Probing the magnetic microstructure of an amorphous GdFe system with magnetic anomalous small angle x-ray scattering

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The combination of x-ray magnetic circular dichroism (X-MCD) with anomalous small angle x-ray scattering (ASAXS) allows to determine size distributions and correlations lengths in the nanometer range of magnetic precipitates in granular systems. Results on an amorphous GdFe system with a pronounced perpendicular magnetic anisotropy are reported. Standard ASAXS measurements taken at the Fe K edge provide information on the electronic structure yielding a correlation maximum at 75 Å and an average particle radius of 6 Å. The magnetic scattering curves (MASAXS) were obtained at the corresponding Gd L_{3,2} edges. Their intensities can be explained by magnetic contributions to the anomalous scattering factors f' and f". A change of sign in the MASAXS is observed between profiles taken at the L_3 and the L_2 edge and with the change of circular polarization as expected from X-MCD. © 1998 American Institute of Physics.

I. INTRODUCTION

A fundamental understanding of magnetic microstructures is an outstanding challenge both in current research of magnetism and its technological applications. Thereby reliable information on the electronic and magnetic structure on a typical length scale of 1–100 nm is mandatory. Among other recent observations of novel phenomena like the occurrence of the GMR, quantum oscillations or the magnetic in-plane anisotropy in granular systems, the origin of the perpendicular magnetic anisotropy in magnetic thin films or multilayered systems, the origin of the perpendicular magnetic anisotropy in granular thin GdFe films is in particular still an open problem.

An established technique to study size distributions and correlations of particles in the nm range is the small angle x-ray scattering (SAXS). Using tunable x rays with high brilliance being available at synchrotron sources the mode of contrast enhancement (anomalous SAXS=ASAXS) can be engaged, i.e., involving the element-specific anomalous scattering amplitude f_i'(E), which varies with energy by about 20% in the vicinity of absorption edges, thus providing more detailed structural information on multicomponent systems.

In a two-phase model the scattering contrast \Delta c in SAXS is given by \langle n_1 f_1 - n_2 f_2 \rangle with n_i, f_i being the density and atomic scattering amplitudes of phase i. The cross section (d\sigma/d\Omega) is proportional to \Delta c^2 which in the case of anomalous scattering can be related to (n_1 = n_2)

\[
\frac{d\delta}{d\Omega} = |f(E,Z)|^2 = |f_0 + f'(E) + if''(E)|^2, \tag{1}
\]

with the atomic form factor f_0 = Z (atomic number) and f' and f" being the additional anomalous contributions. f' and f" are connected to each other via a Kramers–Kronig relation, whence f" can be related to the absorption coefficient \mu(E) via the optical theorem

\[
f''(E) = \frac{mcE}{4\pi e^2 \hbar} \mu(E). \tag{2}
\]

The effect of x-ray magnetic circular dichroism (X-MCD), i.e., the dependence of the absorption of circular polarized x rays on the projection of the magnetization onto the photon propagation direction (\hat{e}_z) in ferromagnetic samples occurs in the vicinity of inner-core absorption edges. Due to angular momentum conservation in the absorption process the photoelectron acquires both an expectation value of the spin \langle \sigma_z \rangle and the orbital \langle l_z \rangle momentum projected onto \hat{e}_z. It can therefore serve as a local probe for the spin and orbital polarization of the absorbing atom according to the principle of Pauli. \langle \sigma_z \rangle amounts to −50% and +25% at the L_2 and L_3 edges, while \langle l_z \rangle = +75% at both L_2,3 edges. X-MCD has become a powerful tool for the element-specific and symmetry-selective investigation of the local magnetic structure on an atomic scale. Applying magneto-optical sum rules, it is possible to determine in certain cases spin and orbital moments separately. Beyond this local magnetic structure a spin-dependent contribution has been manifested in the extended x-ray absorption fine structure (EXAFS)

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range (magnetic EXAFS=MEXAFS), too, which allows to study the magnetic short-range order in multicomponent systems even on a larger size scale up to 20 Å.

