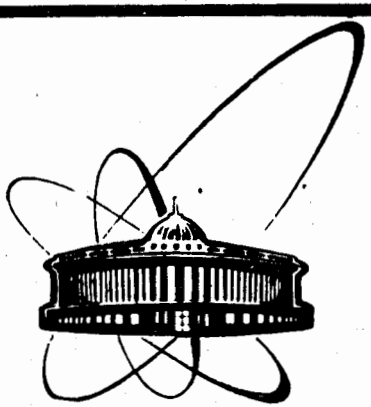

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V.L.Aksenov, E.I.Kornilov, S.A.Sergeenkov

THERMODYNAMICS OF DIPOLE SUPERCONDUCTIVE GLASS MODEL

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1. INTRODUCTION

With the discovery of superconducting oxide ceramics an interest in granular media has noticeably increased. The possibility of a glass-like behaviour in the presence of an externally applied magnetic field is widely discussed in particular. The mechanism that ensures the appearance of the so-called superconducting glass consists in frustration of the order parameter phase[1,2]. However, as mentioned in reference 3, in granular systems another mechanism of glass behaviour may appear possible, which is not connected with the action of an external magnetic field but with frozen-in randomly oriented moments induced by closed current loops in a network of weak Josephson junctions. The present work suggests a model of this mechanism and discusses the possibility of its realization in superconductive oxide ceramics.

2. THE MODEL

Let us consider a Josephson medium which is a composite of disordered superconducting grains coupled through Josephson tunnel junctions (Fig.1). Below T_c, the transition temperature to a superconductive state, the i-th grain is characterized by a complex order parameter $\Psi_i=\rho_i e^{i\phi_i}$. At sufficiently thin insulating host between grains i and j there arise Josephson currents

$$I_{ij}= I_o \sin (\phi_i-\phi_j) , \qquad (1)$$

where $(\phi_i-\phi_j)$ is the phase difference arising on transition through the barrier and a maximum superconducting current I_0 for two identical superconductors ($\rho_i= \rho_j= \rho$) has the form

$$I_o= 2 K \rho / \hbar , \qquad (2)$$

where K(T) is a constant of coupling between two superconductors which depends on specific features of tunneling. In the absence of an external magnetic field the magnitude and direction of current in each link are random. In a macroscopic sample in a system of random currents there are formed closed loops which can be ascribed magnetic dipole moments $\mathbf{p}$.

So we have a certain dipole moment $\mathbf{p}$ (Fig.1). It is in a local field $\mathbb{H}$, generated by other dipoles. The classical Hamiltonian of the dipole-dipole interaction has the form

$$\mathbf{H}_{dip}= \sum_{\alpha\beta} \{ \mathbf{p}_\alpha \mathbf{p}_\beta - 3(\mathbf{p}_\alpha \mathbf{n}_{\alpha\beta})(\mathbf{p}_\beta \mathbf{n}_{\alpha\beta}) \} r_{\alpha\beta}^{-3} , \qquad (3)$$

where $\mathbf{n}_{\alpha\beta}=\mathbf{r}_{\alpha\beta}/r_{\alpha\beta}$, $r_{\alpha\beta}$ is the distance between dipoles α and β . Note that due to the fact that closed loops are randomly distributed in a Josephson medium both $r_{\alpha\beta}$ and $\mathbf{n}_{\alpha\beta}$ have random values. In the mean-field approximation Hamiltonian (3) may be presented in the form

$$\mathcal{H}_{dip}= \sum_{\alpha} \mathbf{p}_{\alpha}\mathbb{H}_{\alpha} \quad , \tag{4}$$

where

$$\mathbb{H}_{\alpha} = \sum_{\beta} \{\mathbf{m}_{\beta}- 3\, \mathbf{n}_{\alpha\beta}(\mathbf{m}_{\beta}\, \mathbf{n}_{\alpha\beta})\}r_{\alpha\beta}^{-3} \quad , \tag{5}$$

and $\mathbf{m}_{\beta}= <\mathbf{p}_{\beta}>_T$ is the mean thermodynamic value for the moment $\mathbf{p}_{\beta}$. As the dipole-dipole interaction potential changes its sign and the dipoles are randomly distributed in space, local fields $\mathbb{H}_{\alpha}$ have various directions on each dipole, and, therefore, in the absence of an external field at low temperatures these dipoles can be frozen-in randomly oriented. This freezing is characterized by the appearance of the order parameter which is determined in analogy to that for spin-glasses as follows

$$M = [< \mid \mathbf{p}_{\alpha} \mid >_T]_C,$$

where $[...]_C$ denotes averaging over configurations of loops. This low temperature state of randomly oriented in internal fields dipole moments we shall call the dipole superconducting glass state.

