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Quantum depinning of domain walls in ferromagnets

X X Zhang†, R Zquiak†, B Barbara‡ and J Tejada†

† Departament de Física Fonamental, Facultat de Física, Universitat de Barcelona, Diagonal, 647, E-08028 Barcelona, Spain

‡ Laboratoire de Magnetisme Louis Néel, 38100 Grenoble Cédex, France

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Abstract. In this paper we report on the magnetic relaxation of thin films of Fe of 1000 Å thickness separated by layers of Ag of 15 Å thickness. It is argued that the flattening of the magnetic viscosity at low temperature may be due to quantum diffusion of domain walls. Both the crossover temperature, T_c, from the classical to the quantum regime and the magnetic viscosity extrapolated to $T = 0$ depend on the value of the applied field, in agreement with theories of quantum tunnelling in magnets.

1. Introduction

The physics of relaxing magnetic systems is well understood in terms of the existence of energy barriers separating equilibrium orientations for the magnetic moment. There are two kinds of barriers in magnetic systems: intrinsic barriers due to magnetic anisotropy and barriers due to the pinning of domain walls by defects. Anisotropy barriers are typically of the order of $H_k M_0 V$, while pinning barriers are of the order of $H_c M_0 V$ where H_k is the geometrical average of the anisotropy field, H_c is the coercive field, M_0 is the magnetic moment of the unit volume and V is the volume involved in the relaxation process.

Recently it has been predicted that the magnetization vector $M(r)$ can tunnel quantum mechanically between different configurations corresponding to metastable states separated by energy barriers U [1, 2]. Let such a process occur with a probability $\sim \exp(-B)$, B being the WKB exponent at zero temperature. As the temperature increases one should also be concerned with thermal transitions through the energy barriers, which vary as $\exp(-U/k_B T)$.

At high temperatures, thermal transitions dominate, and at low temperatures quantum transitions have a greater probability. Therefore the escape rate at any temperature can be written as

$$\Gamma = \nu(T) \exp[-U/k_B T^*(T)] \tag{1}$$

where the prefactor ν is usually of the order of the FMR frequency $U \sim 10^{10}$–10^{11} s^{-1}, and $T^* = T$ at $T > T_c$ and $T^* > T$ at $T = T_c$, T_c being the crossover temperature between classical and quantum regime. The theory predicts that the transition from thermal to quantum regime is rather sharp with a well established plateau in the $T^*(T)$ dependence [3, 4]. The effect of the dissipation has been shown to smear the

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transition [5,6]. The dependence $T^*(T)$ therefore gives information on the relative contribution of the dissipation to the tunnelling rate. The crossover temperature T_c for different tunnelling mechanisms (uniform rotation of M in small particles [2], quantum nucleation of magnetic bubbles [2] and tunnelling of domain walls [3], is always of the order of $T_c \sim \mu_B H_k / k_B$.

In this paper we present results of a very systematic set of experiments in which we have studied the motion of the domain walls in iron films.

2. Experimental details

2.1. Physical system

The magnetic unit of our study is a domain wall pinned by a planer defect. This has been achieved by evaporating a very thin layer of Ag of 15 Å thickness (planar defect) between two crystalline iron films of 1000 Å thickness each. The film was prepared by electron beam evaporation in a high vacuum chamber. The crystalline state of the Fe layers was verified by x-ray diffraction patterns and Mössbauer spectroscopy. Both the value of the hyperfine magnetic field (H_{hf}=330 kOe) and the small line width observed in the Mössbauer spectrum (see figure 1) agree well with the existence of perfect BCC iron films suggested by the x-ray data.

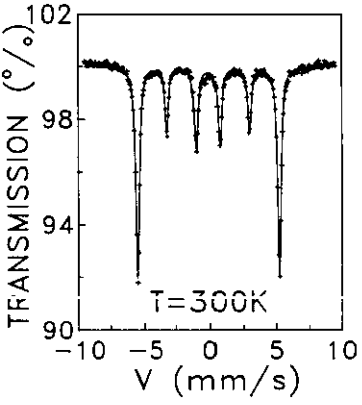

Figure 1. Mössbauer spectrum at a temperature of 300 K.

