

Dual origin in the temperature dependence of the coupling parameter for the strange metal state in heavily overdoped cuprate superconductor

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The real and imaginary parts of the self-energy in the wide energy range have been evaluated from high-resolution angle-resolved photoemission spectroscopy (ARPES) spectra of a heavily overdoped single-layer cuprate superconductor $(\text{Bi, Pb})_2\text{Sr}_2\text{CuO}_{6+\delta}$ in the normal state. The real part of the self-energy has the zero-point crossing at -0.6 eV, where the lifetime broadening takes maximum and the ARPES spectral intensity is significantly suppressed forming a high-energy anomaly (HEA). The self-energy part responsible for the HEA is almost temperature independent and the coupling parameter is $\lambda_{\text{HEA}} \sim 1$ at 300 K, indicating strongly correlated nature of the strange metal state. Meanwhile, the self-energy part responsible for the low-energy kink (LEK) near the Fermi level shows significant temperature dependence: it is $\lambda_{\text{LEK}} \sim 0.1$ at 300 K but enhances steeply below ~ 150 K up to $\lambda_{\text{LEK}} \sim 0.8$, leading to the total coupling strength of $\lambda_{\text{tot}} = \lambda_{\text{HEA}} + \lambda_{\text{LEK}} = 1.8$ at 20 K. The temperature-dependent enhancement cannot be explained by the electron-phonon interaction with a fixed magnitude of the Eliashberg function, which suggests an unexplored mechanism that enhances the coupling parameter at lower temperatures. Our results clearly indicate distinct energy scales in the self-energy, providing insight into the strange metal state as well as the temperature-dependent interplay of many-body interactions.

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Since the discovery of high-transition-temperature (T_c) superconductivity in cuprates [1], extensive studies have been done to elucidate unusual physical properties such as metal-insulator transition, strange/bad metal behavior, pseudogap state, charge ordering, and magnetic fluctuations [2–7]. While the electrical conductivity in the normal state increases with doping in the overdoped region around vanishing T_c , the metallic state is non-Fermi liquidlike and ferromagnetic fluctuation emerges in Pb-doped $\text{Bi}_2\text{Sr}_2\text{CuO}_{6+\delta}$ (Pb-Bi2201) [8]. Earlier muon spin relaxation experiments on $\text{Tl}_2\text{Bi}_2\text{CuO}_{6+\delta}$ (Tl2201) clarified that T_c and the superfluid density were correlated and both decreased to zero upon hole doping in the overdoped region [9]. Recent detailed magnetic penetration depth and the phase stiffness measurements

for $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (LSCO) thin films indicated that T_c is principally controlled by the superfluid density or phase stiffness [10]. Notably, the obtained scaling law near $T_c \sim 0$ is incompatible with the mean-field theory such as the d -wave Bardeen-Cooper-Schrieffer theory even with the dirty limit, pointing to the local pairing and massive phase fluctuation in the real space [10]. Note that nematic fluctuation in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Bi2212) [11] and reentrant charge order in Pb-Bi2201 [12] have been reported in the overdoped region.

The presence of superconducting puddles embedded in the metallic state has been suggested in overdoped LSCO [13], and the nanoscale superconducting puddles have been experimentally observed by the scanning tunneling microscopy/spectroscopy for Pb-Bi2201 [14,15]. The observed superconducting gap was not closing but filling at the zero bias; the superconducting gap persists beyond the T_c dome and the heterogeneity in the real space is closely linked to the magnitude of the gap filling at the zero bias [14]. The metallic state filling the gap was not derived from the impurity scattering nor thermal phase fluctuations, but likely from the strange metal state [14]. The significant role of the antinode-to-antinode scattering connecting the flat portion of the energy bands was pointed out for the pair breaking and formation of the normal state in the overdoped region [15,16].

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Clarifying the strange metal state and superconducting puddles in the overdoped region is important to understand why T_c is decreasing with hole doping. It also provides clues to the microscopic mechanism of the high- T_c superconductivity beyond the mean-field theories.

