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Non-Universal Behaviour of Paraconductivity in $YBa_2Cu_3O_{7-\delta}$ Films

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Abstract

Our analysis of in-plane paraconductivity measurements on $YBa_2Cu_3O_{7-\delta}$ (YBCO) films indicates that short-wavelength cutoff effects are significant even very close to the critical point because of the short coherence length ξ. Consequently, the Aslamazov-Larkin (AL) and Lawrence-Doniach expressions are inapplicable to YBCO in the *whole* Ginzburg-Landau mean-field region, while a generalized AL expression in three-dimensions, that replaces the conventional AL expression in the case of short ξ, accounts for the data within the experimental error. We conclude that the superconducting state of YBCO is three-dimensional and that the universal AL relation between the critical exponent of paraconductivity and the dimensionality of the superconducting fluctuations is no longer valid in superconductors with sufficiently short ξ.

1. Introduction

The discovery of the layered structure of the cuprate superconductors raised the fundamental question of the dimensionality of the superconducting state of these materials. Several authors answered this question by measuring the excess of the electrical conductivity (paraconductivity) above T_c in a number of cuprates and analyzing the experimental data in the framework of the Aslamazov-Larkin (AL) theory (see eq. (1) and Ref. [1]). In fact, the AL theory was originally developed for conventional, long coherence length superconductors and its application to the cuprate superconductors lead to controversial conclusions.

Our analysis of in-plane paraconductivity measurements on YBCO films explains the above controversy in terms of the inapplicability of the AL theory to short coherence length superconductors, that is the case of the cuprates. However, we demonstrate that an exact generalized result [2], that replaces the conventional AL result in the case of short coherence length, accounts for our experimental data within the experimental error. This gives evidence for the three-dimensional nature of the superconducting state in YBCO and the breakdown of the universal prediction of the AL theory in superconductors with sufficiently short coherence length.

2. AL theory in conventional superconductors

The AL theory [1] establishes an universal relation between the critical behaviour of the paraconductivity $\delta\sigma$ and the dimensionality D of the superconducting Gaussian fluctuations above T_c in the Ginzburg-Landau (GL) mean-field region:

$$\delta\sigma \sim t^{-\gamma}, \gamma = 2 - D/2 \qquad (1)$$

where $t \equiv T/T_c - 1$ and T_c is the mean-field critical temperature. Eq. (1) is valid if the *whole* Lorentzian spectrum of the Gaussian fluctuations contributes to the paraconductivity. However, thermal energy can activate *only* spatial fluctuations with wavelength λ much larger than the range a of the interatomic forces [2]. Hence, it is *necessary* to introduce a cutoff wavelength $\tilde{\lambda}$ in the fluctuation spectrum, where $\tilde{\lambda} >> a$ for all cases [3], in *any* microscopic *or* phenomenological theory. It follows that the AL eq. (1) is valid *only* if the superconducting coherence length $\xi = \xi_0 t^{-1/2}$ is much larger than $\tilde{\lambda}$ at *any* t in the GL mean-field region. In this case, the limits of integration in the AL integral [1]:

$$\delta\sigma \sim \int_{k \le \tilde{k}} \frac{(\mathbf{k u})^2}{(1+\xi^2 k^2)^3} d^D k \qquad (2)$$

where $\mathbf{u}$ is the electric field unit vector and $\tilde{k} \equiv 2\pi/\tilde{\lambda}$ is the cutoff wavevector of the fluctuations, can be approximated by infinity. As a consequence of this approximation, the critical exponent γ depends on D only, since its dependence on $\tilde{\lambda}$ disappears and eq. (1) is obtained. The validity of eq. (1) has been confirmed by several studies on amorphous metals and alloys [4,5].

