Temperature Evolution of the Pseudogap State in the Infra-Red Response of Underdoped La$_{2-x}$Sr$_x$CuO$_4$

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The $ab$-plane optical spectra of two single crystals of underdoped La$_{2-x}$Sr$_x$CuO$_4$ were investigated. The reflectivity of La$_{1.87}$Sr$_{0.13}$CuO$_4$ has been measured in the frequency range 30 – 9,000 cm$^{-1}$ (0.004 – 1 eV) both parallel and perpendicular to the CuO$_2$ planes, whereas La$_{1.86}$Sr$_{0.14}$CuO$_4$ was studied only in the $ab$-plane. The extended Drude model shows that the frequency-dependent effective scattering rate $1/\tau(\omega,T)$ is strongly suppressed below the high-frequency straight-line extrapolation, a signature of the pseudogap state. This suppression can be seen from temperatures below the superconducting transition up to 400 K. In the case of underdoped LSCO the straight-line extrapolation is temperature independent below 200 K, whereas above 200 K there is a strong temperature dependence of the high-frequency $1/\tau(\omega,T)$. The out-of-plane direction is also examined for evidence of the pseudogap state.

PACS numbers: 74.25.Gz, 74.7.2.Dn, 74.72.Jt, 74.72.-h, 78.20.Ci

The presence of a pseudogap in the normal state of underdoped high temperature superconductors is by now widely accepted. The strongest evidence for the pseudogap state comes from recent measurements of angle resolved photoemission spectra as well as vacuum tunneling. However, these techniques both demand extremely high surface quality and have therefore mainly been restricted to Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi221) and YBa$_2$Cu$_3$O$_{7-\delta}$ (Y123) materials, both with two CuO$_2$ layers per unit cell. Techniques that probe deeper into the sample such as dc transport, optical conductivity and NMR were not only the earliest to show evidence of the pseudogap but have been extended to a much larger variety of materials, including several materials with one CuO$_2$. In all cases evidence for a pseudogap has been reported.

The pseudogap in LSCO as seen by NMR and neutron scattering is rather weak and has led to the suggestion that the existence of the pseudogap in the spin excitation spectrum is only possible in bilayer compounds such as Y123 and YBa$_2$Cu$_3$O$_{4}$ (Y124). In particular, Millis and Monien attribute the pseudogap (or the spin gap) to strong antiferromagnetic correlations between the planes in the bilayer, which are responsible for a quantum order-disorder transition.

Apart from having only one CuO$_2$ layer La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) is also a good model system for the study of doping dependences since it can be doped by the addition of strontium over a wide range: from the underdoped, where $T_c$ increases with Sr content, to the optimally doped where $T_c$ reaches its maximum value of $\approx 40$ K at $x = 0.17$, and to the overdoped region where $T_c \to 0$ at $x = 0.34$.

The characteristic signatures of the pseudogap state in the dc resistivity are seen clearly in LSCO. These are the striking deviations below a temperature $T^*$ from the high temperature linear resistivity, resulting in a clear break in slope at $T^*$. It was found by B. Batlogg et al. that in LSCO $T^*$ decreases from 800 K to approximately 300 K as the doping level is increased from the strongly underdoped to just over the optimal doping level. Similar behavior at $T = T^*$ has been observed in the Hall effect coefficient and the magnetic susceptibility.

The pseudogap can also be observed if the conductivity is measured in the frequency domain, $\sigma(\omega)$, where it shows up as a striking depression of the frequency dependent scattering rate at low frequency. It is found that below a frequency $\Omega_p \approx 600$ cm$^{-1}$, the scattering rate drops below its high temperature, high frequency, linear behavior. This effect has been clearly identified in the bilayer materials. One of the aims of this paper is to see if this behavior can also be observed in LSCO. A pseudogap state can be defined in terms of this suppression of scattering: the material is in the pseudogap state when the scattering rate falls below the high frequency straight-line extrapolation. In the low frequency limit the scattering rate is proportional to the dc resistivity. Due to this, the $1/\tau(\omega,T)$ suppression should be compared to the suppression of $\rho_{DC}(T)$ at temperatures below the linear $T$ dependence region. The IR measurement gives us the possibility to see both the frequency and the temperature dependence of this feature.