To understand unusual physical properties, it is crucial to clarify the roles of the entangled many-body interactions such as the electron-phonon interaction, electron-electron interaction, and electron-magnon (spin wave) interaction. The characteristics of these interactions are reflected in the functional form of the self-energy, $\Sigma(k, \omega; T)$. The real part of the self-energy ($\text{Re}\Sigma$) gives an energy shift and the imaginary part of the self-energy ($\text{Im}\Sigma$) gives the lifetime broadening [17–21]. To experimentally elucidate the self-energy, angle-resolved photoemission spectroscopy (ARPES) is the most direct method because an ARPES spectrum corresponds to the occupied part of the single-particle spectral function, $A(k, \omega; T) = (-1/\pi)\text{Im}G^R(k, \omega; T)$, where $G^R(k, \omega; T) = 1/[\omega - \omega_k^0 - \Sigma(k, \omega; T)]$ is the retarded Green's function. Along the nodal direction of cuprates, there is no energy gap opening even below the superconducting transition temperature. The ARPES spectra along the nodal direction, therefore, provide a direct probe to investigate many-body interactions that induce strange metal states and pair formations.

In cuprate superconductors, one of the well-known manifestations of the many-body interaction in the spectral function is the kink structure in the energy band dispersion (an abrupt change of the group velocity) that appears from ~ 100 meV to ~ 20 meV below the Fermi level (E_F) [22–25]. Several attempts have been made to extract the Eliashberg function by analyzing the low-energy kink (LEK) in high-resolution ARPES spectra [26,27]. The extracted Eliashberg function showed prominent peaks around ~ 80 meV and ~ 40 meV below the E_F , and they were assumed to correspond to the in-plane breathing phonon and the out-of-plane buckling phonon modes (B_{1g}), respectively [23,24]. Note that the buckling phonon and magnetic resonance modes [28] are overlapped in this energy range [24], and the origin of the LEK is still under debate. We should also note that a single-electron band or noninteracting band assumed in the line shape analyses in the energy range of ~ 100 meV below the E_F is arbitrary in most cases.

In the wide energy range, on the other hand, a significant suppression of the ARPES spectral intensity, so-called a high-energy anomaly (HEA) or waterfall-like spectral feature has been reported [29–31]. The HEA has been explained in terms of the coupling to the magnetic excitation or electron correlation effects [32–35]. However, as the real and imaginary parts of the self-energy in the wide energy scale have not been experimentally revealed so far, the origin of the HEA remains elusive. Note that the self-energy for the HEA influences the single-electron band (or noninteracting band) assumed in the analysis of the LEK. Absolute magnitudes of the coupling parameters at the E_F , which is closely connected to the T_c , remain uncertain because the self-energy responsible for the HEA is unclear.

One of the most drastic changes of the spectral function is the superconducting gap opening below T_c that is represented by an anomalous self-energy [36,37]. Various attempts have been made to separate the normal and anomalous self-energies

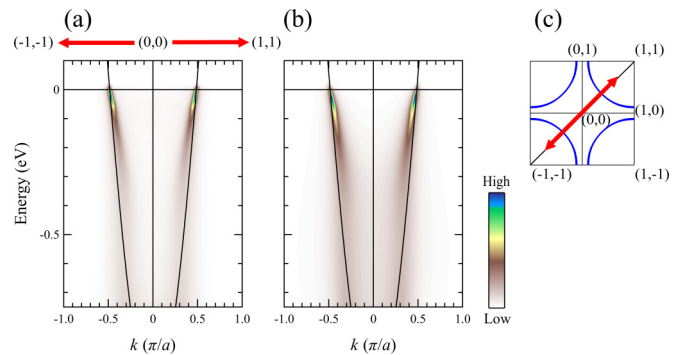


FIG. 1. (a) ARPES spectra of Pd-doped Bi2201 along the nodal direction taken at $h\nu = 22$ eV and at the temperature of $T = 100$ K. The wavenumber k is in the unit of π/a , where a is the lattice constant of CuO_2 plane. The ARPES image is symmetrized with respect to the Γ point. (b) The simulated ARPES intensity plot using the evaluated $\Sigma_{\text{HEA}}(\omega)$. Solid lines in (a) and (b) indicate the single-electron band used in the present analysis. (c) The Brillouin zone and the Fermi surface (blue lines) calculated using the tight-binding model. Here the wavenumber is in the unit of π/a . Red arrow indicates the nodal direction.