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3. AL and LD theories in the cuprates: controversial conclusions

The aforementioned controversy in the interpretation of the experimental paraconductivity data on the cuprate superconductors is particularly striking in the case of YBCO. In fact, three- [6-8], two- [9-11] and even one- [12] dimensional paraconductivities were reported. One might expect such controversy, since the fluctuations of YBCO can be neither purely three-, nor purely two-dimensional because of the layered structure. In fact, several authors [11,13-15] carried out their analysis also in the framework of the Lawrence-Doniach (LD) model for layered superconductors. Under the assumption of Josephson coupling between infinitely thin superconducting layers, this model leads to the following expression for the in-plane paraconductivity $\delta\sigma_{||}$ [16]:

$$\delta\sigma_{||} = \frac{\pi e^2}{8h}\frac{1}{d\,t}\left[1+\left(\frac{2\xi_{zz,0}}{d}\right)^2\frac{1}{t}\right]^{-\frac{1}{2}} \tag{3}$$

In eq. (3), d and $\xi_{zz,0}$ are, respectively, the interlayer distance and the coherence length at zero temperature along the direction z perpendicular to the planes. Eq. (3) predicts a crossover of γ from the two-dimensional AL value $\gamma = 1$ at high temperatures to the three-dimensional AL value $\gamma = 1/2$ at low temperatures. However, also the application of eq. (3) to YBCO lead to contradictory conclusions: some authors claimed the validity of this equation to account for their experimental data [13], while others claimed the opposite [11,14].

We argue that the reason for so controversial conclusions is twofold. First of all, different groups applied eqs. (1) and (3) on the basis of different choices of T_c, whereas, in the framework of AL and LD theories, the determination of the critical exponent γ depends strongly on the choice of T_c, as already pointed out elsewhere [8]. Secondly, several studies on YBCO report a complex, *non monotonic* behaviour of γ as a function of temperature for *any* choice of T_c [8,9,15]. This is also confirmed by our results reported in the experimental section of the present work (see Fig. 2). Hence, the determination of γ on the basis of the experimental data turns out to be arbitrary [17], independently on the choice of T_c, and we conclude that neither AL eq. (1) nor LD eq. (3) are applicable to ours and other experimental data on YBCO.

4. Generalizing the AL theory to short coherence length superconductors

Johnson, Tsuei and Chaudhari [5] and Freitas, Tsuei and Plaskett [6] first explained some deviations from the predictions of eq. (1) observed in amorphous alloys [5] and in YBCO polycrystals [6] in terms of the failure of the approximation $\xi >> \tilde{\lambda}$ in the case of short ξ_0, that is indeed the case of amorphous and cuprate superconductors. More recently, Hopfengärtner, Hensel and Saemann-Ischenko [15] confirmed these findings in YBCO films. All the above authors noticed the importancy of these effects especially at high temperatures and interpreted them as the signature of the breakdown of the GL mean-field theory at sufficiently high temperatures. By keeping finite the limits of integration in the *numerical* integration of eq. (2), it was possible to account satisfactorily for the experimental data on amorphous alloys [5]. In the case of YBCO, such numerical procedure was not completely satisfactory, since it explained only the gross features of the experimental curves (in particular the drop of the paraconductivity at high temperatures), while the non monotonic behaviour of γ remained unexplained [6,15].

To improve this kind of analysis, we used the following result in three (3D) and two (2D) dimensions that has been obtained by calculating *exactly* the integral in eq. (2) [2]:

$$\delta\sigma_{||}^{(3D)} = \frac{e^2}{8h}\frac{1}{\xi_{zz,0}}\left[\frac{1}{\sqrt{t}}\arctan\left(\frac{\tilde{u}}{\sqrt{t}}\right) - \frac{\tilde{v}}{t+\tilde{v}^2} - \frac{2}{3}\frac{\tilde{w}^3}{\left(t+\tilde{w}^2\right)^2}\right] \tag{4}$$

$$\delta\sigma_{||}^{(2D)} = \frac{\pi e^2}{8h}\frac{1}{d}\left[\frac{1}{t} - \frac{1}{t+\tilde{u}^2} - \frac{\tilde{v}^2}{\left(t+\tilde{v}^2\right)^2}\right] \tag{5}$$

In the above equations, d is the thickness of the two-dimensional system and $\tilde{u}$, $\tilde{v}$ and $\tilde{w}$ are the averages over the directions in the reciprocal space of the short-wavelength cutoff parameter $2\pi\xi_0/\tilde{\lambda}$ that appears in the three (two) terms in the bracket of eq. (4) (eq. (5)). These equations are adapted from Ref. [2] to the case of current flow in the twinned *ab*-plane of our *c*-oriented YBCO films. As expected, both equations transform into the universal AL eq. (1) at sufficiently low temperatures or if ξ_0 is sufficiently large. Eqs. (4) and (5) predict significant deviations from the universal AL predictions of eq. (1) *in the whole GL mean-field region* if $\xi_0 \lesssim \tilde{\lambda}$. In particular, even a non-monotonic behaviour of γ is predicted for some particular values of the parameters $\tilde{u}$, $\tilde{v}$ and $\tilde{w}$ [2].