A pseudogap feature can also be observed in the $\epsilon$-
axis IR conductivity in the form of a gap-like region of depressed conductivity at low frequency. It has been reported in YBa$_2$Cu$_3$O$_{7-x}$ (Y123) and YBa$_2$Cu$_4$O$_8$ (Y124) materials \([2,3]\) as well as in LSCO \([4,5]\). In slightly underdoped LSCO the pseudogap state in the \(c\)-axis direction is not as well defined as it is in the two plane materials. \([5]\) However, as the doping is reduced further, the \(c\)-axis pseudogap state features below 0.1 eV become clearer. \([17]\)

Previous work on the in-plane \(\sigma(\omega)\) of the single layer lanthanum strontium cuprate includes work on the oxygen doped La$_2$CuO$_{4-\delta}$ \([5]\), thin films of LSCO \([18]\) as well as work done on LSCO single crystal at room temperature \([18]\). To our knowledge, a study of the temperature and doping dependence has not been done. We fill this gap here by performing optical measurements on high-quality LSCO single crystals at temperatures ranging from 10 K to 300 K at two different doping levels, both slightly underdoped. Also the optical properties of both the \(ab\)-plane and \(c\)-axis of La$_{1.87}$Sr$_{0.13}$CuO$_4$ were measured on the same crystal.

To better display the effect of increased coherence on \(\sigma(\omega)_{ab}\) resulting from the formation of the pseudogap state we use the memory function, or extended Drude analysis. In this treatment the complex optical conductivity is modeled by a Drude spectrum with a frequency-
dependent scattering rate and an effective electron mass. While the optical conductivity tends to emphasize free particle behavior, a study of the frequency dependence of the effective scattering rate puts more weight on displaying the interactions of the free particles with the elementary excitations of the system. The temperature evolution of the frequency dependent scattering rate and effective mass spectra are of particular interest and are defined as follows:

\[ \frac{1}{\tau(\omega, T)} = \frac{\omega^2}{4\pi} \text{Re} \left( \frac{1}{\sigma(\omega, T)} \right) \]  

\[ \frac{m^*(\omega, T)}{m_e} = \frac{1}{\omega^2} \frac{\omega}{4\pi} \text{Im} \left( \frac{1}{\sigma(\omega, T)} \right) \]  

Here, \( \sigma(\omega, T) = \sigma_1(\omega, T) + i\sigma_2(\omega, T) \) is the complex optical conductivity and \( \omega_p \) is the plasma frequency of the charge carriers.

The single crystals of La\(_{2-x}\)Sr\(_x\)CuO\(_4\) with approximate dimensions 5x3x3 mm\(^3\) were grown by the traveling-solvent floating zone technique at Oak Ridge in the case of \( x = 0.14 \) and in Tokyo in the case of \( x = 0.13 \). The critical temperature was determined by both SQUID magnetization and resistivity measurements and was found to be 36 K for the nominal concentration of Sr \( x = 0.14 \) and 32 K for \( x = 0.13 \). Since the highest \( T_c \) in the LSCO system has been found to be 40 K for \( x = 0.17 \), we conclude that both crystals are underdoped.

The crystal with \( x = 0.14 \) was aligned using Laue diffraction and polished parallel to the CuO\(_2\) planes. The crystal with \( x = 0.13 \) was polished in Tokyo to yield both ab-plane and ac-plane faces. Both surfaces were measured. Polarizers were used for the ac-face data to

FIG. 4. The reflectance of La\(_{1.87}\)Sr\(_{0.13}\)CuO\(_4\) with \( E \parallel c \) axis is shown. The temperature sequences are 10 K, 40 K, 150 K, 200 K, 300 K and 400 K.

FIG. 5. The c-axis conductivity of the La\(_{1.87}\)Sr\(_{0.13}\)CuO\(_4\) is shown at different temperatures. Since the phonon peaks are dominant in the direction perpendicular to CuO\(_2\) planes, the graph is focused at the background conductivity. Two inserts are the c-axis conductivity of the underdoped La\(_{1.87}\)Sr\(_{0.13}\)CuO\(_4\) measured at 450 cm\(^{-1}\) and at 600 cm\(^{-1}\). The c-axis conductivity at 450 cm\(^{-1}\) is depressed below 300 K, however, it is somewhat constant above 600 cm\(^{-1}\). This could be a signature of the pseudogap formation at the temperatures less than 300 K and with the size of 500 cm\(^{-1}\).

