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LONGITUDINAL EXCITATIONS IN AMORPHOUS MAGNETS

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Abstract. - The concept of longitudinal spin fluctuations, previously used to take into account the dynamics of the longitudinal magnetization of amorphous ferromagnets, is extended for disordered magnetic solids where the total magnetic moment is not conserved. A local relaxation time is introduced and we study the processes by which a spin can relax in an amorphous magnetic solid.

INTRODUCTION

In an amorphous ferromagnet due to the existence of frustration the spins are not collinear on the ground state \( \left( \frac{1}{2} \right) \left( \frac{3}{2} \right) \). In these systems besides the usual transverse spin wave excitations one has to consider longitudinal spin fluctuations \( \left( \frac{3}{2} \right) \).

The picture of a metallic ferromagnetic glass as a collection of spins exposed to an inhomogeneous distribution of local fields \( \left( \frac{4}{1} \right) \), has been evoked mainly in connection with the resistivity minimum problem \( \left( \frac{5}{2} \right) \). This picture however does not describe correctly the low frequency magnetic excitations. In an isotropic ferromagnetic glass which conserves the total magnetic moment these excitations are longitudinal diffusive modes \( \left( \frac{3}{2} \right) \) and long wavelength transverse spin waves. This is not the case if there is some mechanism as for example coupling to the "lattice" or conduction electrons which allows for relaxation of the spins.

TWO LEVEL SYSTEMS IN MAGNETIC GLASSES

A characteristic feature of amorphous substances is the existence in these materials of localized structural excitations which are well represented by two level systems (TLS) \( \left( \frac{6}{7} \right) \). These tunneling states contribute to the specific heat with a term linear with the temperature at very low temperatures \( \left( \frac{8}{7} \right) \). These defects have initially been found in insulating glasses \( \left( \frac{8}{7} \right) \) and later in amorphous metals \( \left( \frac{9}{8} \right) \). In magnetic metallic glasses there is no direct evidence of these modes on the specific heat since their contribution is probably obscured by the large magnetic term \( \left( \frac{10}{11} \right) \). It has been suggested however that the resistivity minimum found in these glasses is due to a coupling of the conduction electrons with the TLS \( \left( \frac{2}{2} \right) \).

In this paper we study the effect of the structural TLS on the magnetic properties of a magnetic glass. We show that, besides other effects, they produce a mechanism which allows for a ferromagnetic spin to relax interchanging energy with the "lattice". This relaxation process can be described by a longitudinal magnetic susceptibility with the diffusive pole \( \left( \frac{3}{2} \right) \) replaced by a local relaxation time characterizing the rate of relaxation of the spins.

Consider the following Heisenberg describing an amorphous magnetic system

$$ H_{\text{mag}} = -\frac{1}{2} \sum_{i,j} J_{i,j} \mathbf{S}_i \cdot \mathbf{S}_j + \sum_i D_i (\mathbf{S}_i \cdot \mathbf{r}_i)^2 \quad (1) $$

The first term is the usual Heisenberg term and the second represents a local anisotropy which is random both in direction and in magnitude \( \left( \frac{13}{1} \right) \). In the case of a magnetic glass it is useful to rewrite (1) on a local set of axis \( \left( \frac{14}{1} \right) \), the spins being treated as classical vectors. Besides other contributions one gets in the case of uniaxial symmetry, terms like

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where $\theta_{ij} = \theta_j - \theta_i$ and $\theta_i$ is the angle between the local spin direction and the laboratory $z$ axis. $\psi_i$ is the angle between the local easy axis of magnetization and the spin direction. In a rigid lattice terms like (2) do not contribute due to stability requirements on the ground state [14]. This is not the case if the atoms are allowed to move and the exchange interactions and local anisotropy become time dependent. Consider for simplicity just the exchange term

$$S_i \cos \psi_i \sin \psi_i \sin \psi_i \quad (2)$$

where $S_i$ is a double well potential and can perform quantum mechanical tunneling from a position to another, the term in brackets can be imagined as a time dependent transverse field acting on spin $i$. When the spectrum of fluctuations of this local field has frequencies which are synchronous to the processing frequency $\omega_0$ of spin $i$ about the local axis, it will induce transitions on spin $i$. The relaxation time associated with this process is given by [15]

