Fermi Liquid Universality Revealed by Electron Spectroscopy

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We present a combined soft x-ray and high-resolution vacuum-ultraviolet angle-resolved photoemission spectroscopy study of the electron-overdoped cuprate Pr$_{1.3-x}$La$_7$Ce$_x$CuO$_4$ (PLCCO). Demonstration of its highly two-dimensional band structure enabled precise determination of the in-plane self-energy dominated by electron-electron scattering. Through analysis of this self-energy and the Fermi-liquid cut-off energy scale, we find – in contrast to hole-doped cuprates – a momentum isotropic and comparatively weak electron correlation in PLCCO. Yet, the self-energies extracted from multiple oxide systems combine to demonstrate a logarithmic divergent relation between the quasiparticle scattering rate and mass. This constitutes a spectroscopic version of the Kadowaki-Woods relation with an important merit – the demonstration of Fermi liquid quasiparticle lifetime and mass being set by a single energy scale.

The Fermi liquid quasiparticle concept underpins much of our understanding of correlated metals [1–4]. Electron-electron interaction renormalizes the quasiparticle lifetime and mass whereas spin and charge quantum numbers are identical to the non-interacting limit. This quasiparticle identity assures electronic specific heat $C$ to scale with temperature $T$ and a resistivity proportional to $T^2$ below an energy scale $\omega_c$. In the limit $k_B T \ll \omega_c$, the Wiedemann-Franz law [5] dictates a fundamental relation between heat and charge conduction. Under sufficiently strong electron correlation ($\omega_c \rightarrow 0$), the Fermi liquid breaks down and is replaced by a Mott insulating or non-Fermi liquid state. Studying this breakdown route is an important step to conceptualize non-Fermi liquids that are often found in the context of unconventional superconductivity [6–9]. The Kadowaki-Woods relation [10, 11] suggests a link between quasiparticle lifetime and mass renormalization. The resistivity coefficient $A$ in $\rho = AT^2$ reflects a momentum integrated lifetime whereas the Sommerfeld coefficient $\gamma$ – inferred from specific heat – yields the mass. Accumulated empirical evidence supports the Kadowaki-Woods proposal of the ratio $A/\gamma^2$ being invariant with respect to the electron-electron interaction strength [10–13].

Although photoemission spectroscopy has angle (momentum) resolving capability and direct access to the self-energy, no spectroscopic evidence of the Kadowaki-Woods relation has been established. This lack of progress stems from a chain of challenges: (i) Photoemission spectroscopy is best suited for two-dimensional systems [14], narrowing down the range of studiable materials. (ii) Self-energy analysis of quasi two-dimensional systems is limited by residual $k_z$ and disorder broadening [15] in the weak coupling limit. (iii) The strong coupling limit leads to energy scales below the resolving power.

Here, we demonstrate by soft x-ray (SX) angle-resolved photoemission spectroscopy (ARPES) that the electron-overdoped cuprate superconductor Pr$_{1.3-x}$La$_7$Ce$_x$CuO$_4$ (PLCCO) has a two-dimensional electronic structure with negligible $k_z$ dispersion. This result justifies and enables extraction of the in-plane self-energy using vacuum-ultraviolet (VUV) ARPES. In contrast to hole-overdoped La$_{2-x}$Sr$_x$CuO$_4$ (LSCO), which hosts non-local interactions [17, 18], an essentially momentum-isotropic Fermi-liquid self-energy is found.
FIG. 1. Two-dimensional Fermi surface of PLCCO \((x = 0.15)\). (a) In-plane Fermi surface, for the integration window \(E_F \pm 30\) meV, measured at \(T = 25\) K and \(h\nu = 427\) eV. (b),(c) Out-of-plane Fermi surface maps recorded along the nodal and off-nodal directions, respectively, as indicated in (a). (d) Energy distribution map taken along the nodal direction. Cu \(d\)-orbital characters are assigned as in Ref. 16. Gray lines in (a)–(d) indicate Brillouin-zone boundaries. (e) Energy distribution map taken along \(k_z\) for a fixed in-plane momentum – \(k_{\text{nodal}} = \pi/a\). White dashed lines are guides to the eye. (f) Schematic Fermi surface with the nodal and off-nodal cuts.

from the nodal to antinodal region. Again in direct comparison to LSCO, much weaker electron-electron interactions are observed in PLCCO. This result is reflected both in quasiparticle lifetime and the Fermi liquid cut-off energy scale linked to the mass renormalization factor \(Z\). Combined with results on other correlated (non-superconducting) oxide systems, these results sum into a spectroscopic version of the Kadowaki-Woods relation where the quasiparticle scattering rate \(\beta\) scales with \(Z^{-2}\) over more than an order of magnitude.