FIG. 6. The ab-plane conductivity of the La\(_{1.87}\)Sr\(_{0.13}\)CuO\(_4\) is shown at different temperatures.
separate the contribution of CuO$_2$ planes from the c-axis optical response.

To get an uncontaminated ab-plane measurement, it is important to have the sample surface accurately parallel to the ab-plane to avoid any c-axis contribution to the optical conductivity. The miscut angle between the polished surface normal and the c-axis was checked by a high precision triple axis x-ray diffractometer and was determined to be less than 0.8%.

All reflectivity measurements were performed with a Michelson interferometer using three different detectors which cover frequencies ranging from 10 to 10000 cm$^{-1}$ (1.25 meV – 1.25 eV). The experimental uncertainty in the reflectance data does not exceed 1%. The dc resistivity measurements were carried out using a standard 4-probe technique.

The result of the resistivity measurement on the same La$_{1.86}$Sr$_{0.14}$CuO$_4$ single crystal used in the optical measurements is shown in Fig. 1. It is commonly accepted that the DC-resistivity is linear at high temperatures for LSCO and that the pseudogap begins to form near the temperature where the resistivity drops below this linear trend. At lower temperatures there is a region of superlinear temperature dependent resistivity. The $T^*$ value for our samples with $x = 0.13$ and $x = 0.14$ extracted from the phase diagram of Batlogg et al., are 650 K and 450 K, respectively. In agreement with this, the resistivity shows a superlinear temperature dependence below room temperature as expected in the pseudogap region.

In Fig. 2 we present the reflectivity data at temperatures above and below $T_c$ for the two samples. For clarity, only three temperatures are shown: $T = 300$ K, an intermediate temperature above the superconducting transition and a low temperature $\approx 10$ K in the superconducting state. In the frequency region shown the reflectance is strongly temperature dependent for both materials, dropping by approximately 10% as temperature is increased from the lowest temperature to $T = 300$ K. The plasma edge is observed at 7800 cm$^{-1}$ (see insert of Fig. 2). The distinct peaks at approximately 135 and 365 cm$^{-1}$ in the LSCO reflectivity spectra correspond to the excitation of ab-plane TO phonons and the peak at 500 cm$^{-1}$ corresponds to a LO phonon. As in all other HTSC materials, the ab plane has a coherent response with very high reflectance.

FIG. 7. The ab-plane conductivity of La$_{1.86}$Sr$_{0.14}$CuO$_4$ is shown at different temperatures.

FIG. 8. Top panel: the low temperature frequency dependent scattering rate of La$_{1.87}$Sr$_{0.13}$CuO$_4$ below $T^*$ (a) and above $T^*$ (b) is calculated using Equation (1). The onset of the suppression in a conductivity corresponds to a drastic change in the frequency dependence of the scattering rate below $T^*$. Above 700 cm$^{-1}$ the scattering rate is nearly temperature independent and has a linear frequency dependence below $T^*$. Below 700 cm$^{-1}$ the scattering rate varies as $\omega^{1+\delta}$ and shows a strong temperature dependence. Bottom panel: The effective mass of La$_{1.87}$Sr$_{0.13}$CuO$_4$ below $T^*$ (a) and above $T^*$ (b) is calculated using Equation (2). The onset of enhancement of $\sigma_{xy}(\omega)$ corresponds to the onset of the suppression of the scattering rate.

The complex optical conductivity $\sigma(\omega)$ was obtained by Kramers-Kronig analysis of the reflectivity data.
Since, in principle, this analysis requires knowledge of the reflectance at all frequencies, reflectivity extensions must be used at high and low frequencies. The Hagen-Rubens formula was used for the low frequency reflectivity extrapolation, with parameters taken from the dc resistivity measurements on the same sample with $x = 0.14$ shown in Fig. 3 and the results of H. Takagi et al. [27] for the sample with $x = 0.13$. For the high-frequency extension for $\omega > 8000 \text{ cm}^{-1}$ we used the reflectivity result of Gao et al. [15, 7, 30]. At frequencies higher than 40 eV reflectivity was assumed to fall as $1/\omega^4$.

