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INTERPRETATION OF MICROWAVE MAGNETORESISTANCE ABOVE AND BELOW T_c IN A SINGLE CRYSTAL $YBa_2Cu_3O_{7-\delta}$ SUPERCONDUCTOR

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Dedicated to Professor Mladen Paić on the occasion of his 90$^{\mathbf{th}}$ birthday

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Field dependence of the microwave surface resistance in $YBa_2Cu_3O_{7-\delta}$ single crystal is analysed in terms of the mixed state and superconducting fluctuations. Careful fitting of the appropriate parts of the magnetoresistance curves yields the upper critical field, and mean field T_c. The microwave fluctuations conductivity is found to scale as predicted for a three dimensional (3D) superconductor.

1. Introduction

Superconducting transition in high-T_c cuprate superconductors are characterized by an extended region in which fluctuations of the order parameter play a significant role [1-5]. Therefore, the determination of a critical temperature T_c requires some choice of criteria. The authors usually quote the measured values of the "onset" temperature, or the temperature of the "half height", or "zero resistance" temperature. All these, and other similar criteria, lack precision and physical justification. A better analysis can be provided by the application of scaling laws which are expected to hold for various thermodynamic quantities in the fluctuation regime. Such procedures yield T_c as a fit parameter for best scaling. However, there may be some uncertainty with these methods since the same experimental data can often be equally well scaled by different theoretical laws, each yielding a different T_c value. In such cases, there is no independent confirmation for the correctness of a given choice.

Recently, we have developed a method which can yield mean field T_c in an unambiguous way [6]. It consists in measuring magnetic field dependence of the microwave absorption in the mixed state of superconductors, and fitting to the theoretical expressions [7], which yield the upper critical field $H_{c2}(T)$. Mean field T_c is defined as the temperature at which the coherence length diverges, and this is the temperature at which $H_{c2}(T)$ vanishes. The salient feature of this method is that H_{c2} is determined from the behaviour of the microwave absorption at fields $H < H_{c2}$, i.e. well below the transition to the normal state. In contrast, the determination of H_{c2} by other conventional methods is based on the measurement of the extended field value at which the transition to the normal state occurs. However, when this point is approached in high-T_c superconductors one enters the regime of strong fluctuations with no sharp transition to the normal state so that the above definition of H_{c2} looses ground.

In the present paper, we show that the experimentally observed field dependence of the microwave surface resistance can be analysed in the fluctuations regime both above and below mean field T_c. We first give the necessary experimental information in Sect. 2. The measurements are described in Sect. 3, while in Sect. 4 we analyse the scaling laws for the fluctuation conductivity. Section 5 concludes the paper.

2. *Experimental*

We carried out our microwave measurements on a high quality $YBa_2Cu_3O_{7-\delta}$ single crystal. It was grown by the standard flux method in ZrO_2 crucibles. The size of the crystal was 1 mm×1 mm×0.03 mm with the larger face parallel to the copper-oxygen plane. The crystal was annealed in oxygen at 450 °C for a period of four weeks in order to achieve full homogeneity.

The microwave measurements were made in a TE_{102} cavity at 9.3 GHz. We used Brucker 046MRP microwave bridge equipped with microwave pulsing so that lock-in technique could be used to reduce the noise level. The sample was mounted on the sapphire holder of a home built cryostat, and positioned in the center of the microwave cavity. The cavity was placed between the poles of an electromagnet whose field could be varied from zero up to 2.25 T. The change of the temperature of the sample, and/or the external magnetic field resulted in the change of the surface resistance of the sample, giving rise to a change of the microwave absorption. The detection of this change was done by the microwave bridge and lock-in amplifier. The data were stored in a computer.

