Phase-glass scaling near the coherence transition in granular HoBa$_2$Cu$_3$O$_{7-\delta}$ superconducting thin films

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Systematic measurements of electrical magnetoconductivity near the coherence transition of granular HoBa$_2$Cu$_3$O$_{7-\delta}$ thin films are reported. Experiments performed in magnetic fields ranging from 0 to 2500 Oe reveal that close to the coherence transition temperature $T_c(0)$, the correlation length scales as a power law of temperature with a thermal-dependent critical exponent, $\nu$. In low external fields the corresponding value of $\nu$ is consistent with the two-dimensional phase-glass model, which is in the same dynamical universality class of the so-called vortex-glass model. At applied fields $H > 1000$ Oe, the vortex dynamics becomes stronger and the coherence transition is not observed.

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1 Introduction

It is known that the granular high temperature superconductors are characterized by the occurrence of a two-stage transition from the normal phase to the long-range superconducting state [1]. This behavior is described by supposing that the pairing transition stabilizes a superconducting state in mesoscopic regions (grains) of samples at critical temperature $T_c$, which corresponds to that of the bulk specimen. This is the so-called pairing transition [2]. In absence of magnetic fields, at a lower critical temperature $T_{c,0}$, the whole network of ceramic material is driven into a long-range coherent state by a percolation-like process that activates weak-links between the grains. This constitutes what is known as coherence transition [2]. At the coherence transition, a long-range ordered state for the phase of the order parameter is established in the whole granular array. The static and dynamic universality classes for the coherence transition are that of the 3D-XY model described by the phase-glass Hamiltonian [3]

$$H = -\sum_{i,j} J_{ij} \cos (\theta_i - \theta_j - A_{ij}),$$

where $J_{ij}$ is the Josephson energy coupling between grains $i$ and $j$, $\theta$ denotes the phase of the order parameter in grain $i$ and the sum considers all the grains of a disordered system. The gauge factor $A_{ij}$ is given by $A_{ij} = \frac{2\pi}{\Phi_0} \int_A A \cdot dl$, where $\Phi_0$ is the flux quantum, $A$ represents the potential vector, $dl$ is an infinitesimal element of longitude and the line integral is evaluated between centers of grains $i$ and $j$. The
model represented by Eq. (1) belongs to the 3D-XY class with non-trivial (associated to frustration) disorder. Frustration is primarily introduced by a random distribution of the factors $A_{ij}$ [4]. The possibility for negative values of the $J_{ij}$ coupling due to, e.g., the occurrence of $\pi$-junctions, may also introduce frustration, much as in the conventional spin-glass models [5]. In three-dimensional systems, the vortex-glass model considers that the flux lines, due of the penetrating magnetic flux into the samples, acquire analogous configurations to those of the magnetic ordering which occurs in spin-glasses [6]. These are magnetically disordered and frustrated. The disorder does not permit the establishing of a global state of the system, in which the interactions between whole spin pairs may be simultaneously satisfied. In granular superconductor systems, the phase-glass is characterized by disorder, due to existence of pinning centers and frustration [4]. In two-dimensional systems, the transition is believed to be in the same dynamical universality class as the 3D-vortex-glass [7]. In this work, we present measurements of electrical magnetoconductivity near the coherence transition of granular HoBa$_2$Cu$_3$O$_{7-\delta}$ thin films. The aim of the paper is to show that is possible to experimentally identify the coherence transition into the phase-glass model, in presence of several applied magnetic fields.

2 Experimental

We have prepared in-situ HoBa$_2$Cu$_3$O$_{7-\delta}$ thin films by a high-pressure dc-sputtering technique in an atmosphere of pure oxygen, deposited on SrTiO$_3$ (100) single crystal [8]. The X-ray diffraction spectra indicated that the $c = 11.67(7)$ Å crystallographic parameter are oriented normal to the surface of the substrate. The conductivity experiments were performed by means of an ac-technique. Temperatures were measured with a Pt-100 thermometer corrected for magnetoresistivity effects. Magnetic fields up to $H = 2500$ Oe were applied perpendicular to the transport current direction and the measurements were performed in accordance to the field cooling procedure.

