Charge order, metallic behavior and superconductivity in La$_{2-x}$Ba$_x$CuO$_4$ with $x = 1/8$

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The $ab$-plane optical properties of a cleaved single crystal of La$_{2-x}$Ba$_x$CuO$_4$ for $x = 1/8$ ($T_c \simeq 2.4$ K) have been measured over a wide frequency and temperature range. The low-frequency conductivity is Drude-like and shows a metallic response with decreasing temperature. However, below $\simeq 60$ K, corresponding to the onset of charge-stripe order, there is a rapid loss of spectral weight below about 40 meV. The gapping of single-particle excitations looks surprisingly similar to that observed in superconducting La$_{2-x}$Sr$_x$CuO$_4$, including the presence of a residual Drude peak with reduced weight; the main difference is that the lost spectral weight moves to high, rather than zero, frequency, reflecting the absence of a bulk superconducting condensate.

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It has been proposed that charge inhomogeneity, especially in the form of stripes, is a phenomenon intrinsic to doped antiferromagnets such as cuprate superconductors [1, 2, 3, 4, 5]. Static spin and charge stripe order has been observed by diffraction in a couple of cuprate compounds [6, 7, 8]; however, it appears to compete with superconductivity [9]. Kivelson, Fradkin, and Emery [10] argued that especially in the form of stripes, is a phenomenon intrinsic to doped antiferromagnets such as cuprate superconductors [1, 2, 3, 4, 5]. Static spin and charge stripe order has been observed by diffraction in a couple of cuprate compounds [6, 7, 8]; however, it appears to compete with superconductivity [9]. Kivelson, Fradkin, and Emery [10] argued that especially in the form of stripes, is a phenomenon intrinsic to doped antiferromagnets such as cuprate superconductors [1, 2, 3, 4, 5]. Static spin and charge stripe order has been observed by diffraction in a couple of cuprate compounds [6, 7, 8]; however, it appears to compete with superconductivity [9].

The optical conductivity initially shows a normal (for the cuprates) metallic response with decreasing temperature. Below $\simeq 60$ K, the conductivity at very low frequency appears to either remain roughly constant or increase slightly as the temperature is reduced; however, there is a general loss of spectral weight (the area under the conductivity curve) below $\simeq 300$ cm$^{-1}$, a consequence of the substantial reduction in the density of carriers. The missing spectral weight is redistributed to higher frequencies, and is fully recovered only above about 2000 cm$^{-1}$. Inciding with the depression of the carrier density, the transition to superconductivity is depressed to 2.4 K. The gapping of the single-particle excitations looks remarkably similar to that recently reported for superconducting La$_{1.85}$Sr$_{0.15}$CuO$_4$ [11], which is known to have a $d$-wave gap [11]. The presence of a residual Drude peak indicates that charge order is compatible with a “nodal metal” state [11].

Single crystals of La$_{2-x}$Ba$_x$CuO$_4$ with $x = 1/8$ were grown by the floating zone method. The sample used in this study had a strongly suppressed bulk $T_c \simeq 2.4$ K as determined by magnetic susceptibility. The sample was cleaved in air, yielding a mirror-like $ab$-plane face. The $ab$-plane reflectance has been measured at a near-normal angle of incidence over a wide temperature and spectral range using an in-situ evaporation technique [20]. The optical properties are calculated from a Kramers-Kronig analysis of the reflectance, where extrapolations are supplied for $\omega \rightarrow 0, \infty$. At low frequency, a metallic Hagen-Rubens response is assumed ($R \propto 1 - \omega^2$). Above the highest-measured frequency in this experiment the reflectance of La$_{1.85}$Sr$_{0.15}$CuO$_4$ has been employed to about 40 eV [21]; above that frequency a free-electron approximation has been assumed ($R \propto 1/\omega^4$).

The reflectance of La$_{1.875}$Ba$_{0.125}$CuO$_4$ is shown from $\approx 20$ to 25,000 cm$^{-1}$ in Fig. 1 for a variety of temperatures. The reflectance is typical of many cuprates, with a plasma edge at $\approx 1$ eV and a low-frequency reflectance that increases with decreasing temperature, indicative of a metallic response. However, below $\approx 60$ K the low-frequency reflectance in the 200–2000 cm$^{-1}$ region stops increasing and begins to decrease, as shown in more detail in the inset of Fig. 1. Note that below $\approx 180$ cm$^{-1}$ the reflectance continues to increase below 60 K. This suppression of the far-infrared reflectance is unusual and has not been observed in other studies of LSCO or LNSCO [12, 14, 17, 21, 22, 23, 24] for $T > T_c$.