by model fittings [38], and machine learning techniques [39], but the energy range of these analyses have been limited near the E_F . To evaluate the anomalous self-energy below T_c , it is essential to determine the normal self-energy over a wide energy range using a reasonable method.

Here, we evaluate the normal self-energy of cuprates in the wide energy range along the nodal direction by means of high-resolution ARPES experiments. We investigate the origin of the interaction that forms the HEA and quantitatively clarify the unusual temperature-dependent enhancement of the self-energy part responsible for the LEK. As a suitable system for this study, we have selected the heavily overdoped Bi-based cuprate, Pb-Bi2201, which has a single CuO_2 plane in the unit cell and hence the interaction between CuO_2 planes is negligible. The low T_c (~ 6 K) allows us to evaluate the normal self-energy at low temperature by suppressing the thermal broadening. In addition, the Pb doping suppresses the structural modulations of the BiO plane and hence the superstructure reflections in the ARPES spectra.

In this study, we have developed a method that allows us to extract the self-energy over a wide energy range by ensuring the Kramers-Kronig (K-K) relation between the real and imaginary parts of the experimentally determined self-energy. We show that the self-energy inducing the HEA is weakly temperature dependent and plays a major role in the effective mass enhancement even at 300 K. It clearly indicates strongly correlated nature of electrons in the normal state or strange metal state. On the other hand, we found an unusual temperature dependence in the self-energy part responsible for the LEK: it is enhanced significantly below ~ 150 K. This temperature dependence cannot be explained solely by the self-energy due to the electron-phonon interaction based on the temperature-independent Eliashberg function. Our results provide insight into the strange metal state as well as the origin of the superconductivity in cuprates.