We calculate the plasma frequency of the superconducting charge carriers and the London penetration depth using the following formula: [28]

$$\epsilon_1 = 1 - \frac{\omega^2_{ps}}{\omega^2}.$$

The slope of the low-frequency dielectric function $\epsilon_1(\omega)$, plotted as a function of $\omega^{-2}$ in Fig. 3a,b, gives plasma frequencies of 6100 cm$^{-1}$ and 5700 cm$^{-1}$ in superconducting state. The corresponding London penetration depths are $\lambda_L = 1/2\pi\omega_{ps}$ = 250 nm and 280 nm for La$_{1.86}$Sr$_{0.14}$CuO$_4$ and La$_{1.87}$Sr$_{0.13}$CuO$_4$, respectively. These values are in good agreement with those obtained previously by Gao et al. in films [13] ($\lambda_L = 275 \pm 5$ nm) and by muon-spin-relaxation [29] ($\lambda_L = 250 \text{ nm}$).

The c-axis reflectance of the $x = 0.13$ sample is shown in Fig. 3. The corresponding conductivity is low and dominated by optical phonons (Fig. 3).

In YBCO 123 and 124 the pseudogap in c-axis conductivity manifests itself as a depression in conductivity at low frequency. [24, 25] There is no coherent Drude peak and the conductivity is flat and frequency independent in the temperature and doping range where a pseudogap is expected. A low frequency depression of conductivity seen with an edge in the 300-400 cm$^{-1}$ region where conductivity rises to the high frequency plateau.

In order to isolate the electronic features of our LS c-axis spectrum we magnify the low value region of the frequency infrared data for underdoped LSCO as shown in Fig. 3. There is no sharp pseudogap edge in the frequency infrared data for underdoped LSCO as $\Delta$ is in the case of Y123. It is possible that such a feature could be hidden under the large phonon structure. Efforts to subtract the phonons in order to extract the background conductivity were found to be extremely sensitive to the choice of their shape in fitting procedures. Nonetheless, the raw data clearly show that there is low frequency depression of the c-axis conductivity. Conductivity at 450 cm$^{-1}$ is uniformly suppressed below T=300 K (Fig. 3 insert), whereas the conductivity at 600 cm$^{-1}$ is nearly constant at all temperatures. Based on this analysis one can conclude that the pseudogap state in the c-axis opens up below 300 K and its size is approximately equal to 500 cm$^{-1}$.

Manifestations of the pseudogap in the $ab$-plane conductivity exist as a loss of spectral weight between 700

![FIG. 9. Top panel: the high temperature effective scattering rate of La$_{1.86}$Sr$_{0.14}$CuO$_4$ below T$^*$ (a) and above T$^*$ (b) is calculated using Equation (1). Above 700 cm$^{-1}$ the scattering rate has a linear frequency and temperature dependence below T$^*$ (a) and temperature dependent above T$^*$ (b). Below 700 cm$^{-1}$ the scattering rate varies as $\omega^{1+\delta}$ and shows a strong temperature dependence. Bottom panel: The effective mass of La$_{1.87}$Sr$_{0.13}$CuO$_4$ below T$^*$ (a) and above T$^*$ (b) samples is calculated using Equation (2).]
and 200 cm$^{-1}$ balanced by increases both below and above this frequency. In both Fig. 6 and Fig. 7 one can see the temperature evolution of the sharp depression in ab-conductivity below 700 cm$^{-1}$ at temperatures above $T_c$. A much clearer picture of the pseudogap state can be seen from the effective scattering rate, $1/\tau(\omega,T)$, calculated from the conductivity using equation (1) which is shown along with the effective mass in Fig. 8 and Fig. 9. The $1/\tau(\omega,T)$ spectra can conveniently be divided into two regions. In the high frequency region, starting at about 700 cm$^{-1}$, the scattering rate varies linearly with frequency while in the low frequency region there is a clear suppression of $1/\tau(\omega,T)$ below this linear trend. The temperature where this suppression first appears serves as a definition of $T^*$, the onset temperature of the pseudogap state. As the temperature is lowered below $T^*$ this suppression becomes deeper. We find that for underdoped La$_{2-x}$Sr$_x$CuO$_4$ $T^* \geq 400$ K, an order of magnitude higher than the superconducting transition temperature $T_c$ (32 K). This is significantly different from previous results on cuprates where $T^*$ more or less coincides with $T_c$ near optimal doping.