3. THERMODYNAMICS OF THE MODEL

Systems with dipole-dipole interaction are well studied in the theory of ferroelectric systems[4]. To calculate mean values for thermodynamic quantities we used the method described in reference 5. Let be known the expression for the thermodynamic quantity Q_1 in a fixed (internal or external) magnetic field $\mathbb{H}$, $Q_1(\mathbb{H},\beta)$. Then by averaging over local fields (5) one can obtain $Q_1(\beta)$ for a dipole. Under assumption of a small concentration of dipole moments N_d we have the following expression for the whole system

$$Q(\beta)= N_d[Q_1(\mathbb{H},\beta)]_c = N_d \int P(\mathbb{H})\, Q_1(\mathbb{H},\beta)\, d\mathbb{H} \quad , \tag{6}$$

where $P(\mathbb{H})$ is the distribution function of local fields of disordered dipoles, $\beta=(k_BT)^{-1}$, T is the absolute temperature, k the Boltzmann's constant. The value of $Q_1(\mathbb{H},\beta)$ is usually obtained from the expression for the partition function of a dipole

$$Z(\mathbb{H},\beta)=\sum_{\mathbf{p}} e^{\beta \mathbf{p}\mathbb{H}} \quad , \tag{7}$$

where summation is made over all allowed values of p . The averaging over random fields in (6) takes the place of the averaging over random configurations of loops. Therefore in the further we shall abandon indices in Greek letters, having introduced the dependence on local fields $\mathbb{H}$. For the distribution function $P(\mathbb{H})$ there was obtained in reference 5 a self-consistent system of equations

$$\mu = \int P(\mathbb{H})\, m(\mathbb{H},\beta)\, d\mathbb{H} \ , \tag{8}$$

$$P(\mathbb{H}) = \pi^{-2} \frac{\Delta\ \mu}{(\Delta^2\mu^2 + \mathbb{H}^2\ )^2} , \tag{9}$$

$$m(\mathbb{H},\beta) = \Big| \sum_{p} p e^{\beta p \mathbb{H}} / \sum_{p} e^{\beta p \mathbb{H}} \Big| = \Big| \frac{d}{d(\beta\mathbb{H})} \ln Z(\mathbb{H},\beta) \Big| \ . \tag{10}$$

In these equations Δ is a certain width of the distribution function . In the case of Josephson induced magnetic moments it is natural to suppose that the value of the moment is proportional to the magnetic flux Φ through a loop

$$p = \Phi\ \vartheta_g ,$$

where ϑ_g is a certain geometrical characteristic of the loop ($\vartheta_g \sim S/L$,where $S \sim R^2$,L is the loop inductance) and

$$\Phi = n_z\ \Phi_0 \ , \tag{11}$$

Here Φ_0 is the magnetic flux quantum, n_z is an integer. By taking the z-axis in the direction of the local magnetic field one can write down the condition of magnetic moment quantization for its z-component as follows

$$p^z = p^z_{max}\ n_z / n \ , \tag{12}$$

where n is the maximum value for n_z , the value of n_z varies from -n to n , and the quantity $p^z_{max} = \Phi_0\ \vartheta_g$ is a natural limit imposed on the value of the magnetic moment by the existence of a critical current (2) destroying the conductivity between the grains.

The summation extended to all n_z in (7) leads to the known expression for the partition function of a magnetic dipole in the field $\mathbb{H}$

$$Z_n(\mathbb{H},\beta) = \mathrm{sh}\Big(\frac{2n+1}{2n}\ p\beta\mathbb{H}\ \Big) \ / \ \mathrm{sh}\Big(\frac{1}{2n}\ p\beta\mathbb{H}\ \Big) , \tag{13}$$

where we have accepted a simplified notation for $p=p^{z}_{max}$. By assuming that all the configurations are characterized by one and the same maximum number of magnetic flux quanta n we may calculate the exact value for $m(\mathbb{H},\beta)$ in the system of equations (8-10). Then the equation for the order parameter $\mu = [\langle p^{z}/p \rangle_{T}]_{c}$ takes the form

$$\mu = \frac{4}{\pi} \int_{0}^{\infty} H^{2} dH \frac{\Delta\mu}{(\Delta^{2}\mu^{2}+H^{2})^{2}} B_{n}(p\beta\mathbb{H}) \quad , \tag{14}$$

where

$$B_{n}(\alpha) = \frac{2n+1}{2n} \operatorname{cth}\left(\frac{2n+1}{2n}\alpha\right) - \frac{1}{2n} \operatorname{cth}\left(\frac{1}{2n}\alpha\right) \tag{15}$$

is the Brillouin function and $\alpha = p\beta H$.

The specific heat of a dipole in a local field $\mathbb{H}$ is

$$C_{n}(\beta,\mathbb{H}) = k_{B}\alpha^{2}\frac{dB_{n}(\alpha)}{d\alpha} \quad . \tag{16}$$

According to (6) the specific heat of a system of dipoles has the form

$$C(\beta) = N_{d}\frac{4k_{B}p\,\beta\,\Delta\,\mu}{\pi} \int_{0}^{\infty} \frac{H^{4}dH}{(\Delta^{2}\mu^{2}+H^{2})^{2}} \left\{\left[\frac{2n}{2n+1} \operatorname{sh}\left(\frac{2n+1}{2n} p\beta\mathbb{H}\right)\right]^{-2} - \right.$$

$$\left. - \left[2n \operatorname{sh}\left(\frac{1}{2n} p\beta\mathbb{H}\right)\right]^{-2}\right\} \quad , \tag{17}$$

where μ is found from (14).