Single crystals of PLCCO with \(x = 0.15\) were synthesized by the traveling-solvent floating-zone method. After reduction annealing [19, 20] at 800 °C for 24 h, the overdoped sample showed superconductivity with \(T_c = 19\) K – lower than the optimal \(T_c \sim 27\) K [20]. SX and VUV ARPES experiments were carried out at the P04 and Surface/Interface Spectroscopy (SIS) beamline at DESY and Swiss Light Source [21], respectively. Samples were cleaved \textit{in situ} under ultra high vacuum (< \(5 \times 10^{-11}\) Torr) by employing a top-post method. Circularly polarized incident photons of \(h\nu = 30 – 600\) eV were used for both experiments. The effective energy resolution (temperature) was set to \(\sim 50\) meV (25 K) for the SX and 14–17 meV (18 K) for the VUV measurements.

Using SX-ARPES, which provides comparatively good \(k_z\) resolution [15], we evaluate the dimensionality of the electronic structure in PLCCO. Along the nodal and off-nodal cuts [see in-plane Fermi surface map in Fig. 1(a)], the Fermi surface was investigated in the \(k_z\) direction over three Brillouin zones [Figs. 1(b) and (c)]. Within the experimental resolution, the Fermi surface (with \(d_{x^2-y^2}\) character) has no \(k_z\) dispersion. Consistently, none of the \(d\) bands (\(t_{2g}\) and \(d_{z^2}\)) at deeper binding energies [Fig. 1(d)] [16] exhibit any significant dispersions along the \(k_z\) direction [Fig. 1(e)]. These highly two-dimensional characteristics of PLCCO are in contrast to the recently unveiled three-dimensional electronic structure of the hole-overdoped cuprate LSCO [23, 24]. This difference stems from a reduced inter-layer hopping due to the absence of apical oxygen atoms in the electron-doped cuprates [25]. The two-dimensional nature of the electron-doped cuprates is also reflected by a large resistivity anisotropy \(\rho_c/\rho_{ab} > 10000\) [26]. This is ten and hundred times larger than the anisotropies reported in \(\text{Sr}_2\text{RuO}_4\) [27] and overdoped LSCO [28], respectively.

The established two-dimensional electronic structure...
FIG. 2. In-plane isotropic self-energy structure of PLCCO. (a) Fermi surface recorded at the indicated temperature and photon energy. (b),(c) Nodal and antinodal energy distribution maps with momentum distribution curves (MDCs) at $E_F$.

(d) Nodal and antinodal band dispersions extracted from MDC analysis. Solid curves and dashed lines represent bare bands and extrapolation of low-energy dispersions, respectively. (e) Fermi velocity $v_F$ of PLCCO and LSCO ($x = 0.22$) [22] plotted as a function of the Fermi surface angle $\phi$ [see inset of (g)]. (f) Near nodal self-energy $-\text{Im}\Sigma(\omega)$ plotted versus $\omega^2$ for PLCCO and LSCO ($x = 0.23$) [17]. Dotted curves are fits revealing the $-\text{Im}\Sigma(\omega) \propto \beta \omega^2$ dependence and black arrows mark high-energy deviation (Fermi liquid cut-off). Low-energy part is magnified in the inset. (g) Coefficient $\beta$ for the $\omega^2$ term of $\text{Im}\Sigma(\omega)$ for PLCCO and LSCO ($x = 0.23$) [17].

of PLCCO justifies use of surface-sensitive VUV light for extraction of the self-energy. The Fermi surface recorded at $h\nu = 55$ eV [Fig. 2(a)] – essentially identical to that observed with SX [Fig. 1(a)] – corresponds to a filling of 15 % electron doping. While there have been extensive reports on additional electron doping by reduction annealing of electron-doped cuprates [20, 29–33], this filling is consistent with the nominal Ce concentration.

The two-dimensional Fermi surface and the absence of (i) hot spots [34] and (ii) van Hove singularities near the Fermi level form the basis for self-energy analysis across the entire Brillouin zone. Low-energy quasiparticle excitations were recorded along nodal and antinodal directions [see Fig. 2(a)]. Nodal and antinodal energy distribution maps shown in Figs. 2(b) and (c), taken respectively with $h\nu = 55$ and 30 eV incident light, reveal sharp and dispersive quasiparticle peaks. In agreement with previous studies [35–37], both dispersions exhibit (possibly electron-phonon coupled) kinks at the binding energy of $\sim 0.05$ eV [Fig. 2(d)]. Fermi velocities $v_F$ – plotted as a function of the Fermi surface angle $\phi$ in Fig. 2(e) – are extracted by fitting the quasiparticle dispersion up to the kink energy scale. In contrast to the strongly anisotropic $v_F$ in overdoped LSCO ($x = 0.22$) [22], $v_F$ is found to be almost independent of momentum in PLCCO. This marked difference is linked to the proximity of the van Hove singularity to the Fermi level in LSCO [38].

ARPES spectra contain information about the electronic self-energy $\Sigma(k, \omega)$ through its relation to the spectral function $A(k, \omega) = -1/\pi \text{Im}[1/(\omega - \varepsilon_k - \Sigma(k, \omega))]$ where $\varepsilon_k$ is the bare band dispersion. The quasiparticle lifetime is obtained through $\text{Im}\Sigma(k, \omega) = v_k \Gamma_k$ where $v_k = \partial \varepsilon_k / \partial k$ is the bare band velocity and $\Gamma_k$ is momentum-distribution-curve (MDC) half width at half maximum [40–42]. To estimate the bare band velocity, we fitted the Fermi surface to a single-band tight-binding model (see Supplemental Material [43]) including nearest ($t$), second-nearest ($t'$), and third-nearest ($t''$) neighbor hopping parameters. With $\epsilon_0$ being the band center, we find $\epsilon_0/t = -0.04$ and $t'/t = -0.19$.
with \( \Im \Sigma \) proportional to low-temperature transport properties [8, 46, 47].