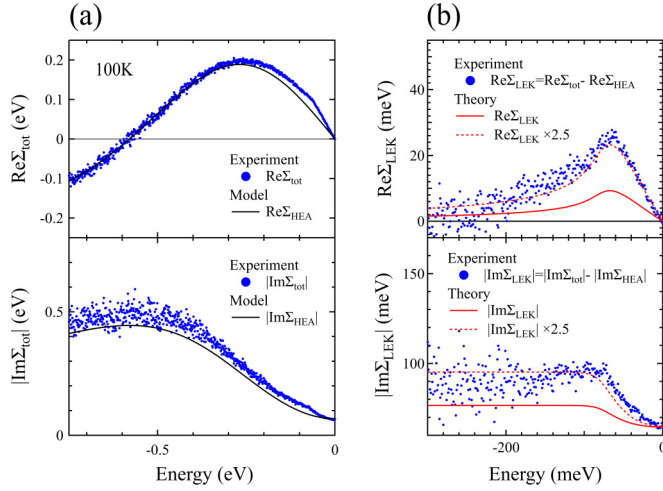


FIG. 2. (a) Circles in top and bottom panels, respectively, show experimentally evaluated $\text{Re}\Sigma_{\text{tot}}(\omega)$ and $|\text{Im}\Sigma_{\text{tot}}(\omega)|$ in the wide energy range at 100 K. Lines in top and bottom panels show $\text{Re}\Sigma_{\text{HEA}}(\omega)$ and $|\text{Im}\Sigma_{\text{HEA}}(\omega)|$ that best explain experimental results. (b) Circles in top and bottom panels, respectively, show $\text{Re}\Sigma_{\text{LEK}}(\omega) = \text{Re}\Sigma_{\text{tot}}(\omega) - \text{Re}\Sigma_{\text{HEA}}(\omega)$ and $|\text{Im}\Sigma_{\text{LEK}}(\omega)| = |\text{Im}\Sigma_{\text{tot}}(\omega)| - |\text{Im}\Sigma_{\text{HEA}}(\omega)|$. $\text{Re}\Sigma_{\text{LEK}}(\omega)$ and $|\text{Im}\Sigma_{\text{LEK}}(\omega)|$ are responsible for the LEK near the E_F . Red lines in top and bottom panels show theoretical $\text{Re}\Sigma_{\text{LEK}}(\omega; T = 100 \text{ K})$ and $|\text{Im}\Sigma_{\text{LEK}}(\omega; T = 100 \text{ K})|$ calculated using the Eliashberg function ($\alpha^2 F(\tilde{\omega})$) [25]. The dashed lines in (b) show theoretical $\text{Re}\Sigma_{\text{LEK}}(\omega)$ and $|\text{Im}\Sigma_{\text{LEK}}(\omega)|$ multiplied by 2.5. The experimentally determined coupling parameter as determined by the gradient of $\text{Re}\Sigma_{\text{LEK}}(\omega)$ at E_F was $\lambda \sim 0.4$ at 100 K.

Figure 1(a) shows the ARPES intensity plots along the nodal direction of Pb-Bi2201 taken at the photon energy of $h\nu = 22 \text{ eV}$ ($T = 100 \text{ K}$) [40]. Here, we have symmetrized the ARPES intensity with respect to $k = 0$ to minimize the matrix element effects. One can clearly see the HEA below $\omega \sim -0.3 \text{ eV}$. In order to perform the analysis assuming single $d_{x^2-y^2}$ band, we have restricted the energy range between the E_F and -0.7 eV because there exists additional bands derived from d_{xz} , d_{yz} , $d_{3z^2-r^2}$ bands below $\omega \sim -0.8 \text{ eV}$ [31,41]. The multiband effects such as the hybridization gap should be taken into account near the band bottom region.

Figure 2(a) shows evaluated $\text{Re}\Sigma_{\text{tot}}(\omega)$ and $|\text{Im}\Sigma_{\text{tot}}(\omega)|$ [40]. The K-K relation between the evaluated $\text{Re}\Sigma_{\text{tot}}(\omega)$ and $\text{Im}\Sigma_{\text{tot}}(\omega)$ was confirmed referring to the real and imaginary parts of the model $\Sigma_{\text{HEA}}(\omega) = \frac{g\omega}{(\omega - \xi + i\eta)(\omega + \xi + i\eta)}$ [solid lines in Fig. 2(a)] together with the theoretical Σ_{LEK} in Fig. 2(b), which will be discussed below [40]. Here we have employed $\omega_k^0 = \frac{\omega_B}{1-\alpha} \{[(\frac{k}{k_F})^2 - 1] - \alpha[(\frac{k}{k_F})^4 - 1]\}$ for a single-electron band, and the parameters were determined to be $\omega_B = -1.09 \pm 0.02 \text{ eV}$ and $\alpha = 0.12 \pm 0.01$ [40]. On the other hand, the parameters for the model self-energy were determined to be $g = 0.37 \pm 0.03 \text{ eV}$, $\xi = 0.31 \pm 0.03 \text{ eV}$, and $\eta = 0.49 \pm 0.05 \text{ eV}$. Details of the ARPES line shape analysis and the functional form of the self-energy part for the HEA and LEK are described in Supplemental Material [40].

It is clear that $\text{Re}\Sigma_{\text{tot}}(\omega)$ takes a maximum value around $\omega \sim -0.3 \text{ eV}$ and crosses zero point around $\omega \sim -0.6 \text{ eV}$, where $|\text{Im}\Sigma_{\text{tot}}(\omega)|$ takes maximum. The relevance of the

evaluated self-energy can be confirmed by the simulated ARPES intensity plot using $\Sigma_{\text{HEA}}(\omega)$ in Fig. 1(b), which reasonably reproduces the experimental one.