By averaging in an analogous manner over "single-particle" susceptibility

$$\chi(\beta,\mathbb{H}) = \beta\frac{\partial^{2} \ln Z(\beta,\mathbb{H})}{\partial\,(\beta\mathbb{H})^{2}}$$

the magnetic susceptibility of a system may be calculate. Figure 2 presents the results of the numerical calculation of the temperature dependence of susceptibility per dipole, as well as of the order parameter (14) and specific heat. The behaviour of these thermodynamic quantities is analogous to that observed in dipole

dielectric glasses[4]. This fact allows speaking about a transition to a dipole superconducting glass phase in the frame of model (3).

4. DISCUSSION

The calculation of the thermodynamic characteristics of model (3) establishes the fact that in it a glass-like state arises at a certain temperature T_g . Let us note that the simple approximation used allow the qualitative estimation of the situation in a three-dimensional system, while earlier investigations of a superconducting glass state in granular superconductors were performed for the two-dimensional lattice. In order to estimate the interval this state exists in we shall consider the mean energy of the dipole-dipole interaction $U_{dd}=\langle H_{dip}\rangle_T$ for the case of oxide ceramics. It is convenient to express characteristic linear dimensions of a system of currents through the average dimension of a grain f . Let the linear dimensions of a closed loop be $R\sim Nf$, and the distance between dipoles $r\sim Kf$ (Fig.1).

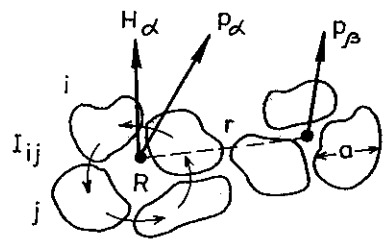

FIG.1. Schematic representation of the Josephson medium.

For a typical[6] Josephson current density of $j_0\sim$ 430 A/cm^2 and a grain dimension of $f\sim$ 5 μm one obtains an estimate of $U_{dd}\sim$ 33 N^4K^{-3} (Kelvin). It is seen that the dimensions of loops and their relative orientation play an important role in the numerical estimation of the interaction energy. The critical temperature of magnetic dipole ordering in various samples may vary in a wide range from about 10 K to few mK.

At present of all the calculated quantities only specific heat permits the comparison with the experiment. The data on heat capacities of yttrium and lanthanum compounds are reviewed in reference 7. These data are evidence of the fact that the behaviour of specific heat in the low temperature range is far from being clear. A number of works[8-10] report the observation of a peculiarity of the Schottky type with the maximum in the vicinity of 0.9 K. This peculiarity behaves very much like that connected with the phase transition in model (3) and shown in Fig.2.

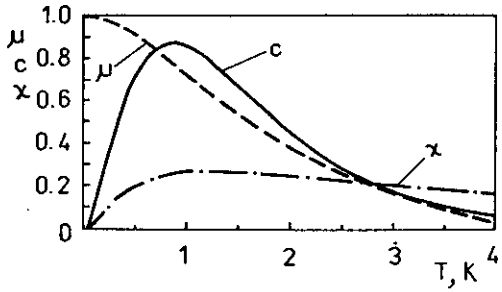

FIG.2. Temperature dependence of the order parameter μ (---), susceptibility χ (-.-) and specific heat C (——) in the model. The thermodynamic functions are given in arbitrary units.

More detailed information on the peculiarities of the transition to a glass phase can be derived from the dynamic consideration of the model as done in reference 11 for the case of superconducting glasses.

REFERENCES

[1] C.Ebner and D.Stroud, Phys.Rev. , 31B (1985) 165 .

[2] I.Morgenstern, K.A.Muller and J.G.Bednorz, Z.Phys., 69B (1987) 33.

[3] S.John and T.C.Lubensky, Phys.Rev., 34B (1986) 4815.

[4] B.E.Vugmeister and M.D.Glinchuk, Sov. Phys. Usp., 28 (1985) 606.

[5] M.W.Klein, C.Held and E.Zuroff, Phys.Rev., 13B (1976) 357 .

[6] M.Giura, R.Marcon and R.Fastampa, Phys.Rev.,39B (1989) 2796.

[7] H.E.Fischer, S.K.Watson and D.G.Cahill, Comments on Cond. Matt. Phys., 14 (1988) 65.

[8] N.E.Phillips, R.A.Fisher, S.E.Lacy, C.Marcenat, J.A.Olsen, W.K.Ham and A.M.Stacy, Jpn. J. App. Phys.,26 (1987) 1115 , Suppl. 26-3.

[9] T.Sasaki et al, Physica , 153C-155C (1988) 1012.

[10] R.A.Fisher et al., Physica , 153C-155C (1988) 1092.

[11] V.L.Aksenov and S.Sergeenkov,Physica, 156C (1988) 235.

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