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DIAMAGNETIC CORRELATIONS OF SUPERCONDUCTIVE GLASS MODEL

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1. Introduction

Recent data on uSR [1] and magnetic [2-5] measurements surely confirm the existence of a Josephson-like medium in sintered high-T_c ceramics. In previous papers [6-11] the diamagnetic response and superconductive correlations due to Josephson currents between grains in an external magnetic field were studied in the frame of the superconductive glass (SG) model.

This paper considers the space-time correlations between these diamagnetic (DM) moments in the region of frustration. The influence of such correlations on the behaviour of the critical neutron scattering intensity for sintered high-T_c ceramics will be discussed as well.

2. Model of the Superconductive Glass

As is well known [7,9] the Hamiltonian of the SG model in the pseudospin representation has a form

$$\hat{H} = -\mathrm{Re} \sum_{ij} J_{ij} S_i^* S_j \quad , \tag{1}$$

where

$$J_{ij} = J(T)\exp(iA_{ij}), \qquad S_i = \exp(if_i),$$

$$A_{ij} = \frac{\pi H}{\Phi_o}(x_i + x_j)(y_i - y_j), \qquad \Phi_o = hc/2e \quad . \tag{2}$$

The model (1) describes the interaction between superconductive grains (with phases f_i) via Josephson junctions (with an energy $J(T)$) on a 2-D disordered lattice (with cluster coordinates (x_i, y_j)) in a frustrated external magnetic field $\vec{H} = (0,0,H)$. So, as usually (see, however, [11]), we have neglected the shielding current effects.

Josephson currents $I_{ij} = i_c \sin(f_i - f_j - A_{ij})$ $(i_c = 2eJ(T)/h)$ induce diamagnetic (DM) moments [6] :

$$m_{ik} = \frac{1}{2c} I_{ik}(x_i y_k - x_k y_i) \quad . \tag{3}$$

A mean value $\overline{\langle m^z \rangle}$ (where $\langle ... \rangle$ means the thermodynamic averaging with a Hamiltonian (1), and the bar denotes the configurational averaging with a Gauss-like distribution function over cluster coordinates (x_i, y_j)) describes the magnetization of a granular sample (see e.g. [6-9]). At the same time according to (3) $\overline{\langle m^z \rangle}$ describes the correlations between Josephson pseudospins S_i, i.e. superconductive correlations in the model (1). Equilibrium and relaxation properties of the induced magnetization (3) were studied in papers [6-9] and [7,8,10,11] , respectively. In particular, in papers [8-11] the predictions of the model were rather successfully interpreted in terms of the observable properties of the high-T_c ceramics.

3. Diamagnetic correlations

Let us consider the possibility of magnetic correlations occuring in a granular superconductor in an external magnetic field. For that we shall calculate the dynamic structural factor (DSF) of the form :

$$S(\vec{q},\omega) = \int dt e^{i\omega t} S(\vec{q},t) \quad , \tag{4}$$

where

$$S(\vec{q},t) = \overline{\langle m_{\vec{q}}(t) m_{-\vec{q}}(0) \rangle} \quad . \tag{5}$$

Here the Fourier transform of m^z_{ik} is :

$$m_{\vec{q}} = \frac{1}{N} \sum_{ik} e^{i\vec{q}(\vec{r}_i - \vec{r}_k)} m^z_{ik} \quad . \tag{6}$$

By using the model coupling approximation scheme (see e.g. [12]) for a Bragg-like DSF one gets :

$$S(\vec{q},t) = S_o \cdot \left| D_{\vec{q}}(t) \right|^2 \quad , \tag{7}$$

where

$$S_o = F(H/H_o) J^2(T)/H_o^2 \quad , \quad H_o = \Phi_o/2\sigma \; , \quad F(x) = \frac{x^2}{(1+x^2)^3} \quad . \tag{8}$$