Next, we consider the origin of the HEA using the obtained parameters. The zero-point energy for $\text{Re}\Sigma_{\text{HEA}}(\omega)$ is determined by $\omega_0 = -\sqrt{\xi^2 + \eta^2}$, namely, both the characteristic excitation energy (ξ) and the scattering strength (η) contribute to the zero-point energy [40]. As the lifetime broadening $\eta = 0.49 \text{ eV}$ ($\sim 1.6 \xi$) is larger than excitation energy $\xi = 0.31 \text{ eV}$, the excited state is strongly damped, and the zero point energy can be expressed as $\omega_0 = -\sqrt{\xi^2 + \eta^2} \sim -2\xi \sim -0.6 \text{ eV}$.

According to the t - J model calculation, the HEA [or the minimum of $\text{Im}\Sigma(\omega)$] exists at the energy of $|\omega| \sim (2-3) \times J$, which is not strongly dependent on doping and temperatures [35]. In our study, as the maximum of $|\text{Im}\Sigma_{\text{tot}}(\omega)|$ exists at $|\omega| \sim 2\xi \sim 0.6 \text{ eV}$, we may assume $2\xi \sim (2-3)J$ and $J \sim 0.2-0.3 \text{ eV}$. On the other hand, the dynamical cluster quantum Monte Carlo calculations of the one-band two-dimensional Hubbard model indicated that the $\text{Im}\Sigma(\omega)$ takes minimum at $|\omega| \sim 3t = 6J$ [32]. Referring to our experimental value, we may assume $|\omega| \sim 2\xi \sim 3t = 6J \sim 0.6 \text{ eV}$, $t \sim 0.2 \text{ eV}$, and $J \sim 0.1 \text{ eV}$. Note that the ARPES spectral features can be captured by a renormalized second-order approximation to the self-energy in which the quasiparticles couple only to spin fluctuations [32].

Meanwhile, the self-energy calculation based on the electron-paramagnon interaction [34] indicates that the minimum of $\text{Im}\Sigma(\omega)$ exists around $|\omega| \sim 0.3 \text{ eV}$, which is smaller than our results $|\omega| \sim 0.6 \text{ eV}$. In the calculation [34], the lifetime broadening was underestimated because the scattering effects beyond the paramagnons were not taken into account. If we assume $\eta \rightarrow 0$ in our model $\Sigma_{\text{HEA}}(\omega)$, the zero-point energy is closer to $|\omega_0| = \sqrt{\xi^2 + \eta^2} \rightarrow \xi \sim 0.3 \text{ eV}$. Note also the energy of 0.3 eV agrees with the maximum energy of the magnon spectrum [34,42].

Dynamical mean-field theory (DMFT) calculations for strongly correlated systems indicate that the k -averaged energy-dependent hybridization function generally induces kinks in the slope of the band dispersion and forms a three-peak spectral function [33]. The middle peak corresponds to the Fermi liquid regime centered at the E_F , while the outer two peaks correspond to the lower and upper Hubbard bands [33]. It is consistent with our assumption separating the self-energy responsible for the HEA and LEK regimes. Furthermore, the functional form of the self-energy given in the DMFT [33] qualitatively reproduces our experimentally deduced self-energy in Fig. 2(a).

Based on the comparison with these theoretical studies, we assume that the origin of the self-energy responsible for the HEA is derived from the local excitation due to the many-body interactions, and its energy scale can be characterized by J (source of spin fluctuation) or t (source of charge fluctuation) depending on the theoretical model.

