Anisotropic dressing of charge-carriers in the electron-doped cuprate superconductor Sm$_{1.85}$Ce$_{0.15}$Cu$_4$O$_4$ from angle-resolved photoemission measurements

A. F. Santander-Syro, T. Kondo, J. Chang, A. Kaminski, S. Paillès, M. Shi, L. Patthey, Zimmers, B. Liang, P. Li, R. L. Greene

1Laboratoire Photons Et Matière, UPR-5 CNRS, ESPCI, 10 rue Vauquelin, 75231 Paris cedex 5, France
2Laboratoire de Physique des Solides, UMR-8502 CNRS, Université Paris-Sud, 91405 Orsay, France
3Ames Laboratory and Department of Physics and Astronomy, Iowa State University, Ames, IA 50011
4Laboratory for Neutron Scattering, ETH Zurich and Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland
5Laboratoire Léon Brillouin, CEA-CNRS, CEA-Saclay, 91191 Gif-sur-Yvette, France
6Swiss Light Source, Paul-Scherrer Institut, CH-5232 Villigen, Switzerland and
7Center for Nanophysics and Advanced Materials, Department of Physics, University of Maryland, College Park, MD 20742

(Dated: March 19, 2009)

Angle-resolved photoemission measurements on the electron-doped cuprate Sm$_{1.85}$Ce$_{0.15}$Cu$_4$O$_4$ evidence anisotropic dressing of charge-carriers due to many-body interactions. Most significantly, the scattering rate along the zone boundary saturates for binding energies larger than $\sim 200$ meV, while along the diagonal direction it increases nearly linearly with the binding energy in the energy range $\sim 50 - 500$ meV. These results indicate that many-body interactions along the diagonal direction are strong down to the bottom of the band, while along the zone-boundary they become very weak at energies above $\sim 200$ meV.

PACS numbers: 74.25.Gz, 74.72.Hs

Strong interactions in many-body systems lead to a rich variety of phenomena, whose understanding is a central question in modern physics. In condensed matter, cuprates are a paradigmatic example – and a continuing challenge – of the physics of strong electronic correlations. Understanding how strong interactions in cuprates affect their electronic structure is important to explain their properties, including the question of the pairing mechanism. In fact, the coupling of the carriers to elementary excitations affects the carriers’ band dispersion and energy-dependent scattering rate $(1/\tau)$, which can be obtained respectively from the positions and widths of the spectral peaks in angle-resolved photoemission spectroscopy (ARPES) experiments [1].

In hole-doped (h-doped) cuprates, $1/\tau$ has been mainly studied in the vicinity of the zone diagonal (D), where the superconducting (SC) gap vanishes. Here, the carriers’ dispersion and scattering rate display a kink at $\sim 70$ meV in the SC state [2,3]. Beyond that energy, $1/\tau$ increases linearly with energy in optimally doped cuprates [4]. A pressing issue in the understanding of the physics of cuprates is how the scattering rate behaves along the zone-edge (ZE), where the SC gap is maximum. An experimental difficulty in h-doped cuprates is that the band along the ZE is very shallow (about 50-100 meV), and the effects of interactions cannot be followed over a large energy range. Thus, only a few experimental reports exist, and the debate is not settled [2,3]. In contrast, in e-doped cuprates, the ZE band-width is $\sim 500$ meV, offering complete access to the momentum dependence of the many-body interactions. However, this kind of study has been scarcely addressed [7].

In this Letter we present a $k$-dependent study of the scattering rate in optimally doped Sm$_{1.85}$Ce$_{0.15}$Cu$_4$O$_4$ (SCCO). Compared to other e-doped cuprates, SCCO has the advantage of being cleaveable, thus yielding a surface that is adequate for accurate ARPES studies. The main results are as follows. First, we find kinks in both the quasi-particle dispersion and scattering rate at $150$ meV along the zone diagonal and $70$ meV along the zone edge. Second, the scattering rate along the diagonal increases with an approximately linear $\omega$-dependence beyond $150$ meV. In contrast, along the zone-edge the scattering rate saturates for $\omega > 200$ meV. These results suggest that the electron interactions are highly anisotropic, being strong down to the bottom of the band along the diagonal, but becoming very weak beyond 200 meV along the zone-edge.

High-quality single crystalline SCCO samples were grown by a flux method and then annealed under low-oxygen pressure to render them SC with a $T_c = 19$ K [8]. Wavelength dispersive X-ray analysis gave a Ce concentration $x = 0.15 \pm 0.01$. The ARPES experiments were done at the Synchrotron Radiation Center (SRC, University of Wisconsin, Madison) and the Swiss Light Source (SLS, Paul-Scherrer Institut, Switzerland) using 55 eV linear and circular photons respectively. A Scienta-2002 detector was used in both cases, with an angular resolution of 0.25°. The energy resolutions were 30 meV at SRC and 20 meV at SLS. The samples were cleaved in-situ at 11 K in pressure better than $6 \times 10^{-11}$ Torr, and kept at these conditions during the measurements. An eventual SC gap of $\sim 1-2$ meV [8] could not be resolved. The results were reproduced in three samples.
responding to an electron-doping of continuous blue line in Fig. 1(a), encloses an area centered at \((\pi, \pi)\), indicating that no antiferromagnetic-induced folding is present\cite{10, 11}. Such a folding has been observed only in as-grown non SC samples\cite{10}, or in underdoped reduced SC samples\cite{12, 13}. We simultaneously fitted the FS and the high-energy part of the band-structure using a single-band tight-binding model:

