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ANGULAR DEPENDENCE OF THE MAGNETIZATION IN ISOTROPIC AND ANISOTROPIC SPIN GLASSES

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We study the angular dependence of the magnetization in CuMn alloys and in the uniaxial anisotropy spin glass Fe_2TiO_5 by rotating the measuring field by ϕ with respect to the cooling field. Pronounced minima which depend on field and temperature are observed around $\phi = \pi$ for both spin glass classes. However, the overall angular dependence differ considerably.

The macroscopic anisotropy which couples to the remanent magnetization in spin glasses has been extensively studied during the years, mostly in classical spin glasses, by a variety of techniques such as magnetization [1] and torque measurements [2] transverse susceptibility [3], ESR [4] and NMR [5] experiments. It has been concluded from these experiments that the remanent magnetization might be viewed as a rigid entity which rotates bodily in response to a rotation ϕ of the magnetic field [6]. We present here a study of the angular dependence $M(\phi)$ for two spin glass classes: CuMn alloys and the uniaxial anisotropic spin glass [7] Fe_2TiO_5. We find remarkably different angular dependence for the magnetization in the two classes, the origin of which is reflected in the different nature of the ac susceptibilities. We identify, however, a feature common to both systems which is correlated with the irreversible characteristics of spin glasses.

The anisotropy properties of all samples were investigated via measurements of the magnetization on a vibrating sample magnetometer (VSM) with a 2π-rotating sample holder. The sample was cooled in a field $\boldsymbol{H}_c$ from well above the freezing temperature, T_g, to the measuring temperature. With the same field on and the temperature stabilized to better than 0.1 K, the sample was rotated by ϕ relative to the magnetic field. (In the sample frame of reference, ϕ is the angle between the cooling field $\boldsymbol{H}_c$ and the measuring field $\boldsymbol{H}$.) We then measure the magnetization M as a function of ϕ. The angular dependence of M for a CuMn 8 at% sample cooled in 250 Oe and for Fe_2TiO_5 cooled in 5 kOe (with $\boldsymbol{H}_c$ parallel to the easy axis) are presented in figs. 1 and 2, respectively, for several representative isotherms. The most striking feature of *both* figures is the presence of pronounced minima at $\phi \approx \pi$, the magnitude of which is a decreasing function of temperature. This is however the only common feature for both samples. The general $M(\phi)$ dependence is very different.

The total sample magnetization of a spin glass system is customarily written as a superposition of a reversible and irreversible parts

$$\boldsymbol{m} = \ddot{\chi}\boldsymbol{H} + \boldsymbol{M}_{irr}. \tag{1}$$

According to the rigid rotation picture [1-6] the irreversible magnetization $\boldsymbol{M}_{irr}$ is rotated bodily by an angle θ due to a rotation ϕ of the field. (The value of θ is given by $\sin\theta = x\sin(\phi - \theta)$, $\chi \equiv HM_{irr}/K$, K being the macroscopic anisotropy energy.) In the VSM technique one measures the projection of $\boldsymbol{m}$ on the axis of $\boldsymbol{H}$ and therefore, for CuMn where $\ddot{\chi}$ is isotropic, the measured magnetization is

$$M = \chi H + M_{irr}\cos(\phi - \theta). \tag{2}$$

The susceptibility $\ddot{\chi}$ of Fe_2TiO_5 is anisotropic in nature [7]. We denote by $\chi_{\parallel}$ and $\chi_{\perp}$ the susceptibility measured parallel and perpendicular to the easy axis respec-

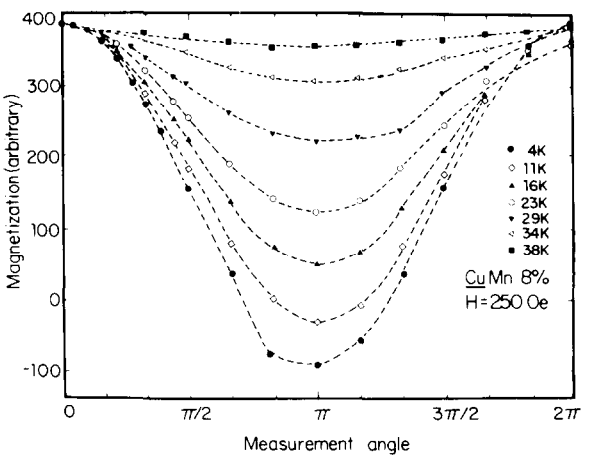

Fig. 1. Angular dependence of the magnetization of CuMn 8 at% after cooling the sample in a field $H_c = 250$ Oe to the denoted temperature.

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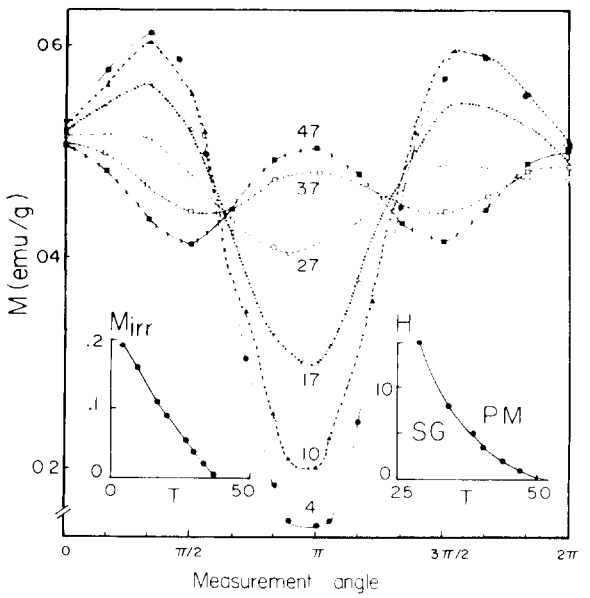

