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LETTER TO THE EDITOR

Two-dimensional ferromagnetism in metallic films

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Abstract. We suggest that uncoupled ferromagnetic films in the monolayer regime provide a physical realisation of the two-dimensional anisotropic Heisenberg ferromagnet. Using a real space renormalisation group approach we calculate the spontaneous magnetisation of this model system. The calculations account for the observed slow decrease of the magnetisation at low temperatures, with reasonable values of the anisotropy and also for its sharp drop close to T_C.

Recent work on ultrathin ferromagnetic films has revealed interesting features of the magnetic behaviour of these systems [1]. Unlike in the case where the films are weakly coupled to a ferromagnetic bulk, the uncoupled films in the monolayer regime show a much slower decrease of the magnetisation with temperature, which cannot be described by spin wave theory [2, 1]. In fact the interpretation of the experimental results seems to imply a quenching of the long wavelength magnons in the uncoupled films and probably the existence of a very large magneto-crystalline anisotropy [1]. The underlying mechanism responsible for this is not yet clear. Another important feature of the magnetic behaviour of the uncoupled films is the sharp drop in the magnetisation as the critical temperature is approached [1].

The quenching of low energy magnons in ferromagnets of rare earths or actinide elements, due to magneto-crystalline anisotropy, is a normal feature of these systems [3]. Spin wave gaps of order 10^2 K give rise to exponential terms in the magnetic contribution to the low temperature thermodynamic properties of these materials [3]. On the other hand, such large anisotropies for ferromagnets of transition metal elements are very unusual, although this is just the order of magnitude of the gaps required to describe the behaviour of the magnetisation in the uncoupled films [4].

In this letter we suggest that the uncoupled films of transition metal elements in the monolayer regime provide a physical realisation of the two-dimensional anisotropic Heisenberg ferromagnet. In order to substantiate our point of view, we have used the real space renormalisation group to obtain the spontaneous magnetisation of this model as a function of temperature.

The Hamiltonian describing the system is:

$$\mathcal{H} = \sum_{i,j} [W(\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y) + K\sigma_i^z \sigma_j^z] + H \sum_i \sigma_i^z + NC \tag{1}$$

where the $\boldsymbol{\sigma}$ are Pauli matrices for neighbour sites in a two-dimensional hierarchical

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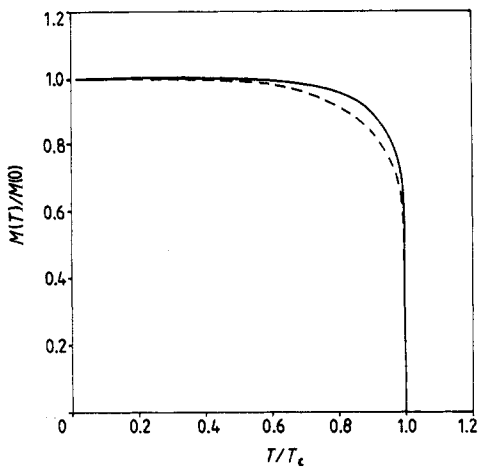

Figure 1. The magnetisation as a function of temperature calculated for (– – –) $\Delta = 1$ (Ising case) compared with (——) Onsager's exact result.

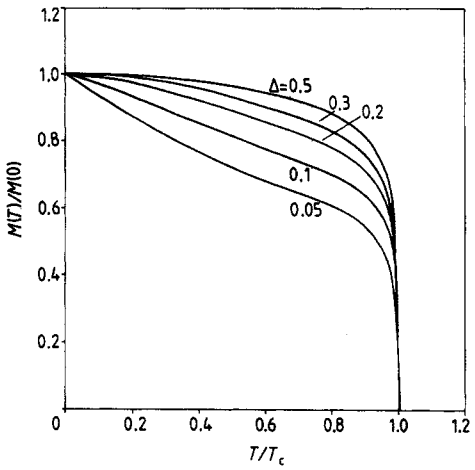

Figure 2. The magnetisation as a function of temperature for different values of the anisotropy parameter Δ.

cell, $K = J/k_B T$, $W = J(1 - \Delta)/k_B T$ and $H = \mu B/k_B T$. B is the external magnetic field, μ the magnetic moment per site, Δ the anisotropy factor, C a constant and N the total number of sites. The renormalisation group method used to study the Hamiltonian given by (1) is fully described elsewhere [5]. Recursion relations for W, Δ, H and C are obtained and allow us to find the phase diagram and the different thermodynamic functions. The isotropic ($\Delta = 0$) case, as is well known, does not order at any finite temperature. The anisotropic case ($\Delta \neq 0$) presents long range magnetic order below a critical temperature T_C which is given, for small anisotropies, by a solution of the implicit equation

$$k_B T_C/J = A/[1 - B \ln(4J\Delta/3k_B T_C)] \tag{2}$$

where $A = 1.39$, $B = 0.52$ and $J\Delta/k_B T_C < \frac{3}{4}$.