The temperature dependence above 700 cm$^{-1}$ is strongly influenced by the level of Sr doping. In the underdoped sample the high frequency scattering rate is nearly temperature independent up to a certain temperature (Fig. 8b and Fig. 9b), which we will call $T^{**}$ above which a pronounced temperature dependence of $1/\tau(\omega,T)$ is seen (Fig. 8a and Fig. 9a). In the $x = 0.13$ sample $T^{**} \approx 200$ K while in the $x = 0.14$ sample $T^{**} \approx 150$ K. In the overdoped samples the scattering rate above 700 cm$^{-1}$ increases uniformly with temperature at all temperatures suggesting $T^{**} \rightarrow 0$ in that limit. This behavior is also seen in other overdoped HTSC.

If one extrapolates the 300 K scattering rates to zero frequency one finds that for the $x = 0.13$ sample the scattering rate $1/\tau_0 \approx 2500$ cm$^{-1}$ and for the $x = 0.14$ sample this rate is $\approx 1500$ cm$^{-1}$. These scattering rates are much higher than what is seen for the higher $T_c$ materials reviewed by Puchkov et al. [31] where at 300 K $1/\tau_0 \approx 1000 \pm 200$ cm$^{-1}$ for several families and many doping levels. This high residual scattering differentiates the LSCO material from the other cuprates.

If we call the frequency below which the scattering rate is suppressed the ab-plane pseudogap $\omega_{ab} \approx 700$ cm$^{-1}$ we find it is clearly bigger than the c-axis pseudogap frequency $\omega_c \approx 500$ cm$^{-1}$.

In addition to the pseudogap depth and temperature dependence, several other features of Figures 8 and 9 should be mentioned. The position of the pseudogap remains at 700 cm$^{-1}$ for all temperatures. There are also several peaks positioned at 500 cm$^{-1}$ in the scattering rate which complicate the analysis, particularly in the case of the sample with $x = 0.14$. These peaks have been observed by other groups and have been attributed to polaronic effects. Another possible explanation is the correlation of the ab-plane conductivity with c-axis LO phonons. We did observe the difference in contribution of LO phonons to the ab plane reflectance with different propagation directions, an effect first observed by Reedlyk et al. [33] and also seen in the $k \parallel c$ vs. $k \perp c$ spectra obtained by Tanner’s group. In Fig. 10 the reflectance with $E \parallel a$ and $k \parallel c$, is compared with the reflectance with $E \parallel ab$ and $k \parallel a$, with the La$_{1.87}$Sr$_{0.13}$CuO$_4$ sample at room temperature. There is an extra feature observed at 500 cm$^{-1}$ in the spectra with $k \parallel c$. Further evidence that the c-axis LO phonons couples to ab plane features can be seen in Fig. 11. The comparison between peaks in the effective scattering rate at 450 cm$^{-1}$ and 580 cm$^{-1}$ to the peaks in Im(-1/$\epsilon_c$) shows the same strong correlation seen in many other cuprates. [35]

For completeness we also plot the effective mass of underdoped samples at low temperatures(Fig. 8c) and high temperatures(Fig. 8d). As expected, $m^{*}(\omega)$ rises to a maximum $\approx 3$ forming a peak at $\approx 400$ cm$^{-1}$. The enhancement of the effective mass in the pseudogap state as well as the upper limit of $m^{*}(\omega)$ are similar to what has been previously reported for Y123, Y124 and Bi2212.

Before closing we compare our results with data of Gao et al. [19] on La$_{2-x}$Sr$_x$CuO$_{4+\delta}$ films and Quijada et al. [15] on oxygen doped La$_2$CuO$_{4+\delta}$. Our results in the underdoped case are comparable with those of the oxygen doped material, although Quijada et al. did not carry out a frequency dependent scattering rate analysis for their underdoped sample. The film results of Gao et al. are quite different from our findings. The films used in that study had a strontium level that would correspond to optimal doping in crystals. However, the $1/\tau(\omega)$ curves deviate markedly from what we observe for slightly under and overdoped samples. The authors performed an extended Drude analysis and found a strongly temperature dependent scattering rate even at low temperatures. This is in sharp contrast to our results which would suggest a very weak temperature dependence in this temperature region. Based on our work, their samples should be in the pseudogap state since they have an $x$ value near optimal doping. Comparing these results with other systems, in particular with Tl2202, two factors suggest the possibility that the films may be overdoped. First, their $T_c$ was near 30 K, lower than that expected for optimal doping. Secondly, it is known that the oxygen level in films can vary substantially and in LSCO oxygen can have a major influence on the doping level. On the other hand, we cannot completely rule out the possibility that all the crystal results are affected by the polishing process, and that the films better represent the bulk material. It is clearly important to measure films where the oxygen content is controlled by selective annealing.