3. *Measurements*

We used a copper plate as a test sample to calibrate the sensitivity of our experimental setup. Thus, the surface resistance of the superconductor sample could be evaluated in absolute units [7]. Figure 1a shows the temperature change of the surface resistance R_s in zero magnetic field. The transition into the superconducting state is not sharp. There are two possibilities for the cause of this rounding. The first is that the sample is inhomogeneous so that various parts have some distribution of their transition temperatures. In this case, one could not speak of a well defined T_c for the whole crystal. The other possibility is that the superconducting fluctuations are extended over a region which is much larger than the residual distribution of inhomogeneous T_c. Then, we could speak of a mean field T_c for the entire sample, but its precise determination remains as subtle problem. Certainly, Fig. 1a above does not suffice to decide between the two possibilities. In the following we show that the question could be answered if we introduce magnetic field as an additional experimental variable. In Fig. 1b we show a set of magnetoresistance curves for $B \parallel c$ taken at the same temperatures as the data points in Fig. 1a. At higher temperatures, there is no field dependence of R_s, which is the expected behaviour in the normal state. As the superconducting transition is approached, one observes a prominent field dependence. The introduction of the external magnetic field at a fixed temperature makes R_s to rise towards its normal state value. Qualitatively, this behaviour is expected for the superconductor in the mixed state, and also in the region dominated by the superconducting fluctuations, with a single T_c, or with a distribution of T_c 's. Our task is to make a quantitative analysis and fit the shape of the magnetoresistance curves to some theoretical expressions, so that one can resolve the above cases.

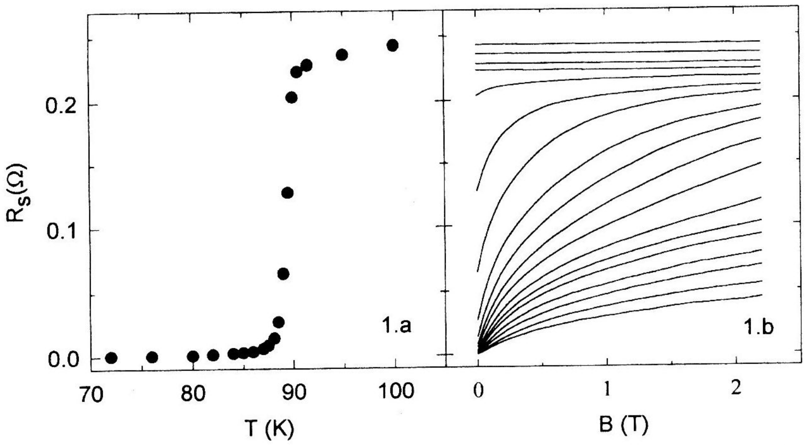

Fig. 1. a) Temperature dependence of the surface resistance R_s in a single crystal $YBa_2Cu_3O_{7-\delta}$ *in zero magnetic field. b) Experimental magnetic field dependences of R_s taken at the same temperatures as the data points in 1a).*

Let us start the analysis with low temperature curves. Well below T_c, the superconductor is expected to be in the mixed state. In our experimental configuration the microwave current induced on the surface of the sample is perpendicular to the flux lines and exerts Lorentz force. The oscillations of the flux lines give rise to an effective conductivity in the mixed state given in Refs. [6,7]:

$$\frac{1}{\tilde{\sigma}_v} = \frac{1 - b(v/v_f)}{(1-b)\sigma + b\sigma_n} + \frac{b}{\sigma_n}\frac{v}{v_f}, \tag{1}$$

where $b = B/B_{c2}$ is the reduced field, σ is the Meissner state microwave conductivity, σ_n is the normal state conductivity, and v/v_f is the velocity factor which ranges from zero in the case of perfectly pinned vortices to unity for the limiting case of flux flow. The surface resistance is the real part of the complex surface impedance

$$R_s = \mathrm{Re}(Z_s) = \mathrm{Re}\sqrt{\mathrm{i}\frac{\mu_0\omega}{\tilde{\sigma}_v}}. \tag{2}$$