5. Experimental

In order to verify the validity of eqs. (4) and (5), we measured the in-plane paraconductivity of several ion-beam sputtered YBCO films. Details on the preparation technique and on film characterization are reported elsewhere [18]. The as-deposited films on $SrTiO_3$ <100> single crystals are 50 nm thick and *c*-oriented. The films are fully oxidized as indicated by their transition temperatures T_{c0}≈90 K and transition widths ΔT_c<1 K (see Fig. 1).

Resistance data were recorded with standard AC technique. Resistivity was obtained from resistance data using the van der Pauw method [19]. The paraconductivity $\delta\sigma$ was determined according to the definition: $\delta\sigma \equiv 1/\rho - 1/\rho_f$, where ρ is the experimental resistivity curve and ρ_f is the fit of this curve above the fluctuation region. We observed that $\delta\sigma$ is stable upon small variations of ρ_f. In particular, we fitted ρ in different temperature intervals, using linear, quadratic and cubic polynomials. Qualitatively, the resulting $\delta\sigma$-curves were equal. Quantitatively, the scattering was within ±10% in the range of interest T_c-100 K, that corresponds to the GL mean-field region $t \ll 1$ [3].

6. Analysis of the experimental results

In all our samples, γ has no definite value, except in narrow temperature intervals (Figs. 1,2). Moreover, the experimental values of γ deviate significantly from the AL predictions in two- and three-dimensions *in the whole GL mean-field region* and not just at high temperatures as reported elsewhere [6,15]. Therefore, we did not use AL eq. (1) to analyze our data. The LD eq. (3) does not account either for the data of any of our films. In particular, its crossover from linear to square-root temperature dependence is too smooth to reproduce the experimental behaviour. This conclusion is in agreement with Hagen, Wang and Ong [11]. The deviation of the best χ^2-fit by eq. (3) from the experimental points can be better appreciated in a logarithmic scale (see Fig. 2).

The 'three-dimensional' eq. (4) accounts for the data on all our YBCO films within the experimental error for $\xi_{zz,0} \approx 1.0$ Å and $\tilde{u}$, $\tilde{v}$, $\tilde{w} \sim 0.1$. In particular, eq. (4) reproduces the non-monotonic behaviour of γ in the temperature interval $-2.3 \lesssim \log_{10} t \lesssim -0.8$ (see Fig. 2). The deviation of eq. (4) from the experimental data outside this region is expected, since the validity of eq. (4) is restricted to the GL mean-field region that corresponds to temperatures not too far from and not too close to T_c [3]. The curve based on eq. (4) and plotted in Fig. 2 recovers the 3D AL behaviour only at temperatures below $\log_{10} t \approx -4.5$ (not visible in Fig. 2).

Following Landau and Lifshitz [3], we assume $\tilde{\lambda} \sim 10$ a (a is of the order of the interatomic distances). Hence, the relations $\tilde{u}$, $\tilde{v}$, $\tilde{w} \sim 0.1$ correspond to $\xi_{zz,0} \sim a$. This is consistent with the estimations of $\xi_{zz,0}$ reported above and in previous studies [20]. Contrary to eq. (4), the 'two-dimensional' eq. (5) accounts neither quantitatively, nor qualitatively for our paraconductivity data. Hence, we conclude on the three-dimensionality of the superconducting fluctuations (and the superconducting state) of our YBCO films.