In Fig. 2(b) we show the real part and imaginary part of the self-energy responsible for the LEK by subtracting $\text{Re}\Sigma_{\text{HEA}}(\omega)$ and $|\text{Im}\Sigma_{\text{HEA}}(\omega)|$ of the model function from the $\text{Re}\Sigma_{\text{tot}}(\omega)$ and $|\text{Im}\Sigma_{\text{tot}}(\omega)|$. To confirm the K-K relation, we employed the reported Eliashberg function due to the electron-phonon interaction [25] and calculated theoretical

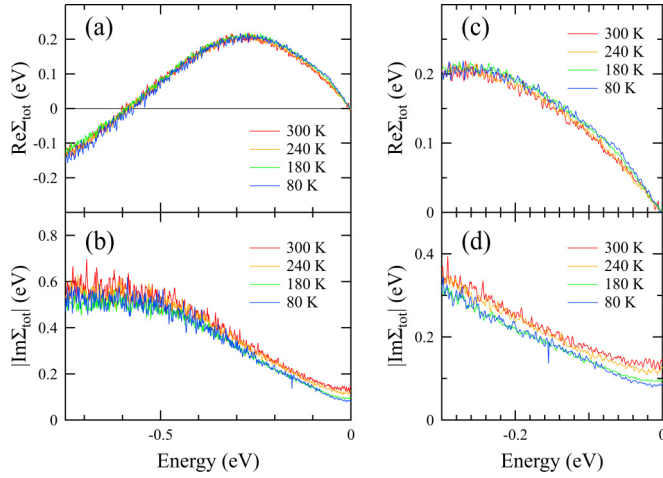


FIG. 3. Temperature dependence of experimental $\text{Re}\Sigma_{\text{tot}}(\omega; T)$ in the wide energy range (a) and near the E_F (c). Temperature dependence of experimental $|\text{Im}\Sigma_{\text{tot}}(\omega; T)|$ in the wide energy range (b) and near the E_F (d). The self-energy in the wide energy range responsible for the HEA does not show significant temperature dependence. The zero point in $\text{Re}\Sigma_{\text{tot}}(\omega; T)$ is persistent up to 300 K.

real and imaginary parts of the self-energy at the temperature of 100 K [40]. The magnitude of calculated real and imaginary parts of the self-energy [solid lines in Fig. 2(b)] are, however, smaller than the experimental ones. If we multiply a factor of 2.5, the theoretical real and imaginary parts of the self-energy reproduce the experimental ones reasonably well. A good agreement between experiment and theory guarantees the K-K relation between the experimental real and imaginary parts of the self-energy part responsible for the LEK. The electron-phonon coupling parameter evaluated from the gradient of the experimental $\text{Re}\Sigma_{\text{LEK}}(\omega)$ is $\lambda_{\text{LEK}} \sim 0.4$ at 100 K, which is larger than the coupling parameter expected from the Eliashberg function, $\lambda_{\text{LEK}} \sim 0.16$ [25], as well as the result of the DFT calculation, $\lambda_{\text{DFT}} \sim 0.14\text{--}0.20$ [43].

To clarify the discrepancy in the magnitude of the theoretical and experimental self-energy for the LEK, we examined the temperature dependence of the self-energy. Figure 3(a) [3(b)] shows $\text{Re}\Sigma_{\text{tot}}(\omega; T)$ [$|\text{Im}\Sigma_{\text{tot}}(\omega; T)|$] at 80 K, 180 K, 240 K, and 300 K. One can see that the experimental self-energy in the wide energy range remains almost unchanged in agreement with the t - J model calculation [35]. As the gradient near the E_F remains high even at 300 K, the electronic states are strongly correlated in the normal state of heavily overdoped Pb-Bi2201. On the other hand, one can clearly see a temperature dependence of the gradient of $\text{Re}\Sigma_{\text{tot}}(\omega; T)$ in Fig. 3(c) and smearing of the depletion above -0.1 eV in $|\text{Im}\Sigma_{\text{tot}}(\omega; T)|$ near the E_F with increasing temperature in Fig. 3(d).

