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Scattering-angle dependence of the magnetic circular dichroism of resonant inelastic X-ray scattering

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The scattering-angle dependence of the magnetic circular dichroism spectra of the resonant inelastic x-ray scattering in the Gd 3d-2p$_{3/2}$ radiative transitions of the ferrimagnetic Gd-Co compound was observed when the incident x-ray energies were lower, exact and sufficiently higher than the Gd L$_{III}$ absorption edge. The obtained results of not only the high-energy off-resonance, but also the low-energy off-resonance and the on-resonance, correspond well with the recent theoretical explanation for the high-energy off-resonant condition.

Keywords: resonant inelastic x-ray scattering; magnetic circular dichroism; scattering angle dependence.

1. Introduction

Magnetic circular dichroism (MCD) measurement of resonant inelastic x-ray scattering (RIXS) is a direct experimental technique used to obtain the final spin state of excited magnetic elements (Iwazumi et al., 1997 & 1998 and Nakamura et al., 1998). In the lanthanoid elements we can observe a large MCD-RIXS signal in the radiative transition from the 3d or 4d level to the 2p level, even if there is no interaction between the magnetic 4f states and the 5d or higher conduction bands, because the 2p core excitation always has the MCD expected from the transition probability determined by the Clebsch-Gordon coefficient. Theoretical calculations of the MCD of x-ray fluorescence spectra, which correspond to the RIXS at the high-energy off-resonance, were performed using a theoretical description of spin-polarized 2p-photoemission and atomic-multiplet calculations of the 3d-2p and 4d-2p radiative decay (de Groot et al., 1997 and Jo & Tanaka, 1998). In the same paper, de Groot et al. mentioned the angular dependence of the MCD-RIXS. According to their theoretical explanation, the circular-polarized RIXS and the linear-polarized RIXS caused by circular-polarized incident x-rays show different scattering-angle dependence; therefore, the MCD-RIXS has a sinusoidal dependence on the incident angle (φ) as that between the incident x-ray and the normal to the magnetization direction of the Gd 4f electrons, and a monotonic increasing or decreasing dependence toward the scattering angle (θ) as that between the outgoing x-ray and the normal to the magnetization direction (see the inset of Fig. 1). In the present study we tried to confirm their theoretical prediction for the high-energy off-resonance, and present the scattering-angle dependence of the MCD-RIXS at the low-energy off-resonant and on-resonant conditions.

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2. Experiments

The experiment was performed at the elliptical multipole wiggler beamline (28B) of the Photon Factory, Institute of Materials Structure Science (Iwazumi et al. 1995). This beamline is equipped with focusing optics, and provides a 2.0 mm horizontal and 0.2 mm vertical focused beam. With a Si(111) monochromator, the flux of the incident beam is estimated to be ~10^{11} photons/s, and the degree of circular polarization of this beam may not be very different from the calculated value, P_c = -0.55, in the energy range around the Gd L$_{III}$ edge. The used specimen was amorphous Gd-Co sputtered on a polyimide film. The composition of Gd-Co was 33 at.% Gd and 67 at.% Co, measured by the inductively coupled plasma method. The sample film was mounted at the focus point and between the pole pieces of an electro-magnet so that the magnetization of the sample could be reversed periodically. The incident angle (φ) was fixed at 74°.