\[
E_{\text{tb}} = \mu + t_1(\cos k_x + \cos k_y) + t_2(\cos k_x \cos k_y) + t_3(\cos 2k_x + \cos 2k_y),
\]

with \((\mu, t_1, t_2, t_3) = (-10, -590, 337, -96.6)\) meV. Such a model is a good approximation of the band-theory result\cite{14}, and our fitting parameters are close to the canonical ones\cite{15}. The resulting FS, shown by the continuous blue line in Fig. 1(a), encloses an area corresponding to an electron-doping of \(x = 0.15 \pm 0.01\), in agreement with the bulk nominal doping.

We now turn to the study of the many-body interactions. Within the sudden approximation, ARPES measures the occupied part of the energy and momentum \(k\) dependent single-particle spectral function \(A(k, \omega)\):\cite{16}

\[
A(k, \omega) = \frac{1}{\pi} \frac{\Sigma''(k, \omega)}{[\omega - \epsilon_k - \Sigma'(k, \omega)]^2 + [\Sigma''(k, \omega)]^2},
\]

Here, \(\epsilon_k\) is the bare band structure, and \(\Sigma = \Sigma' + i\Sigma''\) is the complex self-energy (which quantifies the interactions). Energy distribution curves (EDCs) are obtained when the photoemission intensity is plotted for constant \(k\). Momentum distribution curves (MDCs) are obtained when it is plotted for constant \(\omega\). One can obtain information about the self-energy by analyzing the EDCs and MDCs\cite{1, 16}. Thus, if \(\Sigma\) is nearly \(\omega\)-independent for some extended energy range, then the EDCs in this energy range become Lorentzians, and their full-width at half-maximum (fwhm) is equal to \(2\Sigma''\). Likewise, an MDC is a Lorentzian if, and only if, \(\Sigma\) is independent of \(k\) along the direction of the MDC and if the bare dispersion can be linearized in \(k\). It then follows from Eq. 2 that the position of the MDC peak, plotted as a function of \(\omega\), gives the particle dispersion renormalized by interactions \(\epsilon^* = \epsilon_k + \Sigma'\), and the MDC-fwhm is \(\Delta k = 2\Sigma''/\nu_k\), where \(\nu_k = d\epsilon_k/dk\) is the bare-band velocity—which is experimentally unknown. Here, it is more appropriate to use the scattering rate \(1/\tau\), defined in terms of measurable quantities as \(1/\tau = \Delta k \times (d\epsilon^*/dk)\)\cite{17}.
Lorentzians down to hand, the MDCs along both directions [Figs. 3(b,c)] are dependent down to the bottom of the band. On the other interactions along this direction become strong and remain become broad and asymmetric, suggesting that interac-

\[ \omega \] to be weaker along the D than along the ZE. However, for energies, the coupling strength to other excitations appears the bottom of the band [Fig. 2(d)]. Thus, at low ener-

gle peak that broadens rapidly upon dispersing towards along the D direction, the EDCs around \( \omega \) ≥ 200 meV, pointing to an \( \omega \)-independent scattering rate, as will be confirmed further. By contrast, along the D direction, the EDCs around \( k_F \) show a single peak that broadens rapidly upon dispersing towards the bottom of the band [Fig. 2(d)]. Thus, at low energies, the coupling strength to other excitations appears to be weaker along the D than along the ZE. However, for \( \omega \) ≥ 100 meV [Fig. 2(d)], the EDCs along the D direction become broad and asymmetric, suggesting that interactions along this direction become strong and remain \( \omega \)-dependent down to the bottom of the band. On the other hand, the MDCs along both directions [Figs. 3(b,c)] are Lorentzians down to \( \omega \) ~ 400 meV, validating the MDC analysis that follows.

Figures 4(a) and (b) show the dispersions from the peak positions of the MDCs (symbols) along the ZE and D cuts, respectively. The tight-binding band from Eq. 1 for each direction is also shown (green lines). The arrows mark the energies where the experimental dispersions are farthest from the tight-binding band, defined as the kink positions. The raw MDC widths are shown in Fig. 3(c). Along the ZE, the dispersion presents a kink at \( \sim 60 \) – 70 meV, corresponding to the dip in the EDCs near \( k_F \) [Fig. 2(b)]. A drop in the raw ZE linewidths [Fig. 4(c), full red circles] below a slightly larger energy of \( \sim 100 \) meV is also observed, and is marked by an arrow [18]. Along the D cut, the experimental dispersion deviates from the tight binding fit at about 30 meV, then both dispersions run almost parallel in the range \( \sim 50 \) – 200 meV, and merge at \( \sim 250 \) meV. This broad kink structure, centered at \( \sim 150 \) meV [Fig. 4(b)], is a feature not reported before in c-doped cuprates. The raw D linewidths [Fig. 4(c), full blue squares] present a slight kink at about 50 meV (shown in the inset). At larger energies, the D linewidths increase and present an up-turn at \( \sim 250 \) meV, about the same energy at which the D dispersion and the tight-binding band reconnect.