To see more detailed temperature dependence of the self-energy, we evaluated the temperature dependence of $\text{Re}\Sigma_{\text{tot}}(\omega; T)$ near the E_F by ARPES using ultraviolet laser as shown in Fig. 4(a). In Fig. 4(b) the total coupling parameter $\lambda_{\text{tot}}(T)$ (black circles) obtained from the gradient of $\text{Re}\Sigma_{\text{tot}}(\omega; T)$ near the E_F shows significant temperature dependence; it is $\lambda_{\text{tot}} \sim 1.1$ at 300 K and enhances up to

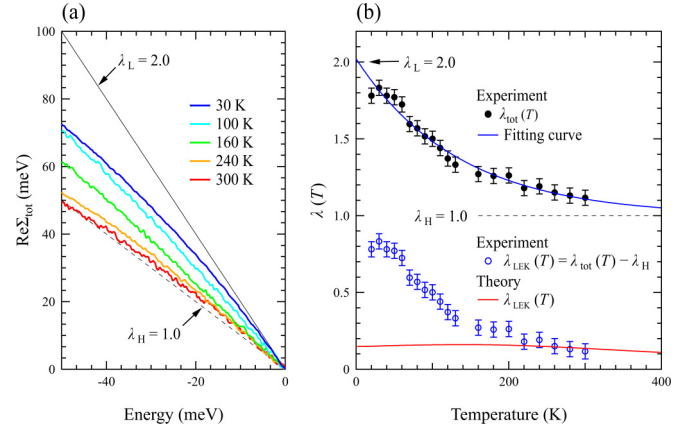


FIG. 4. (a) $\text{Re}\Sigma_{\text{tot}}(\omega; T)$ for some representative temperatures obtained from high-resolution ARPES using ultraviolet laser. Solid and dashed lines in black show the magnitude of the coupling parameters at $T = 0$ ($\lambda_L = 2.0$) and $T \rightarrow \infty$ ($\lambda_H = 1.0$) obtained from a fitting curve shown in (b). (b) The temperature dependence of the coupling parameter. Black circles indicate the experimental total coupling parameter, $\lambda_{\text{tot}}(T)$, evaluated from the gradient of experimental $\text{Re}\Sigma_{\text{tot}}(\omega; T)$ at the E_F in (a). The solid line in blue indicates a fitting curve for $\lambda_{\text{tot}}(T)$ in the form of $\lambda_0 e^{-T/T_0} + \lambda_H$. The obtained parameters are $\lambda_0 = 1.02$, $\lambda_H = 1.00$, and $T_0 = 134$ K. The fitting result indicates $\lambda_L = 2.0$ at $T = 0$, and $\lambda_H = 1.0$ at $T \rightarrow \infty$ (dashed line). Blue circles indicate $\lambda_{\text{LEK}}(T) \equiv \lambda_{\text{tot}}(T) - \lambda_H$, showing the temperature dependence of the experimental coupling parameter for the LEK. The solid line in red indicates the simulation of the temperature dependence of the coupling parameter $\lambda_{\text{LEK}}(T)$ using the Eliashberg function in Ref. [25]. The experimental and theoretical $\lambda_{\text{LEK}}(T)$ are found to coincide above ~ 200 K.

$\lambda_{\text{tot}} \sim 1.8$ at 20 K, leading to the effective mass enhancement of $1 + \lambda_{\text{tot}} \sim 3$.

To extract the temperature dependence in more detail, we have fitted $\lambda_{\text{tot}}(T)$ assuming a functional form of $\lambda_0 e^{-T/T_0} + \lambda_H$, and obtained parameters as $\lambda_0 = 1.02$, $\lambda_H = 1.00$, and $T_0 = 134$ K. The fitting curve in Fig. 4(b) shows $\lambda_L = 2.0$ at $T = 0$ and $\lambda_H = 1.0$ for $T \rightarrow \infty$.

As the self-energy responsible for the HEA, $\Sigma_{\text{HEA}}(\omega; T)$, does not show significant temperature dependence up to 300 K as shown in Figs. 3(a) and 3(b), the coupling parameter for $\Sigma_{\text{HEA}}(\omega; T)$ should be $\lambda_{\text{tot}} \sim \lambda_H \sim 1$. It indicates that the normal state or strange metal state of the heavily overdoped region is strongly correlated and dominated by the self-energy responsible for the HEA, namely the local excitation. Therefore, the dynamical properties of the strange metal state, hosting the superconducting puddle, should be reflected in the functional form of Σ_{HEA} .

