## Dissipation in the Mixed State: Local or Nonlocal?

A question of whether the dissipation in the mixed state of the superconducting cuprates can be described by local electrodynamics is surrounded by controversy. Recently Doyle *et al.* [1] have reported the results of an experiment on $Bi_2Sr_2CaCu_2O_{8+\delta}$ and interpreted them as an evidence for the local conductivity. A similar view was expressed earlier by Eltsev and Rapp [2]. This is in contrast to the conclusions of Safar *et al.* [3] and Keener *et al.* [4], who argued that the local conductivity model (LCM) cannot satisfactorily account for their data.

This Comment is intended to show that a more accurate application of LCM to the data of Refs. [1] and [2] reveals that there is no real contradiction between all existing experiments [1–4]: The results of [1,2] also exhibit a strong deviation from LCM *quantitatively similar,* albeit more subtle, to that found in [3,4].

The validity of the local electrodynamics can be tested by comparing the apparent anisotropies of the resistivity calculated with the help of LCM for different configurations of current and voltage contacts on a sample with eight terminals. Hereafter, we use the same enumeration of the contacts as in [1]. When current is injected through the contacts 1,4 ("$I \parallel ab$" arrangement), the anisotropy determined by the primary $V_{23}$ and secondary $V_{76}$ voltages is given by [5]

$$\eta = \sinh^{-1}\left(\lambda \frac{V_{23}}{V_{76}}\right). \tag{1}$$

Here, $\eta \equiv (\rho_c/\rho_{ab})^{1/2}\pi D/L$, where $L$ and $D$ are the length and thickness of the sample, respectively; $\lambda = 2\sin(\pi l/2L)/\ln\tan(\pi/4 + \pi l/4L)$, where $l$ is the spacing between the contacts 2,3 and 7,6 respectively ($\lambda < 2$). The exponentially small terms $\sim e^{-2\eta}$ here are omitted.

On the other hand, when current is injected through the contacts 1,8 ("$I \parallel c$" arrangement), the potential differences such as $V_{27}$ and $V_{36}$ are given by [6]

$$V_c(x) = \frac{\rho_c ID}{bL}\left(1 + \frac{4}{\eta}\ln\frac{1}{2\sin\frac{\pi x}{2L}}\right), \tag{2}$$

where $x$ is the distance between the current and voltage contact ($0 < x < L$), and $b$ is the width of the sample. Equation (2) is valid as long as $\eta > 3$, so that the exponentially small terms $\sim e^{-\eta}$ also can be omitted. The ratio $V_{36}/V_{27} < 1$ and changes with temperature $T$ due to $T$ dependence of $(\rho_c/\rho_{ab})^{1/2}$. From Eq. (2) follows that

$$\eta = \frac{4\ln(2\sin\frac{\pi x_3}{2L}) - (V_{36}/V_{27})4\ln(2\sin\frac{\pi x_2}{2L})}{1 - (V_{36}/V_{27})}. \tag{3}$$

If LCM is valid, the values of $\eta$ should be the same in $I \parallel ab$ and $I \parallel c$ configurations. The argument in favor of local conductivity [1,2] was based on the observation that the ratios $V_{76}/V_{23}$ and $V_{36}/V_{27}$ in the $I \parallel ab$ and $I \parallel c$ configurations, respectively, change with temperature *qualitatively* as predicted by LCM. Namely, with decreasing $T$, $V_{76}/V_{23}$ increases towards unity, while $V_{36}/V_{27}$ decreases, which corresponds to decreasing $\rho_c/\rho_{ab}$ in both configurations. However, as shown below, the values of the apparent anisotropies calculated with the help of LCM are very different for these configurations.

The data presented in the inset to Fig. 4 in Ref. [1] have a good reference point which allows comparison of the apparent anisotropies calculated with the help of Eqs. (1) and (3). We see that at $T \approx 73$ K, the ratio $V_{36}/V_{27} = V_{76}/V_{23} \approx 0.4$. Since the reported length of the crystal $L \approx 1$ mm and electrode spacing is 0.25 mm, we assume that the appropriate estimates for $x_2/L$ and $x_3/L$ in Eq. (3) are 0.25 and 0.75, respectively. Then Eq. (3) gives $\eta \approx 4.8$. On the other hand, in the $I \parallel ab$ arrangement, if we take $l/L \approx 0.5$, Eq. (1) yields for the same temperature $\eta \approx 2.1$. Therefore, the apparent anisotropies $\rho_c/\rho_{ab}$ for two configurations differ by a factor greater than 5. Equally important is that the relationship between them is the same as that found in [3,4]: The apparent anisotropy obtained on the basis of LCM is *greater* in $I \parallel c$ configuration than in $I \parallel ab$ configuration. A similar analysis of the data of Ref. [2] also shows the same trend. The difference between the anisotropies is too great to be explained away by the uncertainties in sample dimensions, especially in view of the fact that the multiterminal technique measures the ratio $\rho_c/\rho_{ab}$ more accurately than each of the resistivities separately (Eqs. (1) and (3) include only the distances between the contacts).

Our conclusion is that all transport measurements invariably show a nonlocal dissipation in the mixed state of the cuprates under a variety of conditions. A more subtle manifestation of nonlocality in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (with and without columnar defects) [1,4], and at higher currents in $YBa_2Cu_3O_{7-\delta}$ [2] than that in [3], results from the fact that the correlation length of the vortex lines is smaller than the thickness of the sample, but is still *macroscopic*, i.e., much greater than the size of the unit cell.

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