The spontaneous magnetisation is calculated recursively for any value of $\Delta \in [0, 1]$ and K ($> K_C = J/k_B T_C$) from the attractor at $\Delta = 1$, $K \to \infty$. In the neighbourhood of this Ising-like attractor the spins are parallel and the magnetisation $M(T = 0) = 1$. The magnetisation calculations are also described elsewhere [5].

As a test of the accuracy of our method, we first compare our curve, for the case $\Delta = 1$, with the exact result of the Onsager solution. This is shown in figure 1 where a discrepancy of order 10% occurs for a small interval below T_C. In figure 2 we display the magnetisations calculated for several values of the anisotropy factor Δ. At low temperatures, as Δ increases the magnetisation decreases more slowly with temperature due to a quenching of the magnetic excitations. For $\Delta = 0.3$ the magnetisation is almost constant up to approximately a third of the critical temperature as observed in the uncoupled films studied in [1]. For temperatures just larger than the low temperature plateau, the magnetisation decreases linearly with temperature in a certain range. In figure 3 we show our results for $\Delta = 0.3$ and for three different values of the exchange coupling J. The isotropic bulk value J_B is calculated using our method in three dimensions, which yields $K_C = 2.94$ (see also [5] and [6]). The drop in the magnetisation close to T_C is well described by the theory. This sharp drop reflects the Ising criticality of the

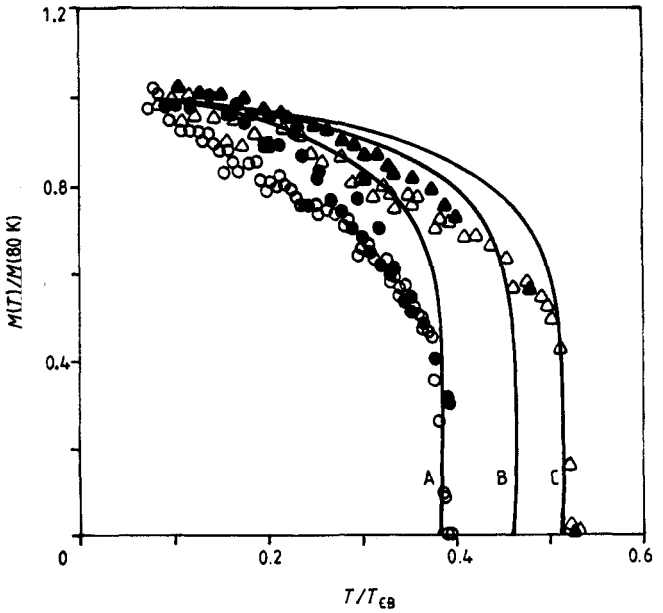

Figure 3. Magnetisation curves as a function of temperature for $\Delta = 0.3$ and different values of the exchange parameter. Curve A: $J = 0.82\,J_B$; curve B: $J = J_B$; curve C: $J = 1.11\,J_B$ where $J_B = 292$ K. The experimental points are taken from figure 4 of [8] with the same meaning for the symbols. Proportionality between $P(T)$, the low energy cascade spin polarisation, and the magnetisation has been assumed.

films. This is consistent with the renormalisation group since in this approach the critical behaviour along the critical line $T_C(\Delta)$ is governed by the Ising fixed point [5, 6]. The fact that the experimental points, in a temperature range below T_C, fall consistently below the theoretical curves, may be a consequence of disorder. It is well known [7] from the study of random magnets that disorder produces a flattening of the magnetisation curve and could account for the discrepancies found here at least for the permalloys films. Furthermore the renormalisation group method with finite cells underestimates the spin wave contribution [5] for $k_B T > J\Delta$.

The effect of anisotropy is much more dramatic in 2D than in 3D Heisenberg systems. Indeed in the former case anisotropy itself is responsible for the existence of a finite temperature phase transition. Consequently in two dimensions there is a much larger effect in quenching the low energy excitations, so it is not necessary to assume unphysically large anisotropies to account for the experimental magnetisation data.

We have obtained the magnetisation curves for the 2D anisotropic Heisenberg ferromagnet using a real space renormalisation group approach. These curves compare well with experimental data on metallic films in the monolayer regime, considering the approximate nature of the method. They show a sharp drop close to T_C and a slow decrease at low temperatures for reasonable values of the anisotropy, providing support for the notion that these films are a physical realisation of this model system.

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