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Rapid note

Giant magnetic susceptibility in Fe and Co epitaxial films

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Abstract. The *static* magnetic susceptibility of *subnanometer thick* Co and Fe films at the Curie temperature is enhanced by *four orders of magnitude* with respect to bulk samples.

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One of the major achievements of contemporary physics is the understanding of the mechanism leading to second order phase transitions [1]: the phase transition occurs via the formation of large regions of statistically correlated spins [1]. Within each "spin block" all spins are aligned, the various spin blocks, however, are disordered. In theory, the linear size ξ of the spin blocks diverges to infinity at the Curie temperature T_c.

A sure sign of the formation of spin blocks is the temperature dependence of the *magnetic susceptibility* $\chi = \lim_{H \to 0} [M(H) - M(0)]/H$. According to simple arguments based on the Renormalization Group method, ξ and χ are related by the equation [1, 2]

$$\chi(T) \approx \xi^2(T) * C/T_c \quad (1)$$

C being the Curie constant. *Thus, the temperature dependence of the susceptibility should immediately pick up the divergence of* ξ *at* T_c.

Clearly, divergences exist only in a mathematical sense. Experimentally realized maximum values of χ in *bulk* Fe, Co *and* Ni are of the order of 10 [3]. At least two factors limit the growth of ξ (and consequently of χ) to infinity: i) the existence of static (Weiss) domains developing at defects – like surfaces – (in other words, the nonvanishing demagnetization factor) and ii) the experimentally achievable temperature accuracy. In bulk, the mean field result $\xi(T) = [T_c/(T - T_c)]^{1/2}$ can be used for a rough estimare of this last factor: inserting in (1) gives $\chi = C/(T - T_c)$. With $C \approx 1$ K, $T_c \approx 1000$ K, an accuracy of 0.01 K is necessary to observe $\chi = 100$. This accuracy was not realized in measuring the static susceptibility of bulk samples [3]. AC-susceptibility measurements on thin Gd films [4] report larger maximum values (about 1000) of χ_{AC}. On the basis of their results these authors anticipate that improving the quality of thin films could lead to very high magnetic susceptibilities at T_c.

In this Note, we have applied the experimental technique based on the magneto optic Kerr effect [5] to measure the susceptibility of Fe and Co thin films. The samples consisted of *subnanometer* thick Fe and Co films grown epitaxially on top of a non-magnetic substrate [6]. For details of the sample preparation see [7, 8]. Epitaxial growth on *non-magnetic* substrates allows the preparation of Fe and Co samples, which are chemically and electronically very similar to bulk crystals [9], but have a different dimensionality: While $d = 3$ *for bulk samples*, $d = 2$ for epitaxial films, because the magnetism is confined to the *two-dimensional plane* defined by the film. The experimental technique uses the fact that the intensity of the light reflected from a mirror-like surface depends on the magnetization within a 20 nm thick surface sheet [5]. Thus, provided the experimental apparatus is sensitive enough to pick up the small signal originating from the topmost 0.2 nm thick layer, the magnetization of ultra thin films becomes accessible in a very simple set up.

Figure 1 reports the temperature dependence of M for Co on Cu(100) and Fe on W(110) at *zero applied magnetic field* for a wide temperature range. Within the context of this paper M is a number between 0 – above T_c – and 1 – at $T = 0$ K. Therefore we divide the measured Kerr values by the Kerr signal at 0 K. The 0 K-Kerr signal is obtained by extrapolating the low temperature part of the $M(T)$ curve in Fig. 1 to 0 K, using a standard spin wave fit, according to the method of [10]. We estimate the error of this procedure – in virtue of the smooth, almost linear T-dependence of M – to be less than 10%.

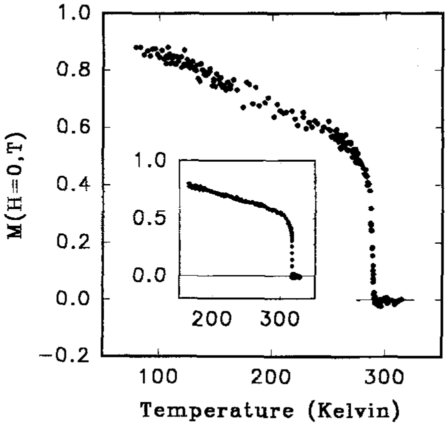

Fig. 1. Temperature dependence of the zero field magnetization for 1.0±0.3 ML Co on Cu(100) and 1.4±0.3 ML Fe on $W(110)$ (inset). Both samples show a well defined transition temperature