3 Analysis and results

As shown in Fig. 1(a), the resistive transition of HoBa$_2$Cu$_3$O$_{7-\delta}$ films in absence of magnetic fields evidences the universal linear behavior characteristic of the cuprate superconductors in the normal state and a transition temperature of $T_c = 92.7$ K, which is obtaining from the maximum peak in the temperature derivative (Inset of Fig. 1(a)). Figure 1(b) exemplifies the resistivity transition as a function of temperature for $H = 50, 100, 250, 500, 1000$ and $2500$ Oe. It is apparent from the results in Fig. 1(b) that the superconducting transition proceeds in two steps.

![Fig. 1](image-url) Representative resistive transition of HoBa$_2$Cu$_3$O$_{7-\delta}$ thin films. (a) Like-linear feature of the normal resistivity and superconducting transition in absence of magnetic field and for an applied current density $j = 5$ A/cm$^2$. The inset in Fig. 1(a) represents the maximum peak in temperature derivative of $\rho(T)$ close to $T_c$. (b) Resistivity as a function of temperature for $H = 50, 100, 250, 500, 1000$ and $2500$ Oe applied fields.
When the temperature gets close enough to $T_c$, the critical thermodynamics of the pairing transition is well described by the 3D-XY universality class [9]. Below $T_c$, near to the zero-resistance state, the resistivity is dominated by effects related to the coherence transition, where the fluctuating phases of the Ginzburg–Landau order parameter in all the grains become long-range ordered [2].

The analysis of experimental data was performed by assuming that the magnetoconductivity excess is given by

$$\Delta \sigma = \sigma - \sigma_R,$$

where $\sigma = \sigma(T,H)$ is the reciprocal of the measured magnetoresistivity and $\sigma_R = 1/\rho_R$ is the corresponding regular term, extrapolated from the high-temperature behavior of resistivity, which is approximately linear in the normal state, as shown in Fig. 1(a). Then, we adopt the simplest approach where it is expected that the magnetoconductivity fluctuation diverge in the power law form

$$\sigma_T = D \varepsilon^{-\lambda},$$

where $A$ is a constant, $\lambda$ represents the critical exponent of the fluctuation regime and

$$\varepsilon = \frac{[T(H) - T_c(H)]}{T_c(H)}$$

is the field-dependent reduced temperature. Thus, we determine numerically the logarithmic derivative of $\Delta \sigma(T,H)$ as

$$\chi_\sigma = -\frac{d}{dT} \ln (\Delta \sigma) = -\frac{1}{\Delta \sigma} \frac{d}{dT} (\Delta \sigma) \quad \text{and} \quad \frac{1}{\chi_\sigma} = \frac{1}{\lambda} [T - T_c(H)].$$

From Eq. (2) the simple identification of linear temperature regions in plots of $\chi_\sigma^{-1}$ as a function of $T$ permits the simultaneous determination of the critical exponent $\lambda$ and the critical temperature $T_c(H)$ of the regime. Figure 2(a) shows our results of $\chi_\sigma^{-1}$ vs. $T$. Straight-line exemplifies the scaling of the data close to the zero resistance state. However, the size limitation in this figure do not permits to observe the parallel lines corresponding to the scaling for several applied fields. In the paracoherent state [1], due to effect of phase fluctuations in the granular array above the coherence transition, two power law regimes with field-independent exponents were identified up to $H = 1000$ Oe. Close to the field-dependent critical temperature $T_{c,0}(H)$, we effectively determine a regime characterized by the exponent $\lambda_{H} = 4.7 \pm 0.2$. At this paracoherent region the phases of the order parameter in the whole granular system begin the ordering process to acquire the long-range order at the critical temperature $T_{c,0}(H)$.

4 Discussion

The critical exponent for fluctuation conductivity is analyzed by considering that [2]

