Fe *K*-edge x-ray magnetic circular dichroism study in R_6Fe_{23} (R=Ho and Y) compounds near compensation temperature

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We present a x-ray magnetic circular dichroism (XMCD) study performed at the Fe *K* edge in R_6Fe_{23} compounds exhibiting magnetic compensation (R=Ho and Y). The Fe *K*-edge XMCD signal has been identified as due to both Fe itself and rare-earth contributions. Following a simple two-sublattices model for the analysis of the dichroic signal the contribution of the rare-earth sublattice to total Fe *K*-edge XMCD signal has been extracted and proven to be directly correlated to the R magnetic moment. © *2000 American Institute of Physics.* [S0021-8979(00)09413-5]

I. INTRODUCTION

In recent years, a large body of research has been developed for the study of the magnetic properties of several rare-earth transition-metal (R–M) compounds by means of the x-ray magnetic circular dichroism (XMCD) technique.[1–3] Special interest has been focused on the XMCD at the $L_{2,3}$ edges of rare earth, probing the R$-5d$ states, as they mediate the magnetic interaction between the R and M sublattices.[4] However, the interpretation of XMCD at these edges is a matter of debate because they do not follow simple rules.[5–8] In a previous work we have proposed an alternative way to overcome this problem and to magnetically characterize the R$-5d$ states which can be found by studying the XMCD at the transition-metal *K*-edge in R–M compounds.[9] The experimental findings have shown that the Fe *K*-edge XMCD signals are directly related to the Fe$(4p,3d)-$R$(5d)$ hybridized band, so that it would be possible to monitor the magnetism of the $5d$ states.[9,10]

To further clarify this behavior we present in this work an XMCD study performed at the Fe *K* edge in the R_6Fe_{23} series showing compensation phenomenon. In these systems the coupling between R and Fe moments is antiferromagnetic for heavy rare earths. It implies that the total magnetization starts to decrease somewhat below the Curie temperature owing to the increasing ordering of $4f$ moments, so that the total magnetization may vanish at a given temperature (defined as a compensation temperature T_{CP}) and at temperatures below T_{CP} the magnetization of the R sublattice prevails.

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II. EXPERIMENT

Polycrystalline R_6Fe_{23} samples with R=(Y, Tb, Dy, Ho and Er) were prepared following standard procedures.[11] Both phase and structural analysis were performed by using a standard x-ray diffractometer. X-ray analysis showed that all the samples are single phase. The magnetic measurements were performed by using commercial superconducting quantum interference device magnetometer (Quantum Design MPMS-S5) equipped with an ac susceptibility attachment.

XMCD experiments were performed at the Fe *K* edge on Y_6Fe_{23} and Ho_6Fe_{23} compounds at the x-ray undulator beamline BL39XU of the SPring8.[12] We have selected Ho_6Fe_{23} as it presents the most convenient T_{CP}. The storage ring was operated with a beam energy of 8 GeV and a maximum stored current of 70 mA. The x-ray radiation was monochromatized using a Si(111) fixed-exit double-crystal monochromator. The XMCD spectra were recorded in the transmission mode using the helicity modulation technique[13] at different fixed temperatures from room temperature down to 50 K using a closed-cycle He cryostat. Samples were magnetized under the action of a 0.6 T magnetic field applied at 45° away from the incident-beam direction. The degree of circular polarization was estimated to be >90%.