The fact that both \( \beta \) and \( \omega_c \) are linked to electron-electron interaction strength. Indeed, as shown in Fig. 2(f), \( \omega_c \sim 0.4\,\text{eV} \) and an approximate \( \Im \Sigma(\omega) \propto \beta \omega^2 \) dependence remains in the considered \( \omega \) range while \( \beta \) is weakly overestimating \( \beta \). The coefficient \( \beta = \lambda/\omega_c^2 \) given by the bare scattering rate & \( \omega_c \) reflects the effective electron-electron interaction strength. In Fig. 2(g), \( \beta \) plotted versus Fermi surface angle appears essentially isotropic (momentum independent). This is in strong contrast to the hole-overdoped counterpart LSCO where \( \beta \) is highly anisotropic and takes on much larger values already in the nodal region [see Fig. 2(g)]. This weaker electron correlation strength found for electron-overdoped cuprates is consistent with theoretical proposals [51–54].

We conclude by discussing the Fermi liquid cut-off energy scale \( \omega_c \) which is expected to vanish with the quasiparticle residue \( Z \) [12, 13, 49]. For the simplest Fermi liquid with isotropic \( \Im \Sigma \), the residue is given by \( Z = \nu_F/\nu_b \). If \( \Im \Sigma \) in addition is monotonically decaying to zero above the cut-off energy \( \omega_c \), then \( Z \propto \omega_c/W \) where \( W \) is a bare energy scale [13]. Hence the cut-off energy \( \omega_c \) is an indicator of electron-electron interaction strength.

Below this cut-off energy scale, the self-energy is expected to contain contributions from both electron-phonon and electron-electron interactions. Probing in the \( \omega \to 0 \) limit allows – in principle – direct comparison to low-temperature transport properties [8, 46, 47]. With our experimental temperature and energy resolution, however, we cannot distinguish a Fermi liquid with \( \Im \Sigma \propto \omega^2 \) from, for example, a marginal Fermi liquid with \( \Im \Sigma \propto \sqrt{\omega^2 + (\pi k_B T)^2} \) [48]. Excitations observed above the kink energy scale (0.06 eV) do not pose these limitations. The electron-phonon self-energy contribution saturates for \( \omega > 0.06 \,\text{eV} \) and hence can be approximated by a constant. Furthermore, our energy resolution does not limit the analysis of the quasiparticle excitations in this regime. The extracted electron-electron interacting self-energy is parametrized by \( -\Im \Sigma(\omega) = \alpha + \beta \omega^2 \), with \( \alpha \) and \( \beta \) being constants. As demonstrated in Fig. 2(f), this parabolic function convincingly fits the \( \Im \Sigma(\omega) \) curves over a wide energy range (0.06 < \( \omega < 0.4\,\text{eV} \)). This functional form of the self-energy is identical to a three-dimensional Fermi-liquid which displays \( \Im \Sigma(\omega) - \Im \Sigma(0) = -\beta \omega^2 \) below a cut-off energy \( \omega_c \) [12, 13, 17, 49]. In two dimensions, a logarithmic correction [50] influences mostly the self-energy for \( \omega \ll E_F \sim 1.5 \,\text{eV} \) and an approximate \( \Im \Sigma(\omega) \propto \beta \omega^2 \) dependence remains in the considered \( \omega \) range while \( \beta \) is weakly overestimating \( \beta \). The coefficient \( \beta = \lambda/\omega_c^2 \) given by the bare scattering rate & \( \omega_c \) reflects the effective electron-electron interaction strength.

In summary, we have carried out SX and VUV ARPES measurements on the electron-overdoped cuprate PLCCO. A two-dimensional electronic struc-
ture was revealed by SX ARPES experiments. This in turn enabled precise determination of PLCCO’s in-plane self-energy using VUV light. In contrast to the hole-doped counterpart LSCO, PLCCO displayed weak momentum-isotropic Fermi-liquid excitations. Characteristic parameters such as the scattering-rate coefficient $\beta$ and the Fermi-liquid cut-off energy $\omega_c$ revealed weak electron correlations compared to those reported in LSCO and Ca$_{1.8}$Sr$_{0.2}$RuO$_4$, but close to LaNiO$_3$. Despite these strong contrasts, the four systems were found to satisfy a common relation that connects $\beta$ to $\omega_c^{-1}$, and hence to the mass renormalization factor $Z^{-1}$. Our results constitute a spectroscopic version of the Kadowaki-Woods relation $\beta \propto Z^{-2}$. We reveal how this relation emerges from the quasiparticle lifetime and mass being set by a single low energy scale $\omega_c$ characterizing any Fermi liquids.

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