Here σ is the projected area of the superconducting loops with a uniform phase. $D_q(t)$ denotes the Fourier transform of the correlator $D_{ij}(t)$:

$$D_{ij}(t) = \overline{\langle S_i^*(t) S_j \rangle} \qquad (9)$$

The transition to the SG phase occurs at a temperature $T < T_c(H)$, where $T_c(H)$ is defined by an equation $L_{q=0}(T_c, H) = 0$. A nonzero dynamic parameter $L_{\vec{q}}(T,H)$ is connected with the correlator (9) in the following way [9] :

$$L_{\vec{q}}(T,H) = \lim_{t \to \infty} D_{\vec{q}}(t). \qquad (10)$$

The nonergodic properties of the model (1) are considered in more detail in [7,8,10] .

In the critical region near the transition to the SG phase (when $\epsilon \ll 1$, $\epsilon = (T - T_c)/T_c$) one obtains [9,10] :

$$S(\vec{q},\omega) = S_o \left[\Delta_c(\omega) L_{\vec{q}}^2 + \Gamma \cdot (\omega^2 + \omega_c^2)^{-1/2} g_{\vec{q}} \right] , \qquad (11)$$

where

$$L_{\vec{q}} = \frac{L_o}{1 + r_c^2 q^2} , \qquad L_o = -2|\epsilon|^{\gamma} ,$$

$$\Delta_c(\omega) = \frac{1}{\pi} \frac{\omega_c}{\omega^2 + \omega_c^2} , \qquad g_{\vec{q}} = \frac{g_o}{1 + r_c^2 q^2} . \qquad (12)$$

Here $\omega_c = \epsilon^{2\beta}/\Gamma$ is a scaling frequency, $r_c = R \cdot |\epsilon|^{-\alpha}$ is a correlation length, Γ is a paraphase relaxation time.

In the mean field approximation one gets the following values for the critical exponents

$$\alpha = 1/2, \quad \beta = 1, \quad \gamma = 1 . \qquad (13)$$

4. Discussion

Let us return to the expression (11) for DSF. First of all note that the L_q^2-dependence of the DSF central peak in (11) is a common feature of the glass-like systems (a similar dependence was observed in [13] for spin glasses). A second remark concerns the DSF dependence on the external magnetic field. On the one hand, this dependence enters (11) through the amplitude S_o, which in turn defines the strong sensitivity of the magnetic neutron scattering intensity to the field. On the other hand, there is a weaker dependence on the field via the critical temperature $T_c(H)$ (for the behaviour of the system (1) in the H-T plane see [8,9]).

As it follows from (11) and (12) the intensity of scattering increases linearly at $H < H_c$, has a maximum at $H = H_c \equiv \frac{1}{\sqrt{2}} H_o$, and decreases as $1/H^4$ when $H >> H_c$. As a whole the intensity dependence on the field correlates with the similar behaviour of the magnetization (see [8,9]). It is necessary to stress that in our case the frustration takes place in the fields $H \gtrsim H_c$.

As is known [14] , the intensity of the small-angle neutron scattering by DM correlations can be estimated as $I \sim N^2 m^2$, where N is the number of superconductive grains, $m = i_c \sigma$ is the mean DM moment per unit cluster. For the typical values of the parameters of the sintered high-T_c ceramics : $i_c = 1\,\mu A$, $\sigma^* = 5\,\mu m^2$, $m = 5 \times 10^5\ \mu_B$, $N = 10^7$, one gets : $I \sim 10^{24}\ \mu_B^2$ (μ_B is the Bohr magneton) and $H_c = 1G$.

To verify the predictions of the model for sintered samples one needs to exclude the effects due to the penetration of magnetic vortices into the sample. For that the measurements should be carried out in the fields range $H_{c_1} > H \gtrsim H_c$. Here H_{c_1} is the first critical field for a single grain (for high-T_c ceramics it is expected that $H_{c_1} >> H_c$).

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