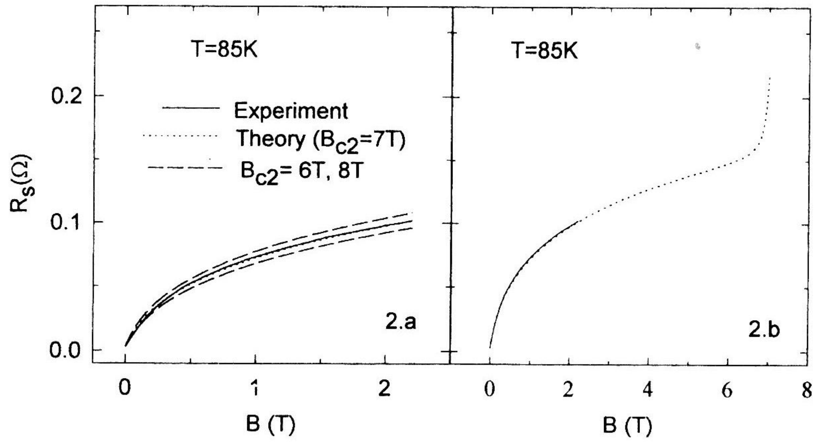

Fig. 2. Experimental magnetic field dependences of R_s at 85 K (solid lines) in a single crystal $YBa_2Cu_3O_{7-\delta}$. a) Also shown are the best theoretical fit (dotted line) and theoretical curves (dashed lines) which correspond to set B_{c2} values which differ by ± 1 T from the best fit. b) Theoretical fit extended over the full range up to $B_{c2} = 7$ T (dotted line).

The important parameter in fitting the experimental magnetoresistance curve by the theoretical expressions (1) and (2) is the upper critical field B_{c2}. In Fig. 2a, we show one of the experimental curves from Fig. 1b and the theoretical fit. The best fit for the curve at $T = 85$ K is achieved with $B_{c2} = 7$ T. Also shown in Fig. 2a are the theoretical curves which would correspond to B_{c2} values which differ by ± 1 T from the best fit. Note that the value of B_{c2} is far beyond the range of the experimentally employed field. In other words, the present technique allows the determination of B_{c2} even when only the initial part of the full magnetoresistance curve is experimentally determined. In Fig. 2b, we show the same experimental magnetoresistance curve, and the theoretical fit extended over the full range up to B_{c2}. The expressions (1) and (2) are valid for the mean field superconductivity, i.e., no fluctuations are assumed. Therefore, these expressions predict a well defined transition to the normal state. The curve such as the dashed line in Fig. 2b was observed in a classical superconductor, where the fluctuations are unobservable [8].

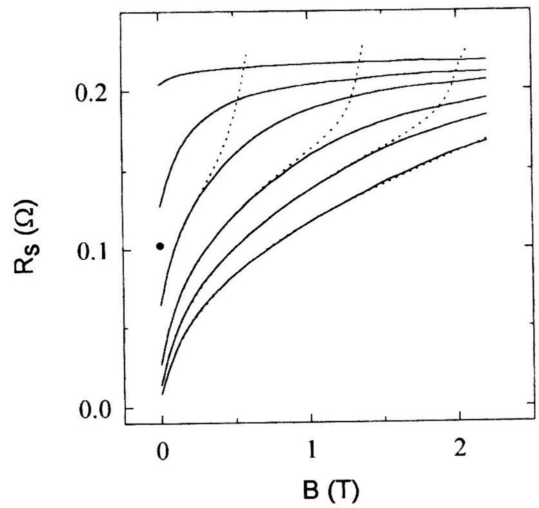

Fig. 3. Experimental magnetic field dependences of R_s (solid lines) in a single crystal $YBa_2Cu_3O_{7-\delta}$ *at various temperatures (from top to bottom:* 90 K, 89.5 K, 89 K, 88.5 K, 88.1 K, *and* 87.5 K*). Dashed lines show the theoretical predictions for R_s in the mixed state. The deviation of the mixed state behaviour from the experimental data is due to the superconducting fluctuations. The circle marks the zero field R_s at T_c.*