The metastability in this ferromagnetic system will be then associated with the existence of magnetic domains and domain wall pinning in the planar defects. For applied magnetic fields lower than the coercive field it will be possible to observe the rotation of the magnetization from one magnetic domain to another.

2.2. Equipment

The magnetic characterization of the sample was done by using an SHE SQUID magnetometer in the temperature range 1.6 K $\leqslant T \leqslant$ 300 K and using a magnetic field up to 5 T.

The dynamics of the films has been investigated by looking at the time dependence of the thermoremanence magnetization by the following procedure. First the sample

is cooled at constant field H_1 from high temperature to a well established new value. Then the field is switched to a new value H_2 and four seconds later we start the relaxation measurements for the thermoremanence magnetization. The average total time of each relaxation measurements is of the order of 4000 s. The applied fields for the relaxation experiments were generated by an external power supply and are resolved better than 0.1 Oe. The constancy with time of these applied fields was checked by measuring, during two hours, the magnetization of a pure paramagnetic sample at different temperatures.

3. Results and discussion

In figure 2 we show the results of the variation with temperature of the magnetization for the zero field cooled (ZFC) and field cooled (FC) processes. The existence of the irreversibility at low temperatures and the constancy of the FC data below 200 K are clear indications of the presence of domain walls in our samples. The hysteresis loops recorded agree also well with the assumption of the existence of crystalline iron films (see figure 3).

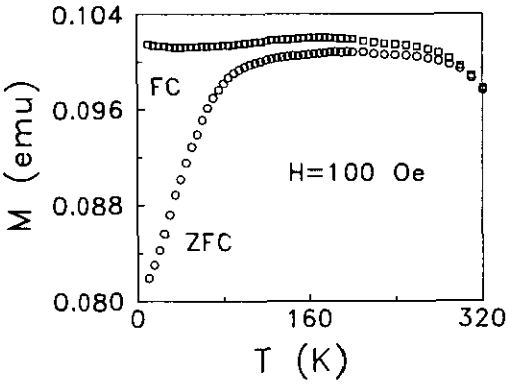

Figure 2. Dependence of low-field magnetization on temperature at an applied field of 100 Oe parallel to the film plane.

Let us list now the major features of the relaxation processes observed experimentally.

(*i*) The thermoremanent magnetization shows near perfect logarithmic time relaxation (see figure 4). This can be due to: (*a*) the existence of a wide distribution of energy barriers U, corresponding to different pinning centres; (*b*) the fact that when the field is suddenly removed, the magnetization immediately drops to a finite value determined by the hysteresis curve. This is the magnetic state where the energy barriers just start to develop and the $\log(t)$ magnetic relaxation can be explained within the Anderson–Kim model [7,8]. The general conclusion of these two different explanations of the $\log(t)$ law is that the magnetization versus time can be written as

$$M(t) = M(t_0)[1 - k_B T/U_0 \ln(t/t_0)] \tag{2}$$

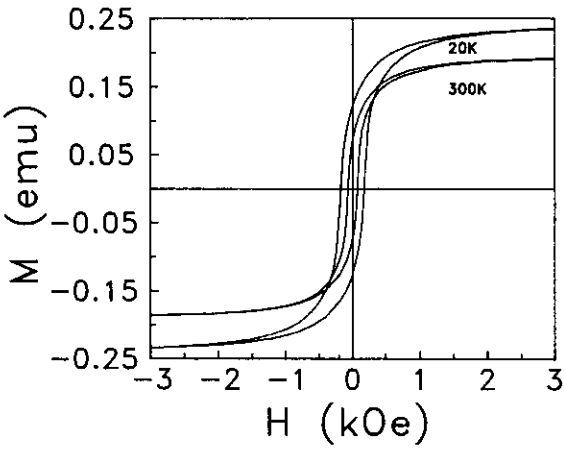

Figure 3. Hysteresis loops of the sample obtained at different temperatures with the field parallel to the film plane.

