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Nodal Landau Fermi-Liquid Quasiparticles in Overdoped La$_{1.77}$Sr$_{0.23}$CuO$_4$

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5 Nodal Landau Fermi-Liquid Quasiparticles in Overdoped La$_{1.77}$Sr$_{0.23}$CuO$_4$ (T$_c$ = 25 K) were recorded at the surface and interface spectroscopy (SIS) beam line $^b$ of the Swiss Light Source (SLS) at the Paul Scherrer Institute, Switzerland. High quality nodal spectra were obtained after cleaving at $T = 15$ K under ultra-high vacuum conditions ($p \sim 10^{-11}$ mbar). Using 55 eV circular polarized photons and a SCIENTA 2002 electron analyzer, angular and energy resolutions corresponding to 0.15° (FWHM) and $\sigma = 9$ meV (standard Gaussian deviation) were achieved. A detailed description of the experimental conditions can be found in Ref. 20.

II. METHODS

Fig. 1(a) shows a colormap – $I$ vs $(k, \omega)$ – of ARPES spectra recorded close to the nodal direction of overdoped La$_{1.77}$Sr$_{0.23}$CuO$_4$. A selection of corresponding momentum distribution curves (MDC) and energy distribution curves (EDC) are displayed in Fig. 1(b,c). We start by discussing the MDCs. As this paper focuses entirely on the low-energy excitations, MDCs are only shown up to the energy scale (80 meV) of the nodal kink shown in the inset of Fig. 1(c). In this energy interval, the MDC line shapes are symmetric peaks on a constant background. Therefore, data at constant $\omega$ were analyzed using a Lorentzian function $I_0 \Gamma/[(\omega - \varepsilon_b)^2 + \Gamma^2]$, where $\Gamma$ is the linewidth (Fig. 2a), $\varepsilon_b$ is the peak position (Fig. 2b), and $I_0$ is an amplitude (Fig. 3). The observed nodal excitations disperse with a Fermi velocity $v_F = 1.62(2)$ eV Å [Fig. 2(b)], consistently with previous reports on LSCO$^{11,12}$. The half-width half-maximum, $\Gamma$, is plotted as a function of excitation energy squared $\omega^2$ in Fig. 2(a). We find that, for $\omega < \omega_c = 0.18 \pm 0.2$ eV, the linewidth is well described by $\Gamma = \Gamma(0) + \eta \omega^2$ with

III. RESULTS

Nodal ARPES spectra of overdoped La$_{1.77}$Sr$_{0.23}$CuO$_4$ (T$_c$ = 25 K) were recorded at the surface and interface spectroscopy (SIS) beam line $^b$ of the Swiss Light Source (SLS) at the Paul Scherrer Institute, Switzerland. High quality nodal spectra were obtained after cleaving at $T = 15$ K under ultra-high vacuum conditions ($p \sim 10^{-11}$ mbar). Using 55 eV circular polarized photons and a SCIENTA 2002 electron analyzer, angular and energy resolutions corresponding to 0.15° (FWHM) and $\sigma = 9$ meV (standard Gaussian deviation) were achieved. A detailed description of the experimental conditions can be found in Ref. 20.

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FIG. 1: (a) Nodal ARPES spectra recorded from overdoped LSCO \( (x = 0.23) \), at \( T = 15 \) K with 55 eV photon. The intensity, displayed versus momentum \( k - k_F \) (horizontal) and excitation energy \( \omega \) (vertical), has a false color scale with white as the most intense as indicated by the colorbar. (b) Momentum distribution curves (MDCs) of the spectra shown in (a), for fixed energies as indicated. Solid lines are Lorentzian fits to the data. (c) Energy distribution curves (EDCs) recorded at momenta as indicated. A \( \omega \)-dependent background defined by the EDC at \( k - k_F = 0 \) has been subtracted. Solid lines display the \( \omega \)-dependence of Eq. 3, multiplied with the Fermi-Dirac distribution and convoluted with the instrumental resolution. For the sake of visibility, data in (b) and (c) are arbitrarily shifted in the vertical direction. The insert of (c) displays the excitation dispersion derived from MDC analysis of the spectra in (a).

\[ \eta = 3.14(4) \text{ eV}^{-2} \text{Å}^{-1}, \text{ and } \Gamma(0) = 0.0117(1) \text{ Å}^{-1}. \] The elastic scattering \( \Gamma(0) \) is lower than what is usually reported for LSCO \cite{25,26}. As impurity scattering is one source of elastic scattering \cite{27}, low values of \( \Gamma(0) \) may be an indication of high sample quality.