When the magnetoresistance curves are analyzed at higher temperatures, one finds that a fit by expressions (1) and (2) is possible only at lower field values. Fig. 3 shows these cases. The experimental curves do not rise to the normal state value but show an extended behaviour. At this point, one may recall the two possibilities of the origin of rounding of the superconducting transition. If the sample is inhomogeneous there should be a distribution of T_c 's, and one might expect the extended magnetoresistance curve with no clear transition to the normal state. Qualitatively, however, we found that each experimental curve in Fig. 3 requires a different assumed distribution of T_c 's for a reasonably good fit. Therefore, we discard this possibility for explanation. The other possible origin of the extended transition could lie in the superconducting fluctuations. Looking at the experimental curves in Fig. 3, we may say that for small fields the superconductor approaches the transition to the normal state. However, at some point, the superconducting fluctuations predominate, and a sharp transition to the normal state is avoided. From Fig. 3, one can see that the theoretical curves, which assume mixed state behaviour without a significant role of fluctuations, can be fitted to the low field segments of the experimental curves. The fitted segments become narrower at higher temperatures, and finally vanish above some temperature. For the latter temperatures, we may conclude that the entire curves are governed by the fluctuations. Clearly, the mean field T_c is somewhere in this region. Rather than setting an arbitrary criterion for the determination of T_c within the extended fluctuation region, we employ the following procedure. The theoretical fits shown in Figs. 2 and 3 provide the values of B_{c2} at various temperatures. These values are found to have a linear temperature dependence, as expected in the Ginsburg-Landau theory. The extrapolation to zero upper critical field yields T_c = 89.3 K, which is the mean field transition temperature. The circle in Fig. 3 marks the zero field R_s at T_c.

4. Scaling laws

The interpretation that the extended shapes of the magnetoresistance curves in Fig. 3 are due to fluctuations, and not to inhomogeneities in the sample, can be verified by the scaling laws. Namely, scaling of the thermodynamic quantities in the fluctuation regime is a very stringent property, and it is very unlikely that some sort of inhomogeneity could mimic this feature.

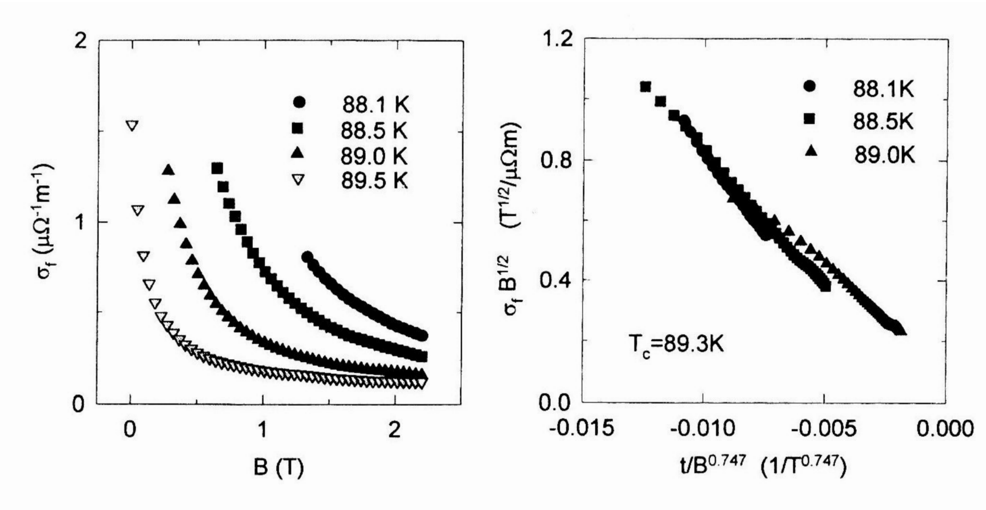

Fig. 4. Field dependences of the excess fluctuation conductivity at various temperatures. The upper three temperatures are below the mean field T_c, while the bottom temperature is above T_c.