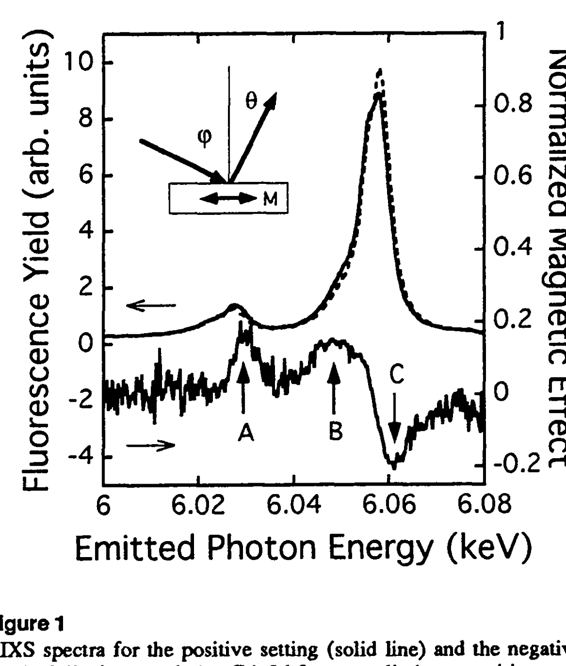

Figure 1
RIXS spectra for the positive setting (solid line) and the negative one (dashed line) around the Gd 3d-2p$_{3/2}$ radiative transitions and its normalized MCD-RIXS spectrum when the incident photon energy was 7270 eV, sufficiently higher than the Gd L$_{III}$ absorption edge, 7248 eV; the scattering angle (θ) was 25°. The inset shows the definition of the incident angle (φ) and the scattering angle (θ) to the magnetization direction (M).

The scattered radiation was analyzed in the vertical plane using a cylindrical-bent Ge(333) crystal. The analyzed x-rays were detected by a position-sensitive proportional counter (PSPC). Both the sample and the detector were arranged on the center axis of the analyzing crystal cylinder, so that we could obtain sagital-focused and meridional-energy-dispersive x-rays. The analyzing crystal and the detector can be rotated around the sample so as to vary the scattering angle. Because of its geometry, the total energy resolution of this apparatus is affected by the scattering angle. To avoid any total-energy-resolution change when the scattering angle has been changed, the position resolution of the PSPC was set to a not-best condition on purpose. Therefore, the total energy resolutions of the present study became 2.7 eV around the Gd L_α fluorescence lines. Incident x-rays have a left-circular polarization with minus helicity. We defined the positive (negative) direction of a magnetic field when the inner product between the **B** vector and the x-ray wave vector was positive (negative). The MCD was defined by subtracting the emission x-rays detected on the positive direction from that on the negative one, and the normalized MCD was defined by dividing the magnetic effect by the sum.

3. Results and Discussion

Figure 1 shows the Gd $3d$-$2p_{3/2}$ radiative transitions for the positive setting (solid line) and the negative one (dashed line) and its normalized MCD spectrum when the incident photon energy was 7270 eV, which was sufficiently higher than the Gd L_{III} absorption edge (7248 eV), and the scattering angle (θ) was 25°. Each emission spectrum has two peaks around 6027 eV and 6057 eV. These peaks correspond to the diagram fluorescence lines, $L_{\alpha 2}$ and $L_{\alpha 1}$, respectively. These peaks have small shoulders on the low-energy side, which are satellites of the diagram lines from multiplet splitting. The normalized MCD spectrum has 3 obvious structures at around 6029 eV, 6048 eV and 6061 eV, as indicated by the arrows labeled A, B and C in the figure. The positive peak A and the negative peak C correspond to the MCD in the $3d_{3/2}$-$2p_{3/2}$ and $3d_{5/2}$-$2p_{3/2}$ diagram lines, respectively, and the positive peak B corresponds to the MCD in the satellite of the $3d_{5/2}$-$2p_{3/2}$ diagram line. These MCD features have already been represented well by the theoretical calculations (de Groot et al., 1997 and Jo & Tanaka, 1998).

Figure 2 shows the scattering-angle dependence of the absolute peak value of peaks A, B and C indicated in Fig. 1. The incident photon energy in Fig. 2(a) was 7270 eV, which was sufficiently higher than the Gd L_{III} absorption edge. This result agrees almost with the theoretical explanation of their monotonic increasing or decreasing dependence toward the scattering angle by de Groot et al. (1997). The incident photon energy in Fig. 2(b) was 7248 eV, which was the energy of the white line of the Gd L_{III} absorption edge, and that in Fig. 2(c) was 7240 eV, at which quadrupolar excitation occured together with the normal dipolar excitation (Iwazumi et al. 1997). These results also show a rough monotonic increasing or decreasing dependence toward the scattering angle. In a previous study, we found magnetic resonance effects, especially the appearance of a new MCD-RIXS structure, around the absorption edge (Iwazumi et al. 1997). Theoretical MCD-RIXS calculations were performed only for the high-energy off-resonant condition, and the appearance of the new MCD-RIXS structure of the on-resonance is not yet theoretically reported. The present results show that the scattering-angle dependence of the MCD-RIXS appeared only at the on-resonance is similar to that at the high-energy off-