Next, we compare the extracted $\lambda_{\text{LEK}}(T)$ with the theoretical one [red line in Fig. 4(b)] calculated using the Eliashberg function due to the electron-phonon interaction [25]. While the experimental coupling parameter $\lambda_{\text{LEK}} \sim 0.1$ is close to the theoretical one at 300 K, it rapidly increases up to ~ 0.8 at 20 K on cooling, deviating significantly from the theoretical calculation. We should note that our previous study on the temperature dependence of the electron-phonon coupling parameter for the free-electron-like surface state on Al(100) was almost perfectly explained by the Eliashberg function given by the DFT calculation [19], showing a marked contrast to

the present result. While the major peak around -70 meV in the real part of the self-energy part responsible for the LEK is likely derived from the coupling to the breathing mode of phonon [24], the DFT calculation [43] on the electron-phonon interaction cannot explain the enhanced magnitude of the coupling strength at low temperature. Note that the temperature dependence of the optical conductivity also indicated the temperature dependence of $\alpha^2 F(\tilde{\omega})$ in $\Sigma_{\text{LEK}}(\omega; T)$ [44] consistent with our observation.

Our results suggest an unexplored cooperative enhancement of the coupling parameters as temperature decreases, or the emergence of additional bosonic modes below ~ 150 K. For example, a temperature-dependent interplay between the electron-phonon interaction and the electron-spin fluctuation interaction can be considered. Theoretical calculations of spin fluctuations have indicated that the coupling parameter increases with decreasing temperature [45–47]. Furthermore, the B_{1g} mode (basis function: $x^2 - y^2$) of the spin fluctuation is favorable for the superconductivity [48], which is compatible with the symmetry of the Cu $3d_{x^2-y^2}$ orbital as well as the B_{1g} phonon mode. Note that the RIXS measurements indicated that magnons persist in the heavily overdoped metallic phase of LSCO [49,50].

Meanwhile, measurements of superfluid density and phase stiffness [10] revealed large phase fluctuations in real space in the overdoped region, and STM measurements confirmed the presence of superconducting puddles embedded in the strange metal state [14]. In this regard, proximity effects [13] and/or temperature-dependent phase fluctuations in the real space may affect the effective interaction between electrons on cooling.

In summary, using high-resolution ARPES spectra, we have evaluated the real and imaginary parts of the self-energy of heavily overdoped Pb-Bi2201 in the wide energy range

based on the Kramers-Kronig relation. The evaluated real part of the self-energy crosses the zero point around $\omega \sim -0.6$ eV, where the imaginary part of the self-energy takes the minimum. Comparing the theoretical results, the high-energy anomaly (HEA) is considered to originate from local excitations that are characterized by J (source of spin fluctuation) or t (source of charge fluctuation). The coupling parameter evaluated near the E_F is $\lambda_{\text{tot}} \sim 1$ at 300 K, indicating that the normal state is strongly correlated. Since Σ_{HEA} is dominant at 300 K, Σ_{HEA} should be responsible for the strongly correlated normal state, namely the strange metal state. As temperature decreases the coupling parameter significantly increases up to $\lambda_{\text{tot}} \sim 1.8$ at 20 K. While the coupling parameter for the HEA is almost temperature independent, the coupling parameter for the low-energy kink (LEK) showed significant temperature dependence; it is $\lambda_{\text{LEK}} \sim 0.1$ at 300 K and rapidly increases below ~ 150 K up to $\lambda_{\text{LEK}} \sim 0.8$ at 20 K. The temperature dependence cannot be explained by the theoretical calculation based on the temperature-independent Eliashberg function of the electron-phonon interaction. It suggests an unexplored mechanism to enhance the coupling parameter emerging from entangled many-body interactions. Our results give insight into the unusual strange metal state as well as the origin of the exotic superconductivity in cuprates.

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