$$\tau^{-1}_L = \frac{S(s+1)\omega_0^2}{\hbar^2} \tau_c \sqrt{1 + \omega_0^2 \tau_c^2} \quad (3)$$

where we assumed the exchange interactions are Markovian stochastic variables characterized by a correlation function

$$\langle J_{ij}(t)J_{ij}(t+\tau) \rangle = J_0^2 \exp \left[-|\tau|/\tau_c \right] \quad (4)$$

with $J_0^2 = \langle \left[ J_{ij} \right]^2 \rangle$. For simplicity we considered only the coupling between spin $i$ and the neighbour with which it interacts more strongly. Expression (4) applies for those spins which have $\hbar \omega_0 \ll k_B T$ [15]. The quantity

$$A = \langle \left[ \sin \theta_{ij} \right]^2 \rangle$$

is a measure of the "aspericity" [10] of the system and for a ferromagnetic glass it is very small. The correlation time $\tau_c$ is related to the relaxation time of the TLS [15].

The interaction between structural defects and the magnetic system can be dealt more directly if we introduce the following Hamiltonian

$$H = H_{\text{mag}} + (1/2)[\epsilon \sigma^z + \Delta \hat{\sigma}^z + K s^z \sigma^z] \quad (5)$$

where $H_{\text{mag}}$ is given by (1), the next two terms refer to the TLS and the symbols have their usual meaning [16]. The last term couples defects and magnetic moments. Writing the spin components on a set of local axis and rotating the matrices $\sigma$ associated with the TLS one gets

$$H = H_{\text{mag}} + (E/2) \sigma^z - (D \sigma^z + W \sigma^x) \hat{S}^x \quad (6)$$

where $2E = 2\left\{ (\epsilon + K \langle \hat{S}^z \rangle^2 + \Delta^2 \right\}^{1/2}$ and $D = K \langle \hat{S}^z \rangle^2 / 4E$ and $W = K \Delta \sin \theta / 4E$. $\langle \hat{S}^z \rangle$ is the average local magnetization. The relaxation process we have considered above is related to the term $\sigma^z \hat{S}^x$ in (6). Another relaxation mechanism is provided by the term $\hat{S}^x \sigma^z$. This corresponds, in first order, to a process in which a spin flips and an atom in the TLS "moves" to another state conserving energy. The relative importance of both mechanisms at different temperatures is studied elsewhere [17].

With respect to the relaxation of the structural defects, there are four basic mechanisms in ferromagnetic glass which can relax a TLS:

1) Direct phonon emission or absorption [16];
2) Direct magnon emission or absorption [17];
3) Thermally activated tunneling which is important at high temperatures [16];
4) Inter TLS coupling [18]. In this case besides the usual phonon coupling [19] one has to consider a "Suhl-Nakamura" type of TLS coupling mediated by virtual excitations (spinwaves) of the magnetic medium [17]. In metallic glasses there is an additional relaxation mechanism due to the inter-
action between conduction electrons and TLS \([20]\). Raman type processes are in general ineffective for structural relaxation \([16]\).

The simplified picture we adopted above, of a magnetic glass as a collection of spins on a distribution of local fields is a reasonable approximation for a ferromagnetic glass \([10]\). For amorphous ferromagnets where well defined magnons are known to exist \([21]\), it is still reasonable for the purpose of calculating a magnetic longitudinal relaxation time, but one has to consider explicitly the effect of the TLS on the spin wave propagation. The interaction with the TLS gives origin to two kinds of spin wave damping \([17]\): a relaxation and a "resonant" damping. Both are small as long as the spin wave energy \(\omega(k)\) satisfies \(\omega(k)\tau \ll 1\) where \(\tau\) is the relaxation time of the defects which is different for each case \([16]\). Another consequence of the spin wave-TLS interaction is to produce a shift in the spin wave frequencies \([17]\). In the case of the "resonant" interaction a softening of the spin wave stiffness may occur \([17]\).

For convenience we assumed that the defects in a magnetic glass are constituted of isolated magnetic atoms. This is not necessary and as long as the exchange interactions become time dependent the effects considered here should take place.

Finally we point out the results we obtained have important consequences for the electrical resistivity, thermal conductivity, ferromagnetic resonance and other physical properties of magnetic glasses.

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References