The spin-dependent absorption coefficient was then obtained as the difference of the absorption coefficient $\mu_c=(\mu^- - \mu^+)$ for antiparallel μ^- and parallel μ^+ orientation of the photon helicity and sample magnetization. The spectra were normalized to the averaged absorption coefficient at high energy μ_0 in order to eliminate the dependence of the absorption on the sample thickness, so that $\mu_c(E)/\mu_0=[\mu^-(E)-\mu^+(E)]/\mu_0$ corresponds to the dimensionless spin-dependent absorption coefficient. The origin of the en-

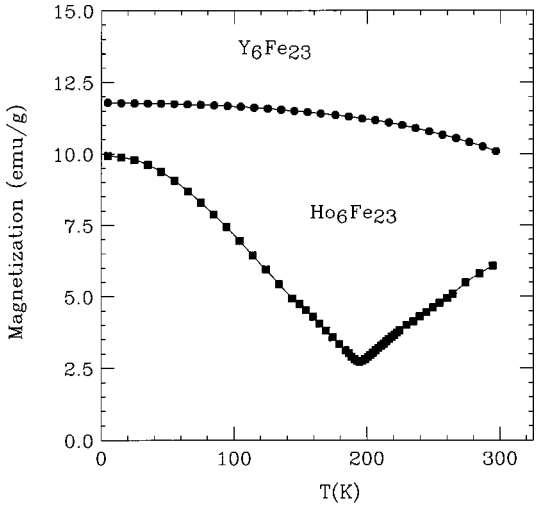

FIG. 1. Thermal dependence of the magnetization of Y_6Fe_{23} and Ho_6Fe_{23} under an applied field of 10 kOe.

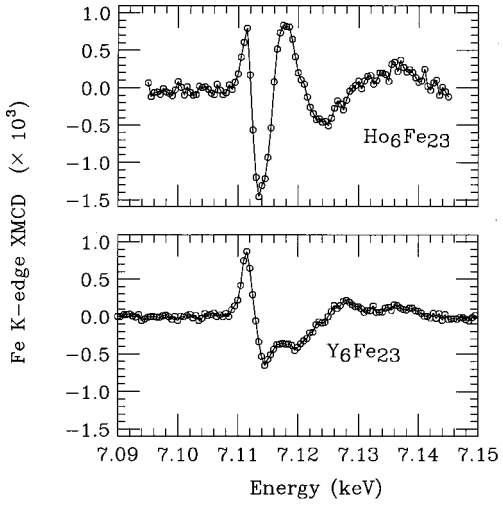

FIG. 2. (a) Fe *K*-edge XMCD spectrum of Y_6Fe_{23} (bottom panel) and Ho_6Fe_{23} (top panel) recorded at room temperature.

ergy scale was chosen at the inflection point of the absorption edge.

III. RESULTS AND DISCUSSION

The thermal dependence of the magnetization of Y_6Fe_{23} and Ho_6Fe_{23} measured under an applied field of 10 kOe are shown in Fig. 1. The magnetization (M) vs temperature (T) behavior of Y_6Fe_{23} shows a slight increase as the temperature decreases corresponding to the enhancement of the Fe magnetic moment at low temperatures.[11] On the contrary, the magnetization of Ho_6Fe_{23} decreases when cooling down from room temperature up to reach a minimum at about $T = 195$ K and then shows a continuous increase up to the lowest measured temperature. This behavior is typical of magnetic compensation between the Fe and Ho sublattices. The commonly accepted model to account for the magnetic behavior of R–Fe intermetallics is based on the existence of an antiferromagnetic coupling between Fe spins and R($4f$) spins.[4] For compounds in which R is a light rare-earth element ($J = L - S$) this implies that the total rare-earth moment (gJ) is coupled parallel to the Fe moments. By contrast, when R is a heavy rare-earth element ($J = L + S$) the total rare-earth moment is antiparallel coupled to the Fe moment. The latter is the case of Ho_6Fe_{23}: the Fe sublattice magnetization dominates at high temperatures but as the temperature decreases the increase of the Ho magnetic moment is large enough to compensate Fe magnetization and therefore total magnetization vanishes. Below this compensation temperature magnetization of the Ho sublattice prevails.[11,14,15] Under such particular behavior the Fe *K*-edge XMCD signals are expected to strongly vary as a function of temperature. In particular the change of sign of the signal is expected to occur below T_{CP}. This latter is due to the fact that below this temperature the magnetization of Fe sublattice is opposite to the total one of the sample which is fixed by the action of the external field applied. This is shown in Fig. 2, where the Fe *K*-edge signal of Y_6Fe_{23} recorded at room temperature is compared to that of Ho_6Fe_{23}. The shape of the Fe *K*-edge XMCD signal of Y_6Fe_{23} is closely related to that of Fe metal: the spectrum shows a 4 eV wide positive peak at the absorption threshold (~7.112 keV) and a broader negative dip at higher energies. By contrast, the Fe *K*-edge signal of Ho_6Fe_{23} shows a dramatic change with respect to those of the Y (nonmagnetic R-based compound) as an additional positive feature arises at ~7.118 keV, just on the dip of the Y_6Fe_{23} signal, that we address as a Ho contribution. Indeed, Fe *K*-edge XMCD signals are directly related to the Fe($4p$,$3d$)–R($5d$) hybridized band, so that the extracted signals resemble the magnetic state of the rare earth through the splitting of the $5d$ component due to the exchange interaction with the $4f$ magnetic moments.[9,10]