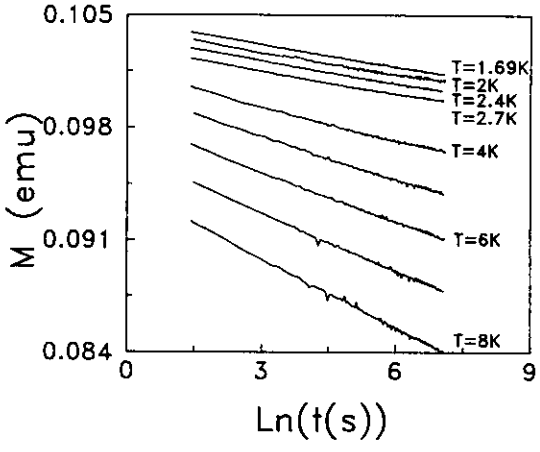

Figure 4. Time dependence of the thermoremanence magnetization of the sample at different temperatures with the applied field $H_1 = 100$ Oe, $H_2 = -195$ Oe.

where t_0 is arbitrary and U_0 is the average energy barrier for the pinning centres. Equation (2) is only valid if the relaxing part of the magnetic moment is small compared to the total moment.

(*ii*) The magnetic viscosity $S \equiv 1/M(t_0)\,\mathrm{d}M/\mathrm{d}\ln(t)$, can be expressed as $S(T) = \beta(H)T^*(T)$ where $\beta(H)$ takes into account the reduction of energy barriers due to the applied magnetic field (different H_2 values) and $T^*(T) = T$ at high temperatures and $T^*(T)$ = constant at low temperatures (see figure 5). The proportionality of $S(T)$ to T is in agreement with theoretical prediction for thermally activated depinning processes. The existence of the plateau in the $S(T)$ dependence at low temperature is exactly what one would expect in the presence of quantum depinning of domain walls [12–14]. The plateau in the $S(T)$ values has been experimentally observed for temperatures down to $T = 50$ mK by using a different experimental set-up [15].

(*iii*) The transition from the classical to quantum regime is rather sharp when the applied field H_2 is smaller than the coercive field. This is in agreement with the theoretical expectation of weak dissipation in magnetic tunnelling [9–11].

(*iv*) The variation of the crossover temperature T_c with the H_2 values follows

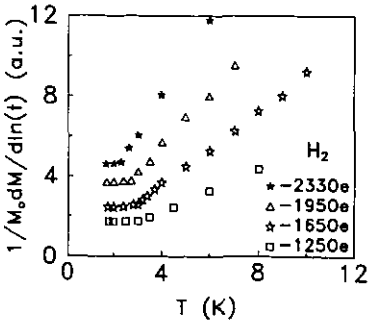

Figure 5. The dependence of magnetic viscosity on the temperature and applied field H_2.

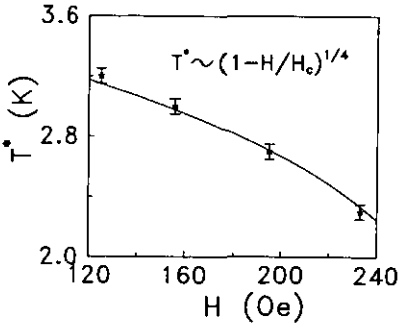

Figure 6. The dependence of crossover temperature from thermal to quantum regime on the applied field H_2. The line is a simulation of the function $T_c \sim (1 - H/H_c)^{1/4}$ using $H_c = 280$ Oe.

very well the dependence $T_c \sim (1 - H/H_c)^{1/4}$ (figure 6), where H_c is the coercive field of the sample at $T = 0$ K. This is an important observation because this is the field dependence, theoretically predicted [2], of the crossover temperature in the presence of pinning barriers for domain walls.

(v) The increase in the magnetic viscosity values extrapolated to $T = 0$ when increasing the H_2 values may also be interpreted as due to the reduction of energy barrier heights.

4. Conclusions

In this paper we have shown experimental results for the relaxation of domain walls pinned by a planar defect. The constancy of the magnetic viscosity below a certain temperature T_c, and the dependence of T_c on the applied magnetic field during the relaxation experiments, are experimental facts which strongly support the existence of quantum depinning of domain walls.

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