The optical conductivity is shown in Fig. 2 with the conductivity between 295 and 60 K in panel (a)
FIG. 1: (Color online) The reflectance at a near-normal angle of incidence for several temperatures over a wide spectral range for a cleaved surface of La$_{1.875}$Ba$_{0.125}$CuO$_4$ ($T_c \approx 2.4$ K) for light polarized in the $a$-$b$ plane. The infrared reflectance increases with decreasing temperature until about 60 K, below which it is suppressed in the 200 $-$ 2000 cm$^{-1}$ region. Inset: The detailed temperature dependence of the far-infrared reflectance at and below 60 K. (The resolution is 2 cm$^{-1}$.)

and the behavior below 60 K in (b). The conductivity can be described as a combination of a coherent temperature-dependent Drude component, and an incoherent temperature-independent component. The “two-component” expression for the real part of the optical conductivity is

$$\sigma_1(\omega) = \frac{1}{60} \frac{\omega^2 p_D \Gamma_D}{\omega^2 + \Gamma_D^2} + \sigma_{MIR},$$

where $\omega^2 p_D = 4\pi n_D e^2/m^*$ is the square of the Drude plasma frequency, $n_D$ is a carrier concentration associated with coherent transport, $m^*$ is an effective mass, $\Gamma_D = 1/\tau_D$ is the scattering rate, and $\sigma_{MIR}$ is the mid-infrared component. (When $\omega_{pD}$ and $1/\tau_D$ are in cm$^{-1}$, $\sigma_1$ has the units $\Omega^{-1}$cm$^{-1}$.) The conductivity in the mid-infrared is often described by a series of overdamped Lorentzian oscillators which yield a flat, incoherent response in this region. To simplify the fitting and reduce the number of parameters, a constant background ($\sigma_{MIR} \sim 850 \Omega^{-1}$cm$^{-1}$) has been used. The fitted Drude parameter values are summarized in Table I.

Between room temperature and 60 K, the normalized Drude carrier density (last column of Table I) remains constant, while the scattering rate scales with the temperature ($h/\tau \approx 2k_B T$), similar to what has been seen in the normal state of other metallic cuprates. Below 60 K, a new and surprising behavior occurs: the carrier density decreases rapidly, with a reduction of nearly 75% at 5 K. We note that this behavior is correlated with the onset of charge-stripe order as detected by diffraction techniques. The scattering rate also continues to decrease as $n_D$ drops.

It is interesting to compare with measurements of the in-plane resistivity, $\rho_{ab}$, shown in the inset of Fig. 2(b), obtained on a sister crystal. On cooling, the decrease in $\rho_{ab}$ is interrupted by a slight jump at the structural transition, at about 54 K. The drop in $\rho_{ab}$ below about 40 K is likely due to filamentary superconductivity, as magnetic susceptibility measurements show that the bulk superconducting transition is at 2.4 K. The non-bulk response can be suppressed through the application of a magnetic field (9 T); the resulting curve shows a nearly constant value for the resistivity below 54 K until the onset of bulk superconductivity at low temperature. The Drude expression for the dc resistivity, in units of $\Omega$cm, is $\rho_{dc} = 60/(\omega^2 p_D \Gamma_D)$. The results obtained from the parameter values in Table I indicated by circles in

FIG. 2: (Color online) The $ab$-plane optical conductivity of La$_{1.875}$Ba$_{0.125}$CuO$_4$ ($T_c \approx 2.4$ K). (a) The conductivity in the infrared region between 295 and 60 K, showing a steady narrowing of the Drude-like component. The sharp features in the conductivity are the normally-allowed infrared active vibrations; a feature at $\approx 125$ cm$^{-1}$ at 295 K is not visible at 60 K. (b) The conductivity for several temperatures below 60 K. A new vibrational feature appears at $\approx 205$ cm$^{-1}$ below about 40 K. Inset: The $ab$-plane resistivity of La$_{2-x}$Ba$_x$CuO$_4$ for $x \approx 1/8$ (solid curve) and in an 9 T magnetic field (dotted curve). The open circles are the estimated values for the dc resistivity calculated from the Drude parameters in Table I.
as discussed by Zhou et al. [30], one would expect the development of a CDW gap within the stripes to occur in the “antinodal” regions of reciprocal space, where the extrapolated Fermi surface has straight, well-nested portions. Note that the antinodal states exhibit a pseudogap in the normal state [18, 31], so that development of a true CDW gap would only affect states at finite binding energy.

