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SUSCEPTIBILITIES, CORRELATION FUNCTIONS AND NEUTRON SCATTERING LAW IN AMORPHOUS MAGNETS

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Abstract. - We calculated the static and dynamic susceptibilities $\chi (Q)$ and $\chi (Q, \omega)$, the neutron scattering cross-section $S(Q)$, and the scattering law $S(Q, \omega)$ for amorphous magnets with small random anisotropy. These results agree fairly well with those of a recent neutron-spin echo experiment on amorphous TbNi$_2$.

Amorphous magnets with random anisotropy commonly are described by the random anisotropy model (RAM) with the Hamiltonian

$$H = -\frac{1}{2} \sum_{ij} J_{ij} S_i S_j - \frac{D}{2} \sum_i (n_i S_i)^2 - h \sum_i S_i, \quad (1)$$

with non-random ferromagnetic exchange interactions $J_{ij} = J_{i-j}$ and an external field $h$ in units of $\mu_B$. The anisotropy of strength $D$ is described by randomly distributed unit vectors $n_i$. In three dimensions, this model most likely has a phase transition at a characteristic temperature $T_c$. Below $T_c$, the system goes into a state without long-range ferromagnetic order which is similar to a spin glass state. Estimates based on the formation of magnetic domains [1] and a site-dependent mean-field-theory (MFT) [2] indicate below $T_c$ ferromagnetic spin correlations of the order $\xi = (J_0 / D)^2$ where $J_0$ is the exchange between nearest neighbours. Linear response theory connects the spin correlation function $\langle S_{i\alpha} S_{j\alpha} \rangle_D$ with the susceptibility $\chi_{i\alpha,\alpha} (\alpha = x, y, z)$. One has

$$T \chi_{i\alpha,\alpha} = \langle \{ S_{i\alpha} S_{j\alpha} \rangle_D - \langle M_{i\alpha} M_{j\alpha} \rangle_D, M_{i\alpha} \equiv \langle S_{i\alpha} \rangle, \quad (2)$$

where $\langle \rangle$ denotes the thermal average and $\langle \rangle_D$ the average over a distribution of random axes. The second term on the r.h.s. of (2) is characteristic for random systems. After Fourier transformation, equation (2) leads to the neutron scattering form factor

$$S_\alpha (Q) = T \chi_\alpha (Q) + q_\alpha (Q), \quad (3)$$

where $q_\alpha (Q)$ is the Fourier transform of the magnetization correlation function $\langle M_{i\alpha} M_{j\alpha} \rangle_D$. In zero field, the system is macroscopically isotropic and $S_\alpha (Q)$ independent of the direction $\alpha$. For arbitrary fields, weak anisotropy and $Q \to 0$, one derives [3]

$$S_\alpha (Q) = \frac{T}{A (Q^2 + \xi_\alpha^2)} + 4 \pi \xi_\alpha D^2 (a - q_\alpha) + M_{i\alpha}^2 \delta (Q). \quad (4)$$

The Lorentzian-squared term in (4) is due to the disorder and vanishes for $T > T_c$ and $h = 0$ with $q \equiv \Sigma q_\alpha \equiv \Sigma_\alpha [M_{i\alpha}^2]_D = 0$. It remains finite either for $T < T_c$ and $h = 0$ with $q_\alpha = q / 3$ or for $T > T_c$, $h \neq 0$ with $q_1 = M^2$ and $q_2 = q_3 = 0$ (and, of course, for $h \neq 0, T < T_c$). This term has been derived already in [2]. For weak anisotropy, the correlation length $\xi_\alpha$ can be approximated by $\xi_\alpha^{-2} = \xi_{FM,\alpha}^{-2} + \xi_D^{-2}$ where $\xi_{FM,\alpha}$ is the correlation length of the ideal ferromagnet (which diverges in zero field below $T_c$), and where $\xi_\alpha \propto (J_0 / D)^2$. This superposition of a Lorentzian and a Lorentzian-squared term has been observed in the form factors of Tb$_{75}$Fe$_{25}$, TbFe$_2$, NdFe$_2$, and other amorphous magnets [4].