Fig. 5. Scaling of the excess fluctuation conductivity σ_f according to the model proposed by Salamon et al. The mean field $T_c = 89.3$ K is predetermined from the mixed state behaviour (right).

In the present case we shall examine the scaling of the excess fluctuation conductivity in field and temperature variables. The surface resistance in the fluctuation regime is given by

$$R_{sf}(T) = \sqrt{\frac{\mu_0 \omega}{2(\sigma_n + \sigma_f)}}, \tag{3}$$

where σ_n is the normal state conductivity which can be determined from the extrapolated normal state behaviour. From the experimental curves in Fig. 3, we can determine the fluctuation conductivity σ_f using Eq. (3). The resulting set of curves for σ_f is shown in Fig. 4. Let us first examine the scaling proposed by Salamon et al. [9]. It is based on a 3DXY model. The attempt to scale the fluctuation conductivity of Fig. 4 according to this sheme is shown in Fig. 5. Here we use the parameter $t = (1 - T/T_c)$, with $T_c = 89.3$ K, as obtained above from $B_{c2}(T)$. One can see that scaling does not bring about a collapse of all the data points onto a universal curve. We note that letting T_c to be free parameter does not improve the scaling. One has to conclude that the superconductor does not behave in accordance with the 3DXY model.

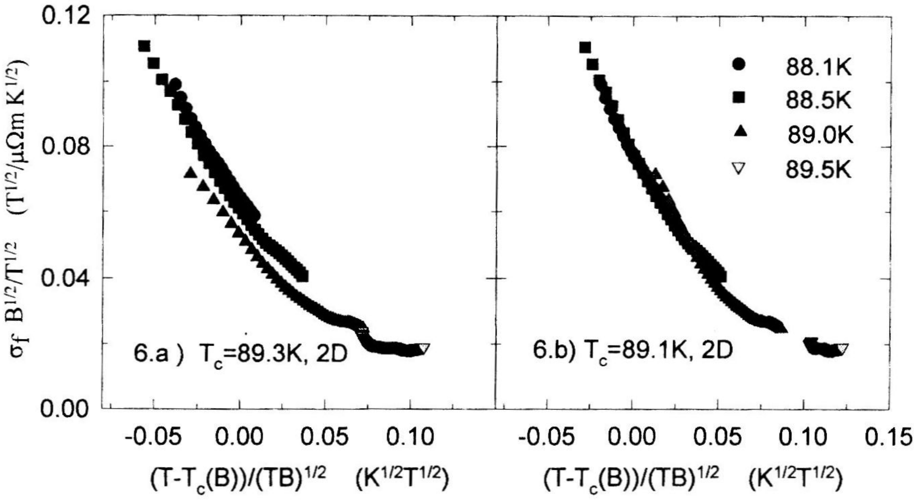

Fig. 6. Scaling of the excess fluctuation conductivity σ_f in the high field regime according to the 2D scaling law proposed by Ullah and Dorsey. a) $T_c = 89.3$ K is predetermined from the mixed state. b) $T_c = 89.1$ K is considered as a free parameter in the attempt to obtain the best scaling of the data.

Ullah and Dorsey [10] considered theoretically the interactions between fluctuations within the Hartree approximation. They could derive the behaviour of the fluctuation conductivity near the transition from normal state to superconducting state. They could also make distinction between two-dimensional (2D) and three dimensional (3D) nature of the system. Fig 6 shows the attempts to scale the data points according to the 2D scaling law. First, we use the value $T_c = 89.3$ K as predetermined from $B_{c2}(T)$ above. The result shown in Fig. 6a is certainly not satisfactory. The importance of having T_c predetermined by an independent analysis becomes evident in Fig. 6b. Here, we assume that T_c is not known, and allow it to be a free parameter in the attempt to obtain the best scaling of the data. We observe that a significant improvement in scaling can be achieved by setting T_c to 89.1 K. If the true value of T_c were not known, we might well be persuaded to conclude that the superconductor behaved almost as a 2D system near the superconducting transition. This conclusion would be erronenous in both, the nature of the scaling law and the determination of T_c.