To reveal the intrinsic physical line shape, a background has been subtracted from the EDCs shown in Fig. 1(c). The energy dependent background was extracted from the spectra using an energy distribution curve on the unoccupied side of the dispersion (indicated by a vertical dashed line in Fig. 1(a)). This is a common procedure \cite{28} and an example of a raw background spectrum can be found in the supplement of Ref. 20. In this fashion, EDCs recorded at a momentum \( |k| \) larger than the Fermi momentum \( |k_F| \) [displayed with open circles in Fig. 1(c)] are featureless, demonstrating the successful background subtraction. On the other hand, EDCs with \( k < k_F \) [full circles] reveal the intrinsic line shape of the excitations.

**IV. DISCUSSION**

The measured ARPES intensities \( I(k, \omega) \) can be modelled by a product of the spectral function \( A(k, \omega) = -(1/\pi) \text{Im} G(k, \omega) \), a matrix element \( M(k, \omega) \), and the Fermi distribution \( f(\omega) \). Matrix elements typically vary weakly as a function of \( (k, \omega) \). Notice that the excitations shown in Fig. 1(b) disperse over less than 10 percent of the Brillouin zone. It is therefore not unreasonable to ignore matrix element effects. In that case, the ARPES intensity becomes a direct measure of the occupied part of the spectral function. It is common practice to separate the spectral function into coherent and incoherent parts, i.e. \( A(k, \omega) = A_{coh}(k, \omega) + A_{inc}(k, \omega) \). The coherent part can be written as:

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

where \( \epsilon_b \) is the \textit{a priori} unknown bare band, and the self-energy must obey \( |\Sigma'| \gg |\Sigma''| \). Experimentally, one would associate sharp dispersing features to the coherent...
To first order, the quasiparticle part yields \( \Sigma' \) is dominated. Because \( Z = v_F v_b \) and \( \Sigma'' = -\eta v_F \omega^2 \), the product \( Z \Sigma'' = -v_F \eta v_F \omega^2 \) can be evaluated without quantitative knowledge of the bare band velocity. The condition for coherent quasiparticle excitations is \( -Z \Sigma'' < \omega^2 \). Using the experimental values of \( v_F \) and \( \eta \), we find that Landau quasiparticles are coherent for \( \omega < 1/v_F \eta \sim 0.19 \text{ eV} \). This energy scale is comparable to \( \omega_c \) – the energy scale below which \( \Sigma'' \propto \omega^2 \) – and hence re-enforces the interpretation of \( \omega_c \) as an energy scale related to the break down of Landau Fermi-liquid quasiparticle excitations.

Finally, we discuss the Kramers-Kronig relation between \( \Sigma' \) and \( \Sigma'' \):

\[
\Sigma' = \frac{\mathcal{P}}{\pi} \int_{-\omega_c}^{\omega_c} \frac{\Sigma''(\omega')}{\omega' - \omega} d\omega' + \frac{\mathcal{P}}{\pi} \int_{-\omega_c}^{\omega_c} \frac{\Sigma''(\omega')}{\omega - \omega'} d\omega' = \Sigma'_{qp} + \Sigma''_{qp}
\]