$$\lambda = \nu(2 + z - d + \eta),$$

where $\nu$ is the critical exponent for the coherence length, $z$ is the dynamical critical exponent, $d$ is the dimensionality of the fluctuation system and $\eta$ is the deviation of the order-parameter correlation function from the Orstein–Zernike behavior. When weak magnetic fields (up to 1000 Oe) are applied, the exponent $\lambda_{H} = 4.7$ would be related to the coherence transition when the frustrated character is introduced by the presence of fields through the $A_i$ term of Eq. (1). At $H > 1000$ Oe, the vortex dynam-
ics becomes stronger and the coherence transition is not observed. From the fluctuation magnetoconductivity analysis, this regime represents a genuine critical behavior with $\nu = 2$, $\eta = 0$ and $z = 2.4$ [10]. This result is approximately compatible with the Ambegaokar–Halperin model [11] for $H \approx 0$, which argues that in 2D systems the dynamical exponent must be $z = 2$. Our value of $z < 4$ is does not in agreement with the conventional spin-glasses [5], where the critical dynamic for $d < 6$, in an $\varepsilon = 6 - d$ first order expansion, gives a dynamical exponent $z \approx 4$. In this scenery $z = 2(2 - \eta)$ [12]. Thus, our result corresponds to a $z$ value significantly larger than the theoretical results of the dynamical exponents from scalings based on isotropic weak pinning in HTSC thin films [13]. On the other hand, the difference of the dynamical exponent for zero and finite applied fields implies that the dynamic universality class is not the same in these cases. This regime, described by the exponent $\lambda_H \approx 4.7$, clearly corresponds to a vortex-glass-like transition. In other words, in low applied fields, the coherence transition is a genuine phase transition, which may be described through the phase-glass model. To clarify that the paraconsistent region is a regime precursory to the coherence transition, we propose that, close to the phase-glass transition, the fluctuation scales as [14]

$$\Delta \sigma(H, T) \sim \xi^{-(2 + z - d + \eta)} S_{\xi}(\frac{H}{\xi^{2 + \eta}}),$$

(3)

where $S_{\xi}(\tau)$ are universal functions of scaling for $T > T_c$ and $T < T_c$, respectively. By a characteristic critical transformation [15], and in the proximity of the vortex-glass transition [6], with $[T_c - T_{\xi}(H)] \sim H^{2\eta}$, Eq. (3) may be written as

$$\Delta \sigma(H, T) - [T_c - T_{\xi}(H)] ^{-2(2 + z - d + \eta)} S_{\xi}(\tau).$$

(4)

From Eq. (4), we obtain the derivative

$$\frac{d}{dT} \ln(\Delta \sigma) = \frac{1}{T_c - T_{\xi}(H)} \frac{d}{d\tau} \ln S_{\xi}(\tau), \quad \text{and} \quad \frac{d}{d\tau} \ln S_{\xi}(\tau) = \chi_{\xi}[T_c - T_{\xi}(H)].$$

(5)

Figure 2(b) shows a plot of $\chi_{\xi}[T_c - T_{\xi}(H)]$ as a function of the new reduced temperature $\tau = (T - T_{\xi})/(T_c - T_{\xi})$ determined from the results presented in Fig. 2(a). A good scaling is indeed obtained up to $H = 1000$ Oe in most of the (0; 0.8) range for the occurrence of the coherence transition. In the (0.8; 1) range some deviations occur due to the event of phase fluctuations of the Ginzburg–Landau order parameter in isolated grains [2]. For $H = 2500$ Oe the scaling, as defined in Eq. (5), is poor.

5 Conclusion

We have presented an extensive study of low-field magnetoconductivity fluctuations in granular HoBa$_2$Cu$_3$O$_{6-\delta}$ thin films. Our results show that below the pairing transition, near the zero-resistance state, the coherence transition occurs at a critical temperature $T_{\xi}(H)$, where the long-range ordered state for the phase of the order parameter is established in the whole granular system. The approach to the zero-resistance-state is dominated by strong phase fluctuations of the order parameter in individual grains. In low magnetic fields the corresponding exponent is related to a dynamic universality class of the 3D-XY model described by the phase-glass Hamiltonian of Eq. (1), where the disorder is nontrivial and the frustration is due to the presence of the random gauge factor $A_{ij}$. A scaling analysis of $\chi_{\xi}$ in the interval between $T_{\xi}(H)$ and $T_c$ shows that the phase-glass in 2D-like-frustrated systems is in the same dynamic universality class of the vortex-glass. In the phase-glass, the percolation difficulty is related to the formation of loops of weakly coupled grains. Thus, the frustration might occur because the coupling energies between all pairs of grains cannot be simultaneously minimized in the presence of the random gauge factors $A_{ij}$. Finally, the coherence transition is achieved when an ideally infinite cluster of coupled grains is formed in the sample.

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