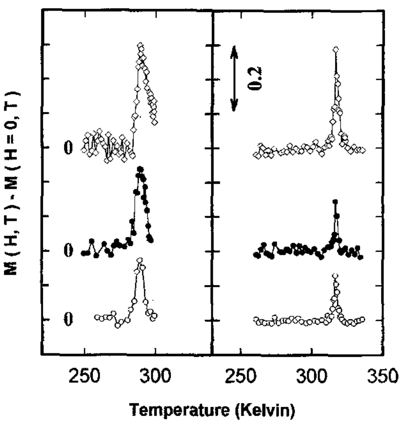

Fig. 2. left: Temperature dependence of $[M(H,T)-M(H=0,T)]$ for the Co film of Fig. 1 at selected values of the applied magnetic field. We introduce an offset for clarity. The magnetic field is given in units of $4\pi\ M_S^{Co}$, where M_S^{Co} is the spontaneous magnetization of bulk Co in Gauss: $4\pi\ M_S^{Co}=18532$ Gauss [4]. Open circles: $H=6.47*10^{-7}$ (corresponds to 10 mGauss). Full circles: $H=183*10^{-6}$ (34 mGauss). Squares: $H=1.08*10^{-4}$ (2 Gauss). right: Temperature dependence of $[M(H,T)-M(H=0,T)]$ for the Fe film of Fig. 1 at selected values of the applied magnetic field. We introduce an offset for clarity. The magnetic field is given in units of $4\pi\ M_S^{Fe}$, where M_S^{Fe} is the spontaneous magnetization of bulk Fe in Gauss: $4\pi\ M_S^{Fe}=222189$ Gauss [4]. Open circles: $H=4.5*10^{-7}$ (10 mGauss). Full circles: $H=2.25*10^{-6}$ (50mGauss). Squares: $H=4.5*10^{-5}$ (1 Gauss)

The feature of Fig. 1 relevant to this paper is the sharp loss of long range order at a well defined temperature, which we identify as the Curie temperature of the system. Notice that in the monolayer range T_c is reduced with respect to the bulk values of 1043 K (Fe) and 1394 K (Co), a well established fact in thin film magnetism [6].

Figure 2 (Co: left hand side and Fe: right hand side) report the quantity $\Delta M(T)=[M(H,\ T)-M(H=0,T)]$ measured at selected applied magnetic fields in the vicinity of T_c. In the limit of small fields $\Delta M(T,H)/H=\chi(T)$. $\Delta M(T)$ peaks sharply at T_c, clearly indicating the development of a phase transition related *singularity*. The maximum value of $\Delta M/H$ is $3\pm0.6*10^5$ for both Fe and Co. The error encompasses i) the uncertainty of the 0 K extrapolation (±10%) and ii) the fact that in the monolayer range the atomic magnetic moment can be slightly larger than in bulk (~10%) [6]. The measured values are *four* orders of magnitude larger than the bulk ones. Evidently, *epitaxial films are able to develop regions of correlated spins with linear size much larger than the corresponding bulk samples*: inserting the maximum value of χ in (1) we obtain $\xi_{max}\approx10^4$ lattice constants, to be compared with 10^2 in bulk samples.

We ascribe this ability to develop larger spin blocks to the reduced dimensionality of thin films. First, they exist *as single domains of macroscopic size*, as shown by the perfect squareness of the hysteresis curve in the ordered phase. Second, *in strict contrast to* $3d$, $2d$-systems are predicted to have large regions of correlated spins, even away from T_c [11]. Thus, the phase transition occurs through the organization into spin blocks of already large correlated regions. Third, the field dependence of χ_{max} is highly non-linear. Increasing the applied magnetic field by a factor of 100 barely affects the value of M (for this reason we prefer to plot $\Delta M\div T$ rather than $\Delta M/H\div T$, because this last quantity requires completely different scales for different H!). This extreme non-linearity is suggestive of a large critical exponent δ in the $\Delta M\div H^{1/\delta}$ curve at T_c, in line with the $2d$ Ising value of 15. Measurements aimed at accurately studying the critical properties of these thin films are in progress.

According to our findings, χ_{max} changes by four orders of magnitude in going from thin films to bulk samples. Thus, by simply recording χ_{max} as a function of film thickness, one should be able to measure quite accurately the thickness at wich the dimensional crossover takes place. In conclusion, we have discovered a giant enhancement of χ in thin Co and Fe films with respect to the corresponding bulk samples. This discovery should open new perspectives for the study of $2d$ magnetism.

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