The intensity of this additional feature is higher than the first positive peak. These results are in agreement with previous findings on the $R_2Fe_{14}B$ series.[9,10] Consequently, it is demonstrated that the dependence of the Fe *K*-edge XMCD signals in R–Fe intermetallics are markedly different as a function of the rare-earth nature, i.e., nonmagnetic, light and heavy rare-earth cases.

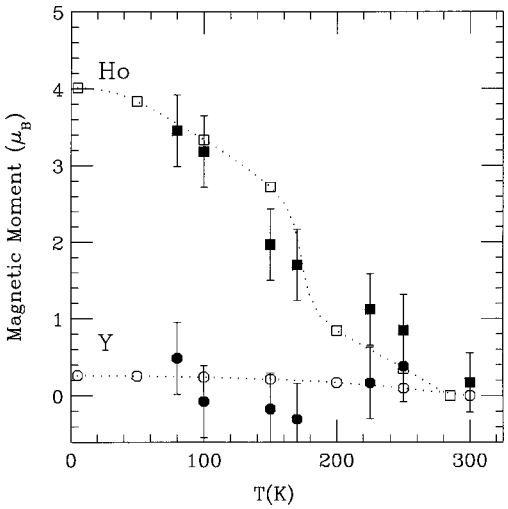

FIG. 3. Comparison between the thermal dependence of μ_{Ho} (□) and μ_{Fe} (○) derived from magnetization data and the normalized intensity of Ho (solid □) and Fe (solid ○) contributions to the XMCD spectrum.

Finally, trying to get a deeper insight into the correctness of our analysis, we have compared the intensity of peaks centered at $E=7.112\,\mathrm{keV}$ (P_{Fe}) and $E=7.118\,\mathrm{keV}$ (P_{Ho}), that we ascribed as being due to Fe and Ho, respectively, to the magnitude of μ_{Fe} and μ_{Ho} magnetic moments derived from our magnetization data following a simple two-sublattice model. If our assignments are correct, what is expected is a greater increase of the intensity of the second peak as temperature decreases, corresponding to the huge enhancement of the Ho magnetic moment needed to compensate Fe sublattice magnetization. This comparison is shown in Fig. 3, which clearly demonstrates how the intensity of the two peaks P_{Fe} and P_{Ho} follows the thermal dependence of Fe and Ho magnetic moments, respectively.

Summarizing, in this work we have presented an XMCD study at the iron *K* edge in the R_6Fe_{23} series. This study identifies the influence of the rare-earth magnetic state on the Fe *K*-edge XMCD signals. Our results demonstrate that the contribution of both Fe and R to the Fe *K*-edge XMCD spectra can be easily isolated following its temperature-dependent behavior through T_{CP}, and that they can be directly correlated to the Fe and R magnetic moments.

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