The scattering rates along the ZE and D directions are shown in Fig. 4(d). Along the ZE direction, \( 1/\tau \) shows a peak at about 80 meV (related to the kink and drop seen in the dispersions and linewidths, respectively), while at energies larger than about 200 meV \( 1/\tau \) prac-
tically saturates, indicating that the electron-scattering mechanisms become weakly or not energy-dependent. An energy-independent self-energy implies Lorentzian EDCs, as we actually observed [Figs. 2(b) and 3(a)]. Moreover, as expected from an energy-independent self-energy, the EDC widths along the ZE in this energy range, shown by the open circles in Fig. 4(d), match very well with $1/\tau$, which should then be close to the actual value of $2\Sigma''$. Along the D direction, on the other hand, a change of slope in $1/\tau$ is seen at about 150 meV [Fig. 4(d)], while at larger energies this quantity continues to grow in an approximate linear way. This indicates that the scattering mechanisms along the D direction are energy-dependent down to at least 500 meV, in agreement with our previous discussion on the EDCs along the D cut.

We now compare our data with other ARPES data for e- and h-doped cuprates. The structures at 70 meV along the ZE and 50 meV along the D reproduce previous results on optimally doped SCCO, Nd$_{1.85}$Ce$_{0.15}$CuO$_4$ (NCCO), and Eu$_{1.85}$Ce$_{0.15}$CuO$_4$, and have been recently ascribed to electron-phonon interaction $\Sigma''$. At higher energies, our data along the D are in qualitative agreement with earlier data on NCCO $\Sigma''$ that found that $\Sigma'' \sim \omega^\alpha$, with $\alpha = 1$ to 1.55, in the range $90 < \omega < 400$ meV. Our results complete the picture for e-doped cuprates, showing that along the ZE the interactions beyond 200 meV become weak, and the scattering rate energy-independent. As for the h-doped cuprates, a striking qualitative similarity with our data is the approximately linear form of the scattering rate along the diagonal [1, 3]. However, we do observe the bottom of the D band, so that no high-energy anomaly of the type reported in h-doped cuprates [21] exists in e-doped cuprates. Note also that, in h-doped cuprates, a kink at an energy of 150 meV was recently unveiled, its physical origin being not yet clear [22]. Thus, our data suggest the existence of what could be a new form of electron coupling that is common to h- and e-doped cuprates.

Other probes in e-doped cuprates show signatures of the energy scales discussed here: infrared data on Pr$_{2-x}$Ce$_x$CuO$_4$ at $x = 0.13$ (0.15) show a broad drop at $\sim 200$ meV (100 meV) in the optical scattering rates [23]. Local-tunneling spectroscopy data on optimally-doped SCCO show a hump at bias voltages $\sim 60$–$80$ meV [24]. Both of these techniques are integrated over the FS. The optical response in cuprates is believed to be most sensitive to the excitations close to the diagonal, while the tunneling current is believed to be most sensitive to the $(\pi, 0)$ regions. Thus, the infrared and tunnel results could be reinterpreted in terms of the energy scales found in our angle-resolved data.

In conclusion, among the $k$-space anisotropies in the carrier-dressing shown by our data, our most significant observation is that the scattering rate along the ZE saturates for binding energies larger than $\sim 200$ meV, while along the D direction $1/\tau$ increases with the binding energy $\omega$, having a nearly linear $\omega$-dependence for $\omega \sim 150 – 500$ meV. These results point to the interaction of electrons with a strongly dispersive excitation with both a characteristic energy and a coupling strength to carriers that are momentum dependent, such that interactions along the diagonal are strong down to the bottom of the band, while they become very weak beyond $\sim 200$ meV along the ZE. In the framework of cuprate superconductivity, two possibilities arise: either this unique scattering mechanism along the ZE is also present in the h-doped cuprates, or the strong antiferromagnetic fluctuations in e-doped cuprates separate two different regions in $k$-space, with a physics describing the D region that is similar in h- and e-doped cuprates, and a different picture describing the ZE region.

We acknowledge the European Union for supporting our work at the Swiss Light Source. The Synchrotron Radiation Center, University of Wisconsin-Madison, is supported by the National Science Foundation under award no. DMR-0537588. The work at the University of Maryland is supported by NSF contract DMR 0653535. Work at Ames Laboratory was supported by the Department of Energy - Basic Energy Sciences under Contract No. DE-AC02-07CH11358. AFSS thanks LPEM-CNRS for financial support.

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