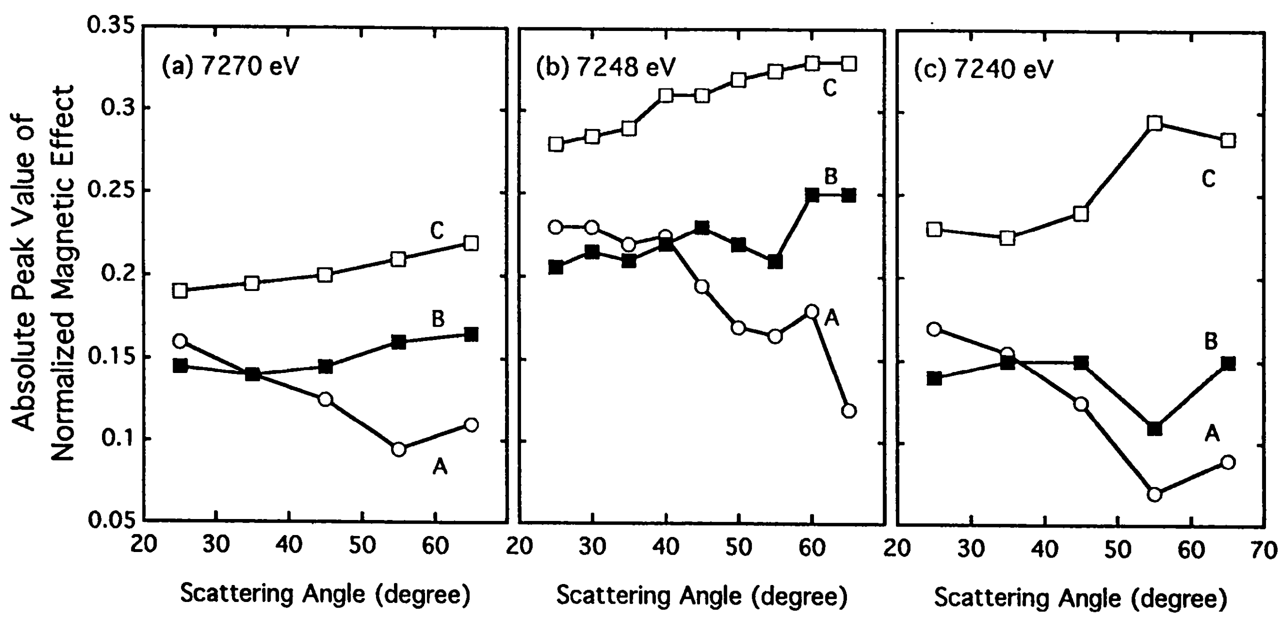

Figure 2
Scattering-angle dependence of the absolute peak value of peaks A, B and C indicated in Fig. 1. The incident photon energies were (a) 7270 eV, (b) 7248 eV and (c) 7240 eV, respectively.

resonance.

In summary, we have measured the scattering angle dependencies of the MCD-RIXS spectra in the Gd 3d-2$p_{3/2}$ radiative transitions of the ferrimagnetic Gd-Co compound. The obtained results of not only the high-energy off-resonance, but also the low-energy off-resonance and the on-resonance, correspond well with the theoretical explanation for the high-energy off-resonant condition.

This work has been performed with the approval of the Photon Factory Advisory Committee (Proposal No. 97G287).

References

de Groot, F. M. F., Nakazawa, M., Kotani, A., Krisch, M. H. & Sette, F. (1997). Phys. Rev. B56, 7285-7292.

Iwazumi, T., Koyama, A. & Sakurai, Y. (1995). Rev. Sci. Instrum. **66**, 1691-3.

Iwazumi, T., Kobayashi, K., Kishimoto, S., Nakamura, T., Nanao, S., Ohsawa, D., Katano, R. & Isozumi, Y. (1997). Phys. Rev. B56, R14267-14270.

Iwazumi, T., Kobayashi, K., Kishimoto, S., Nakamura, T., Nanao, S., Ohsawa, D., Katano, R., Isozumi, Y. & Maruyama, H. (1998). J. Electron Spectrosc. and Relat. Phenom. **92**, 257-260.

Jo, T. & Tanaka, A. (1998). J. Phys. Soc. Jpn. **67**, 1457-1465.

Nakamura, T., Nanao, S., Iwazumi, T., Kobayashi, K., Kishimoto, S., Ohsawa, D., Katano, R. & Isozumi, Y. (1998). J. Electron Spectrosc. and Relat. Phenom. **92**, 261-264.

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