The potential of X-MCD, however, is not restricted to the study of absorption profiles. In principle every method used in spectroscopy or crystallography, where the absorption coefficient for parallel/antiparallel alignment of magnetic electrons relative to the magnetic scattering precipitates. Given the magnetic orientation of the absorbing atoms onto the magnetic scattering profiles of the amorphous GdFe system taken at the Fe K-edge and the Gd L₃ edge.

FIG. 1. ASAXS (●) and MASAXS (◇) scattering profiles of the amorphous GdFe system.
exhibiting a rectangular hysteresis loop with a magnetic coercive field of \( \approx 20 \text{ mT} \).

**III. RESULTS AND DISCUSSIONS**

In Fig. 1 the magnetic scattering curve intensity obtained in that way versus momentum transfer \( Q \) measured at the Gd \( L_3 \) edge (\( E = 7243 \text{ eV} \)) is presented in comparison with the ASAXS profile obtained at the corresponding Fe \( K \) edge indicating the gross similarity of the electronic and magnetic structure. The profile can be interpreted as due to two size distributions, where the \( Q^{-4} \) behavior at small \( Q \) values can be attributed to large particles. After a pronounced maximum at \( Q = 0.06 \text{ Å}^{-1} \), which can be interpreted as a correlation maximum, the tail of a size distribution of smaller particles can be observed.

Fit procedures taking into account a log-normal distribution to the experimental data including a correlation yielded a correlation length of 74.9 Å and size of the particle radius of 5.3 Å with slightly enhanced values for the magnetic case (76.6 Å and 5.8 Å, respectively). The results are shown in Fig. 2, where the \( Q^{-4} \) tail of the large particles had been subtracted. Corresponding EXAFS and MEXAFS studies indicate no wide range ordering compared to pure bcc Fe. Corresponding EXAFS and MEXAFS studies indicate no wide range ordering compared to pure bcc Fe. This points to a rather complex structure of the system studied. Although the crystal structure seems to be amorphous, there is to some extent an ordered chemical structure, which is consistent with the assumption that column-like structures are formed in that magneto-optical films. Furthermore, the observed magnetic anisotropy could also be related to those columns. On the other hand, the magnetic correlation observed in the MASAXS would then originate from a chemical inhomogeneity.

The intensity of the MASAXS profile can be related to accurate experimental measurements of MEXAFS in a wide range around the Gd \( L_3 \) edge with the help of the optical theorem [Eq. (2)] and a Kramers–Kronig relation. The obtained results in a pure Gd system for \( f' \), \( f'' \), and \( f' \), \( f'' \), respectively, as function of energy are shown in Fig. 3. From these data the contrast ratio between ASAXS and MASAXS observed in Fig. 1 can be directly deduced. It is interesting that this ratio is larger than the dichroic effect at \( E = 7243 \text{ eV} \) observed in absorption due to the large contribution of \( f'' \). However, similar enhanced effects have also been observed in magnetic resonant scattering in Ni. Characteristic features of X-MCD can be manifested by performing the MASAXS at the corresponding spin-orbit split \( L_2 \) edge of Gd. Taking into account the different values for \( f' \) at the \( L_{3,2} \) edges they should be a change in sign of the scattering profile comparing the results at the \( L_{3,2} \) edges. The MASAXS profiles shown in Fig. 4 exactly follow this feature as the direction of magnetization profile at the \( L_2 \) edge is decreased compared to the \( L_3 \) edge as expected. As the dichroic signal depends on the relative orientation of the circular polarization photons and the magnetization of the sample MASAXS spectra taken with reversed photon helicity, i.e., above and below the orbital plane (see Fig. 5) proof again a change of sign as expected.

**IV. OUTLOOK AND CONCLUSION**

Magnetic small angle x-ray scattering is a new technique, which allows valuable insights into structural characteristics of magnetic particles in granular systems and diluted alloys on a nm scale. Additional support to establish reliable models of the magnetic structures will be provided by magnetic imaging techniques allowing a quantitative information on the local magnetization with high resolution.

**ACKNOWLEDGMENT**

This work was supported by the German federal ministry of education, science, research and technology (BMBF) Project No. 05-621-WAA-6.

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