The dynamics of the RAM are determined by the Hamiltonian (1) and by the symmetry of its low temperature states. The exchange interactions are rotation invariant, but the random anisotropy breaks this symmetry locally. The breaking of the local rotation invariance is also characteristic for spin glasses, but in this case it is a property of the low temperature states and not of the Hamiltonian. As a consequence, the dynamics of both systems turns out to be rather different above their characteristic temperatures. In addition, one has in the RAM below $T_c$ considerable short-range order which is missing in most spin glasses. Hence, one expects the dynamics of the RAM below $T_c$ and for not too small $Q$-values to be dominated by ferromagnetic modes with two modification. (i) Due to the disorder and also due to the Korringa relaxation, the modes are overdamped and hence diffusive. For spin glasses, this problem has been carefully investigated [5]; (ii) due to the anisotropy, the total spin is no longer conserved.

We describe the system by the Langevin equation

$$\frac{\partial S_\alpha (Q, t)}{\partial t} = -\gamma (Q) \frac{\delta H}{\delta S_\alpha (Q)} + \zeta_\alpha (Q, t), \quad (5)$$

with $\gamma = \text{const}$ for $Q \to 0$ and with the Gaussian noise $\zeta (Q, t)$ with

$$\langle \zeta_\alpha (Q, t) \zeta_\beta (Q', t') \rangle = 2 \gamma (Q) T \delta (t - t') \delta_{\alpha\beta} \delta (Q + Q'). \quad (6)$$

The Hamiltonian (1) in the continuum limit can be written as

\[ J_{ij} S_i S_j - \frac{D}{2} \sum_i (n_i S_i)^2 - h \sum_i S_i, \]
In MFT and for $h \to 0$, one has from (5) and (7) the dynamic susceptibility
\[ \chi_\alpha (Q, \omega) = \frac{1}{\gamma (Q)} \left[ T + A Q^2 - i \omega \right]^{-1} \] (8)
with $T = \chi = 0.6$; for $T < T_c$ and $r = r_0 + \lambda = A \left( \xi_{PM}^2 + \xi_D^2 \right)$ for $T > T_c$. For $\omega = 0$, equation (8) reduces to the static susceptibility $\chi(Q)$ from (3) and (4). The Lorentzian-squared term in (4) is a purely static effect and does not enter into dynamic properties. By means of the fluctuation-dissipation theorem, the result (8) leads to
\[ \langle S_\alpha (Q, t) S_\alpha (Q, 0) \rangle D = T \left( r + A Q^2 \right)^{-1} \times \exp \left[ -\gamma (Q) \left( r + A Q^2 \right) t \right] + q (Q), \] (9)
or to exponential decay of the spin correlations with the relaxation rate
\[ \Gamma (Q) = \gamma (Q) \left( r + A Q^2 \right) \equiv \Gamma_0 + \Gamma_1 Q^2, \] (10)
for not too large $Q$-values.

The results of a recently performed neutron spin-echo experiment on an amorphous TbNi$_2$ sample [6] are in qualitative agreement with these predictions. The “intermediate” scattering function $I_\alpha (Q, t) \sim \langle S_\alpha (Q, t) S_\alpha (Q, 0) \rangle D$ was investigated in the time window $0.05 \times 10^{-9} \text{ sec} \leq t \leq 2 \times 10^{-9} \text{ sec}$ and for the momentum transfer $0.04 \text{ Å}^{-1} \leq Q \leq 0.10 \text{ Å}^{-1}$. Apart from the shortest times, one observes fairly exponential decay and the relaxation rate (10) with $\Gamma_0 \approx 3.5 \times 10^7 \text{ sec}^{-1}$ and $\Gamma_1 \approx 1.5 \times 10^{12} \text{ Å}^2 \text{ sec}^{-1}$. This result differs considerably from the neutron spin echo data for the spin glasses CuMn, LaErAl$_2$ and EuSrS which indicate a broad spectrum of relaxation times with little $Q$-dependence. An exception is the reentrant spin glass Eu$_{0.54}$Sr$_{0.46}$S at temperatures slightly above the transition from the paramagnetic to the ferromagnetic state [7] where one observes the exponential decay (9) and (10) with $\Gamma_0 = 0$.

From the neutron spin echo data of a TbNi$_2$, one can also extract the temperature dependence of the static spin correlation length $\xi_\alpha$. One observes a strong increase of $\xi_\alpha (T)$ near $T_c = 18 K$, where $T_c$ is in good agreement with the freezing temperature derived from the low-field magnetization data on the same sample. This temperature dependence can be attributed to the contribution from $\xi_{PM}$ to $\xi_\alpha$. At low temperatures, $\xi_\alpha (T)$ becomes approximately constant. Details about the neutron spin-echo experiment on a TbNi$_2$ will be published elsewhere.