where \( \mathcal{P} \) is the principal value and \( W \) is the band width. To first order, the quasiparticle part yields \( \Sigma'_{qp} \approx \gamma_{qp} \omega \)
where $\gamma_{qp} = 2v_b\eta\omega_c/\pi$. To gain insight into $\Sigma_{nqp}^\prime$, we define $Z_i(\omega) = (1 - \partial \text{Re} \Sigma_i/\partial \omega)^{-1}$ so that $Z(\omega) = Z_{qp}(\omega) + Z_{nqp}(\omega)$. As $Z(\omega) \sim I_0(\omega)$ varies weakly with excitation energies (see Fig. 3), we infer that $Z_{nqp}$ is temperature independent, but $\Sigma_{nqp}^\prime(\omega) = \gamma_{nqp}\omega$ and $Z = 1/(1 + \gamma_{qp} + \gamma_{nqp})$. As long as the detailed high-energy part of $\text{Im} \Sigma(\omega)$ is unknown, it is not possible to directly extract $\Sigma_{nqp}^\prime = \gamma_{nqp}\omega$. This is known as the "tail" problem. The linear $\omega$-dependence at high-energies, shown in the inset of Fig. 2, yields $\gamma_{nqp} \sim \ln(C/\omega_c)$ where $C$ is an unknown constant. Hence $\gamma_{nqp}$ diverges only logarithmically in the limit $\omega_c \to 0$. On the other hand, for large $\omega$, the role of $\gamma_{nqp}$ will be less important. As $\omega_c = 0.18$ eV is a large energy scale, corresponding to a temperature scale of the order 1000 K, we hypothesize that $\gamma_{nqp} \ll 1$. In that case, $Z \simeq 1/(1 + \gamma_{qp}) = v_F/v_b$ and hence $v_b = \pi v_F/(\pi - 2\gamma_{qp}/v_F) = 3.8$ Å. This is consistent with the nodal LDA Fermi velocity $v_{LDA} = 3.5$ eVÅ, calculated for LSCO and with values of $v_b$ derived from a numeric self-consistent method. The consistent values of $v_b$ further support the conjecture that $\gamma_{nqp} \ll 1$.

The quasiparticle mass is given by $m_b/m^* = Z\tilde{Z}$, where $m_b$ is the bare mass and $\tilde{Z} = 1 + (m_b/\hbar^2k_F)\partial^2\Sigma(0)/\partial k^2$. Since the self-energy is locally independent of momentum, the nodal quasiparticle mass is given by $m^* = m_b/\tilde{Z} \simeq 2.4m_b$. This is comparable to the momentum averaged values $m^* \simeq 3m_b$ extracted from quantum oscillation and electronic specific heat experiments on overdoped Tl$_2$Ba$_2$CuO$_{6+\delta}$ (Tl2201). Remarkably, a Fermi-liquid cut-off energy scale $\omega_c \sim 0.2$ eV was extracted from angle-dependent magneto-resistance measurements on overdoped Tl2201. This is in good agreement with nodal ARPES spectra recorded on LSCO $x = 0.23$. On LSCO, no quantum oscillation or angle-dependent magneto-resistance experiments exist. Insight into the average quasiparticle mass of overdoped LSCO stems, therefore, alone from specific heat measurements. Compared to Tl2201, a somewhat larger Sommerfeld constant $\gamma_{el} \simeq 12$ mJ/(mole K$^2$) is found for overdoped LSCO $x \simeq 0.23$, suggesting a larger average quasiparticle mass. This is not necessarily inconsistent with the ARPES data. The Fermi-liquid cut-off energy scale, $\omega_c$, softens rapidly as a function of Fermi surface angle, and the quasiparticle scattering is globally dependent on momentum. This implies (1) that the contribution from non-Fermi liquid excitations will become increasingly important and (2) that $\tilde{Z} < 1$ on certain portions of the Fermi surface. Both effects would lead to larger quasiparticle masses.

V. CONCLUSIONS

In summary, we have proven that the nodal single particle excitations observed by ARPES in overdoped LSCO are indeed true Landau Fermi liquid quasiparticle excitations. This result, together with consistent MDC and EDC analysis, was obtained without knowing the exact bare band. From Kramers-Kronig consistency of the quasiparticle self-energy $\Sigma$, insight into the bare band $e_b$ and the real part of the self-energy $\Sigma^\prime$ were obtained. An estimate of the nodal quasiparticle residue $Z = 0.42(7)$ allowed comparison to quasiparticle masses obtained from thermodynamic and high-field quantum oscillation experiments on overdoped Tl$_2$Ba$_2$CuO$_{6+\delta}$ compounds.

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There are at least two ways to mimic the effect of instrumental resolution. One is to use the measured $\Gamma_0$ and the width of the Fermi step that already include instrumental resolution. Another method is to use $\Gamma_0(\text{intrinsic}) = (\Gamma_0^2 - \Gamma_k(\text{res})^2)^{0.5}$, where $\Gamma_k(\text{res})$ is the momentum resolution, a Fermi step defined by $k_B T$ and then convolve this with the instrumental resolution. Both methods where tried with essentially identical results.

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