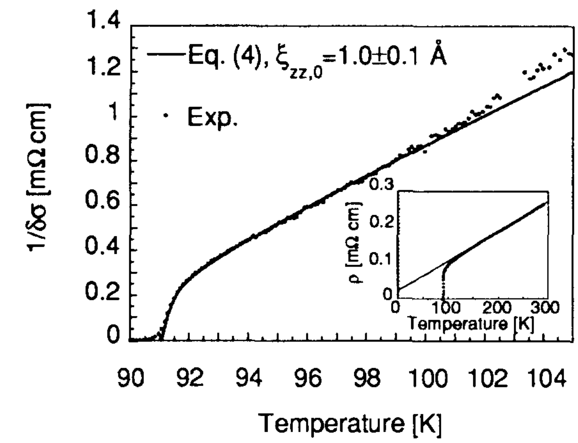

Figure 1. The experimental data of inverse paraconductivity are plotted as a function of temperature for a typical YBCO film. The solid line represents the best χ^2-fit of the data by eq. (4). Eq. (4) agrees within the experimental error between T_c and ≈100 K. We argue that the deviation of eq. (4) from the experimental data outside this interval is due to the breakdown of the GL mean-field theory at temperatures too close to and too far from T_c [3]. The raw resistivity data are shown in the inset.

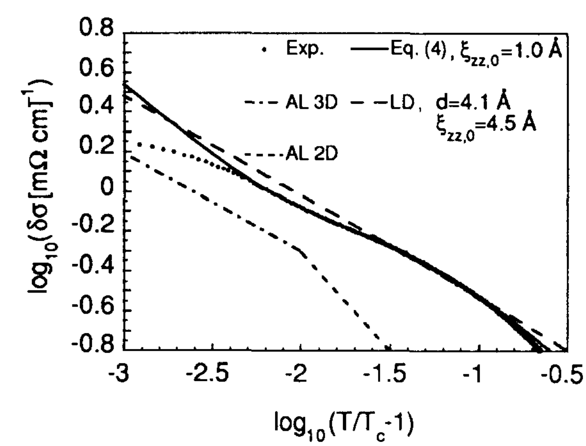

Figure 2. The same curves of Fig. 1 are plotted in logarithmic scale as a function of reduced temperature for a typical YBCO film. The best fit by LD eq. (3) and the predictions by AL eq. (1) in three (3D) and two (2D) dimensions are also plotted for comparison. The slope of the curve, i.e. the critical exponent γ of paraconductivity, deviates *significantly* from the AL and LD predictions *in the whole temperature range*. The 3D AL value $\gamma = 1/2$ is recovered by the fitting curve based on eq. (4) (solid line) only at temperatures below $\log_{10} t \approx -4.5$ (not visible in the plot). Note also the non-monotonic temperature dependence of γ, that is not explained by the universal AL eq. (1), while it is by the non-universal eq. (4).

7. Discussion

Our analysis gives evidence for the *non-universality of the critical exponent* γ in the case of sufficiently short ξ. We note that, in their classic textbook [3], Landau and Lifshitz point out that, when $t \to 0$, $\xi \to \infty$; hence, the significant fluctuations are those with wavevector $k \sim 1/\xi \to 0$, while the fluctuations with $k \sim 1/\tilde{\lambda}$ are less important. On the basis of the above considerations, they argue that it is very probable that the critical exponents describing the singularity of the thermodynamic potential near second order phase transitions are *universal* (hence independent on $\tilde{\lambda}$). Our result gives the experimental evidence for the opposite: in YBCO the critical exponent γ does depend on $\tilde{\lambda}$. This indicates that in YBCO and, in general, in systems with sufficiently short ξ, ξ remains sufficiently small in the whole GL mean-field region and the fluctuations with $k \sim 1/\tilde{\lambda}$ become important.

We argue that our analysis based on eqs. (4) and (5) agrees with the predictions of a generalized exact equation of the renormalization group that has been obtained by Ivanchenko and Lisyansky [21]. This equation predicts that the introduction of a cutoff in phase-transition theory determines the non-universality of the critical exponents, since these are functions of the cutoff parameter in the momentum space, that is also the case of eqs. (4) and (5).

8. Conclusions

Our analysis of in-plane paraconductivity measurements on thin YBCO films shows that the universal AL relation between the critical exponent of paraconductivity and the dimensionality of the superconducting state is no longer valid in superconductors with sufficiently short coherence length. We explained our paraconductivity data by using a generalized exact expression that replaces the AL expression in the case of short coherence length and gives evidence for the three-dimensionality of the superconducting state in YBCO.

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