In conclusion, the optical data in the far-infrared re-
region, taken on two underdoped single-layered high-\(T_c\) superconductors, shows clear evidence of a pseudogap state in both the scattering rate and conductivity along CuO\(_2\) planes. This pseudogap state extends to higher temperatures than that observed in the multi-layered underdoped cuprates such as YBCO and BSCO.

The scattering rate is similar for both systems in the pseudogap state. At low frequencies, \(\omega \leq 700\) cm\(^{-1}\), the scattering rates are temperature dependent and change with frequency in a non-linear fashion. Above 700 cm\(^{-1}\) this behavior becomes linear. Within experimental uncertainty the observed high frequency scattering rate of the underdoped sample is not affected by temperature up to certain temperature \(T^{**}\). This temperature is equal to 200 K in case of La\(_{1.87}\)Sr\(_{0.13}\)CuO\(_4\) and 150 K in case of La\(_{1.86}\)Sr\(_{0.14}\)CuO\(_4\). Above \(T^{**}\) the high frequency scattering rate is temperature dependent. This behavior is identical to the high-frequency effective scattering rate of an overdoped HTSC. [31]

Our findings in the direction perpendicular to the CuO\(_2\) planes showed that the depression of the c-axis conductivity is not as prominent as the one found in the two layer HTSC. Nevertheless, the signature of the pseudogap can be seen at the frequencies below 500 cm\(^{-1}\) up to room temperature.

We would like to thank J.D. Garrett for help in aligning the sample and also P.C. Mason, M. Lumsden and B.D. Gaulin for determining the miscut angle of the underdoped LSCO crystal. We also take this opportunity to thank K.C. Irwin and J.G. Naeini for their useful collaboration. This work was supported by the Natural Sci-
ences and Engineering Research Council of Canada and The Canadian Institute for Advanced Research.