Finally, in Fig. 7, we show that the present system shows 3D behaviour with T_c as determined independently from the measurements of $B_{c2}(T)$. More explicitly, we found that the choice of a slightly different value for T_c would degrade the quality of scaling in Fig. 7, i.e. the predetermined T_c is at the same time the best fit parameter for optimum scaling.

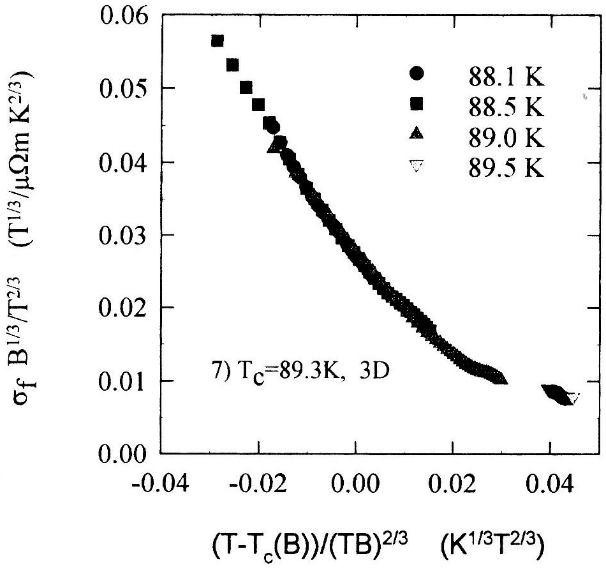

Fig. 7. Scaling of the excess fluctuation conductivity σ_f in the high field regime according to the 3D scaling law proposed by Ullah and Dorsey. Note a collapse of all data points onto a universal curve with the predetermined $T_c = 89.3$ K.

The 3D behaviour is expected in $YBa_2Cu_3O_{7-\delta}$ near the superconducting transition [2,3]. It can be explained as follows. At the mean field T_c, the coherence length diverges. This involves both, the coherence length along the c axis, and the one along the *ab* plane. Thus, just below T_c, we must have an anisotropic 3D superconductor. As the temperature is reduced, the coherence length diminishes. At some temperature below T_c, the coherence length along the *c* axis becomes equal to the separation of the copper oxide layers. The order parameter along the *c* axis becomes highly modulated so that below this temperature one can approximate the superconductor with a 2D system. In $YBa_2Cu_3O_{7-\delta}$ the transition from 3D to 2D behaviour occurs at about 83 K [11].

5. Conclusion

The introduction of the magnetic field as an additional experimental variable in the microwave absorption in the high-T_c superconductors can elucidate the nature of the superconducting state near T_c. From the microwave magnetoresistance curves in $YBa_2Cu_3O_{7-\delta}$ single crystal, we could determine by independent procedures the value of the mean field T_c, and the appropriate scaling law for the fluctuation conductivity. We found $T_c = 89.3$ K, and anisotropic 3D behaviour of the superconductor.

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TUMAČENJE MIKROVALNOG MAGNETOOTPORA IZNAD I ISPOD T_c U SUPRAVODLJIVIM MONOKRISTALIMA $YBa_2Cu_3O_{7-\delta}$

Analizirana je magnetska ovisnost mikrovalnog površinskog otpora monokristala visokotemperaturnog supravodiča $YBa_2Cu_3O_{7-\delta}$ u području miješanog stanja i u području supravodljivih fluktuacija. Prilagodivanjem magnetootpornih ovisnosti u području miješanog stanja na teorijske izraze (teorija efektivne vodljivosti) dobiva se gornje kritično polje B_{c2} i temperatura faznog prijelaza T_c u aproksimaciji srednjeg polja. Mikrovalna fluktuacijska vodljivost se svodi na istu mjeru (skalira) kao što je i predvideno za 3D supravodič.