible for an antiferromagnet, however, where the sample has to be rotated by 90° about the surface normal without changing the s or p geometry to detect both R_L and R_T. Both approaches can satisfactorily be operated using the BESSY soft-x-ray polarimeter set-up, as we showed recently [39]. An (unnormalized) XMLD-in-reflection spectrum measured on an Fe film (30 nm thick, sputter-deposited on Si), using s polarized light and an incidence angle of 72° is shown in figure 5. The ΔR_s signal is large enough to be detected at the L_3-edge, whereas it is small at the L_2-edge. The large incidence angle is needed to obtain a sufficiently large reflectance at the L-edge. That after all a sizable XMLD-in-reflection signal can be measured stems from the $\bar{n}^2 - n_0^2$ term in the denominator. Writing $\bar{n} = 1 - \delta + \mathrm{i}\beta$, this term scales as $(\delta + \mathrm{i}\beta)/(2\delta^2 + 2\beta^2)$ for $n_0 = 1$, which thus becomes large for the small δ and β of the soft-x-ray range.

The XMLD-in-reflection effect is expected to exist at near-normal incidence, too, where $\cos\phi_\mathrm{i}$ and $\cos\phi_\mathrm{t}$ become $\approx$1, see equation (12). At normal incidence our expression for the normalized reflection difference $\Delta R/2R$ becomes equal to two times the expression that can be derived for the MO rotation of the reflection Voigt effect or Schäfer–Hubert effect [44], i.e., $2\theta_\mathrm{SH} \approx \Delta R/2R(\phi_\mathrm{i} = 0) = \mathrm{Re}[Dn_0\bar{n}/(\bar{n}^2 - n_0^2)]$, where now terms of

order Q^2 are neglected. Investigations of the latter quadratic MO effect were recently carried out in the visible energy range on thin ferromagnetic films [51–53]. The equation $2\theta_{\rm SH} \approx \Delta R/2R(\phi_{\rm i} = 0)$ illustrates the connection between the even-in-M MO effect discussed here and the Schäfer–Hubert effect, that are both related to the transmission Voigt effect also, as follows from equation (2). Evidently, the same MO coefficient D is basically determined by these three MO effects.

To summarize, we have analysed and discussed two magneto-x-ray effects that hold promise for the element-selective study of both ferro- and antiferromagnetic materials in magnetic x-ray reflection spectroscopy.

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