Fig. 2. Angular dependence of the magnetization of Fe_2TiO_5 measured after cooling the sample in a field $H_c = 5$ kOe to the denoted temperature. H_c is along the easy axis ($\phi = 0$). Insets: $M_{irr}(T)$ for $H_c = 5$ kOe and the deduced field–temperature phase diagram for Fe_2TiO_5.

tively. The magnetization measured along the applied field H is [8]

$$M = \chi_\perp H + (\chi_\parallel - \chi_\perp) H \cos^2\phi + M_{irr} \cos(\phi - \theta), \quad (3)$$

where we take $\phi = 0$ to be along the easy axis.

Eqs. (2) and (3) provide the basis for an understanding of the angular dependence data. Both equations yield $M_{irr} = (M_0 - M_\pi)/2$ where M_0 and M_π are the magnetization values measured at $\phi = 0$ and π, respectively. Thus, the deep minima which characterize figs. 1 and 2 reflect the magnitude $M_{irr}(H, T)$ of the irreversible magnetization which is the essence of the spin glass state. The decrease in the magnitude of the minima with the increase of temperature signals the approach towards the spin glass/paramagnetic transition [9] $T_g(H)$ which is characterized by the vanishing of irreversible response [10]. It would have been advantageous to deduce M_{irr} directly from $M(\phi)$ data, independently of other experiments, not only for the determination of $T_g(H)$ but also for the evaluation of the anisotropy energy K via the parameter $x = HM_{irr}/K$. However, in CuMn, relaxation phenomena affect the functional form of $M(\phi)$. To take these effects into account needs modeling of the viscosity mechanism. We defer detailed accounts of this phenomenon to a future publication [11]. For Fe_2TiO_5 we find that eq. (3) describes the data for most of the temperature and field regimes. This allows us to evaluate $M_{irr}(T, H)$. Taking the vanishing of M_{irr} as an experimental criterion for $T_g(H)$ we are able to evaluate the de Almeida–Thouless line [9] (inset of fig. 2) which is in agreement with more conventional measurements.

At small angles of rotation the viscosity effects are much less important [2]. It is therefore constructive to look at the temperature and field dependence of the initial slope $(dM/d\phi)_0$ in figs. 1 and 2. For CuMn the initial slope is always negative and it decreases with temperature whereas for Fe_2TiO_5 it is positive in the low-temperature regime and changes gradually to negative values at high temperatures. From eq. (2) it is clear that $(dM/d\phi)_0$ for CuMn depends solely on $x = HM_{irr}/K$ which affects $\theta(\phi)$. The gradual decrease of $(dM/d\phi)_0$ in fig. 1 is a direct result of the increase of x. (An immediate consequence of this conclusion is that K vanishes with temperature faster than M_{irr}.) The initial slope in Fe_2TiO_5 depends not only on $\theta(\phi)$ but also on the difference $\Delta\chi = \chi_\parallel - \chi_\perp$ (see eq. (3)). At low temperature $\chi_\parallel < \chi_\perp$ whereas above 30 K $\chi_\parallel > \chi_\perp$ [7]. Apparently this affects the sign of the $\cos^2\phi$ term and therefore the initial slope of $M(\phi)$.

We conclude this article with preliminary results of similar measurements on CuMn samples with enhanced anisotropy. The enhancement in the anisotropy is achieved either by increasing the Mn concentration or by doping the samples with gold impurities [12]. Fig. 3 exhibits the angular dependence of the normalized magnetization of CuMn 8 at% (circles) and of CuMn 1.2 at% doped with 3 at% gold (squares). Both samples were cooled in $H_c = 2$ kOe to 4.2 K and the figure serves the demonstrate two features: (i) A pure unidirectional behaviour is observed for $x \ll 1$ *even for big angles of rotation* (up to π). This is demonstrated by the $\cos\phi$ function (dotted lines) which perfectly fits the data for the CuMn Au sample for more than half a period. (ii) Uniaxial-like contributions are observed for $x \gtrsim 1$. This is demonstrated by the data for CuMn 8 at%. This behaviour is qualitatively consistent with the rigid-rotation model eq. (2), but viscosity phenomena distort the exact functional form [11].

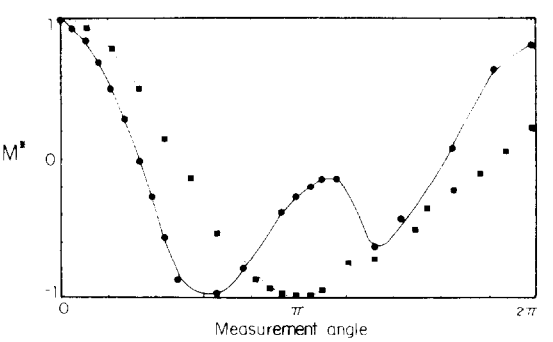

Fig. 3. Angular dependence of the normalized magnetization of CuMn 8 at% (circles) and of CuMn 1.2 at% doped with 3 at% gold (squares). Both samples were cooled in $H_c = 2$ kOe to 4.2 K. The dotted line is a $\cos\phi$ function.

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