[1] T. Timusk and B. Statt, Rep. Prog. Phys. (to be published).
[2] D.S. Marshall, A.G. Loeser, Z.-X. Chen, and D.S. Dessau, Physica C, 263, 208 (1999).
[3] H.J. Tao, F. Lu, and E.L. Wolf, Physica C 282-287, (1987); Ch. Renner, B. Revaz, J.-Y. Genoud, K. Kad-owaki, and O. Fischer, Phys. Rev. Lett. 80, 149, (1998).
[4] B. Bucher, P. Steiner, J. Karpinski, E. Kaldis, and P. Wachter, Phys. Rev. Lett. 70, 2012, (1993).
[5] T. Ito, K. Takenaka, and S. Uchida, Phys. Rev. Lett. 70, 3995, (1993).
[6] B. Batlogg, H.Y. Hwang, H. Takagi, R.J. Cava, H.L. Kao, and J. Kuo, Physica C, 235-240, 130 (1994).
[7] T. Timusk, D.N. Basov, R. Liang, B. Dabrowski, D.A. Bonn, W.N. Hardy, and T. Timusk, Phys. Rev. Lett., 77, 4090 (1996).
[8] A.V. Puchkov, P. Fournier, D.N. Basov, T. Timusk, A. Kapitulnik, and N.N. Kolesnikov, Phys. Rev. Lett., 77, 3212 (1996).
[9] A.V. Puchkov, P. Fournier, T. Timusk, and N.N. Kolesnikov, Phys. Rev. Lett., 77, 1853 (1996).
[10] A.J. Millis and H. Monien, Phys. Rev. Lett., 70, 2810 (1993).
[11] T.E. Mason, G. Aeppli, and H.A. Mook, Phys. Rev. Lett., 68, 1414 (1992).
[12] S. Uchida, I. Ido, H. Takagi, T. Arima, Y. Tokura, and S. Tajima, Phys. Rev. B, 43, 7942 (1991).
[13] H.Y. Hwang, B. Batlogg, H. Tagaki, H.L. Kao, J. Kwo, R.J. Cava, and J.J. Krajewski, Phys. Rev. Lett., 72, 2636 (1994).
[14] S.K. Tolpygo, J.-Y. Lin, M. Girvich, S.Y. Hou, and Julia M. Phillips, Phys. Rev. B, 53, 12454 (1996).
[15] C.C. Homes, T. Timusk, R. Liang, D.A. Bonn, and W.N. Hardy, Phys. Rev. Lett., 71, 1645 (1993).
[16] D.N. Basov, R. Liang, B. Dabrowski, D.A. Bonn and W.N. Hardy, T. Timusk, Phys. Rev.B, 52, R13141 (1995).
[17] S. Uchida, K. Tamasaky, and S. Tajima, Phys. Rev.B, 53, 14558 (1996).
[18] M.A. Quijada, D.B. Tanner, F.C. Chou, D.C. Johnston and S.-W. Cheong, Phys. Rev. B, 52, 15485 (1995).
[19] F. Gao, D.B. Romero, B.D. Tanner, J. Talvacchio, and M.G. Forrester, Phys. Rev.B, 47, 1036 (1993).
[20] W. G"{o}tze and P. Wolfle, Phys. Rev. B, 47, 1226 (1972).
[21] P.B. Allen, Phys. Rev.B, 3, 305 (1971).
[22] A. Gold, S.J. Allen, B.A. Wilson and D.C. Tsui, Phys. Rev.B, 25, 3519 (1982).
[23] S.-W. Cheng, G. Aeppli, T.E. Mason, H. Mook, S.M. Hayden, P.C. Canfield, Z. Fisk, K.N. Clausen, and J.L. Martinez, Phys. Rev. Lett., 67, 1791 (1991).
[24] T. Kimura, K. Kishio, T. Kobayashi, Y. Nakayama, N. Motohira, K. Kitazawa, and K. Yamafuji, Physica C(Amsterdam), 192, 247 (1992).
[25] J. Orenstein and D.H. Rapkine, Phys. Rev. Lett., 60, 968 (1988).
[26] S. Tajima, S. Uchida, S. Ishibashi, T. Ido and H. Takagi, T. Arima and Y. Tokura, Physica C, 168, 117 (1990).
[27] H. Takagi, B. Batlogg, H.L. Kao, J. Kwo, R.J. Cava, J.J. Krajewski, and W.F. Peck, Jr., Phys. Rev. Lett., 69, 2975 (1992).
[28] D.B. Tanner and T. Timusk, in Physical Properties of High Temperature Superconductors I, edited by D.M. Ginsberg (word Scientific, Singapure, 1992), p.363.
[29] G. Aeppli, R.J. Cava, E.J. Ansaldo, J.H. Brewer, S.R. Kreitzman, G.M. Luke, D.R. Noakes, and R.F. Kiefl, Phys. Rev. B, 35, 7129 (1987).
[30] C.C. Homes, T.Timusk, R. Liang, D.A. Bonn, and W.H. Hardy, Physica C, 254, 265-280, (1995).
[31] A.V. Puchkov, D.N. Basov, and T. Timusk, J. Phys.: Condens. Matter, 8, 10049 (1996).
[32] T. Starseea, T. Timusk, M. Okuya, T. Kimura, and K. Kishio, to be published.
[33] Y. Yagil and E.K.H Salje, Physica C, 235-140, 1143 (1994).
[34] G.A. Thomas, D.H. Rapkine, S.L. Cooper, S.-W. Cheong, A.S. Cooper, L.S. Schneemeyer, and J.V. Waszczak, Phys. Rev. B, 45, 2474 (1992).
[35] M. Reedyk, T. Timusk, Phys. Rev. Lett., 69, 2705 (1992)
[36] H. Zhang, H. Sato, and G.L. Liedl, Physica C, 234, 185, (1994).
[37] T. Timusk, D.N. Basov, C.C Homes, A.V. Puchkov, and M. Reedyk, Journ. of Superconductivity, 8, 437 (1995).
[38] K. Tamasaku, T. Itoh, H. Takagi, and S. Uchida, Phys. Rev. Lett., 72, 3088 (1994).
[39] P.A. Lee and N. Nagaosa, Phys. Rev. B, 46, 5621 (1992).
[40] V.J. Emery and S.A. Kivelson, Phys. Rev. Lett., 74, 3253 (1995).
[41] J.W. Loram, K.A. Mirza, J.R. Cooper, and W.Y. Liang, Phys. Rev. Lett., 71, 1740 (1993).