Alternatively, we find that the decrease in the low-frequency conductivity at low temperature in the stripe-ordered state of La$_{1.875}$Ba$_{0.125}$CuO$_4$ looks surprisingly similar to that found in the superconducting state of La$_{1.85}$Sr$_{0.15}$CuO$_4$ [17], both in terms of energy scale and magnitude. A residual Drude peak was also observed in the latter superconductor. This similarity suggests an intimate connection between the charge gap of the stripe-ordered state and the pairing gap of the superconductor. Could the charge gap correspond to pairing without phase coherence?

In either case, the residual Drude peak indicates that states in the “nodal” region are not strongly impacted by the charge gap, so that the stripe-ordered state remains a nodal metal [10]. We note that the coexistence of metallic behavior and an anisotropic gap has been observed in two-dimensional CDW systems [32, 33]. Such behavior is contrary to expectations of a uniform gap for ordered stripes [11].

Before concluding, we should consider how our results compare with others in the literature. The two-component behavior (temperature-dependent Drude peak plus temperature-independent mid-infrared component) has been identified previously in studies of several different cuprate families [19, 22, 25]. The loss of spectral weight in the stripe ordered phase is a new observation. Measurements on La$_{1.275}$Nd$_{0.6}$Sr$_{0.125}$CuO$_4$ [12] seem to be consistent, but a larger low-temperature scattering rate in that sample masks any depression of

| T (K) | ω$_{p,D}$ (cm$^{-1}$) | 1/τ$_D$ (cm$^{-1}$) | n$_D$(T)/n$_D$(60 K) |
|-------|----------------------|---------------------|----------------------|
| 295   | 7010 ± 120           | 657 ± 35            | 0.98 ± 0.12          |
| 150   | 7070 ± 80            | 223 ± 9             | 0.99 ± 0.06          |
| 60    | 7090 ± 50            | 108 ± 2             | 1.00 ± 0.06          |
| 50    | 6560 ± 50            | 89 ± 2              | 0.85 ± 0.05          |
| 40    | 5740 ± 40            | 68 ± 2              | 0.65 ± 0.04          |
| 30    | 4930 ± 40            | 43 ± 2              | 0.48 ± 0.04          |
| 5     | 3690 ± 50            | 28 ± 2              | 0.27 ± 0.04          |

FIG. 3: (Color online) The ab-plane spectral weight N(ω) of La$_{1.875}$Ba$_{0.125}$CuO$_4$ for several different temperatures above and below 60 K. To simplify the units, the conductivity has been expressed in cm$^{-1}$. Inset: The temperature dependence of the spectral weight for cut-off frequencies ω$_c$ = 40, 100 and 300 cm$^{-1}$.
the optical conductivity. In contrast, studies by Lucarelli et al. on La$_{2−x}$Sr$_x$CuO$_4$ and Ortolani et al. on La$_{1.875}$Ba$_{0.125}$CuO$_4$ have found strong, sharp peaks at finite frequency (20 − 100 cm$^{-1}$) in low-temperature measurements. These “far-infrared peaks”, which have not been observed by other groups, have been interpreted as collective excitations of charge stripes [14, 15, 16, 17]. Here we simply note that our measurements on a cleaved sample do not show any indications of far-infrared peaks. Furthermore, the temperature dependence of the conductivity and the loss of the low-frequency spectral weight that we observe is directly correlated with onset of stripe order as detected by diffraction [3, 8]; the behavior of the Drude peak is quantitatively consistent with the measured resistivity.

In summary, the $ab$-plane properties of a cleaved single crystal of La$_{1.875}$Ba$_{0.125}$CuO$_4$ have been examined over a wide frequency range at several different temperatures. The rapid decrease of the carrier concentration $n_D$ below the electronic transition at $\sim 60$ K suggests the development of an anisotropic charge gap associated with the stripe order. Nodal excitations presumably remain ungapped; the deviation from $\rho_{ab} \sim T$ at small $T$ is due to the decrease in carrier density, not to a uniform increase in scattering rate. Thus it appears that stripes are compatible with the nodal-metal state.

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