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Temperature dependence of the coupling parameter in the strange metal state of heavily overdoped cuprate superconductor

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Since the discovery of high-transition-temperature (T_c) superconductivity in cuprates, unusual physical properties due to strong correlations in the underdoped to the optimally-doped region including the metal-insulator transition [1], pseudogap state, spin and charge ordering [2,3], have attracted much interest and extensive studies have been done to elucidate their correlation to the mechanism of the high- T_c. In contrast, the electronic states in the overdoped region have been regarded as the Fermi liquid. However, non-Fermi liquid like behaviors such as the strange metal state [4], ferromagnetic fluctuation [5], and charge order [6], have been discovered in the overdoped region, renewing scientific interests of cuprate superconductors.

These physical properties originate from many-body interactions arising from the complex entanglement of the internal degrees of freedom of spin, charge, lattice, and orbital, and their contributions are reflected in the self-energy. In this study, we have investigated the distinct energy scales in the self-energy, namely low-energy kink (LEK) and high-energy anomaly (HEA), in heavily overdoped Bi-based high-T_c cuprates, $(Bi,Pb)_2Sr_2CuO_{6+\delta}$ (Pb-Bi2201) using high-resolution angle-resolved photoemission spectroscopy (ARPES).

We experimentally extracted the self-energy (Σ_{tot}) based on the Kramers-Kronigh relation. By introducing the model function, we successfully reproduced the self-energy responsible for the HEA (Σ_{HEA}) and extracted the self-energy responsible for the LEK (Σ_{LEK}) by subtracting Σ_{HEA} from Σ_{tot}. Figure 1(b) shows the temperature dependence of the coupling parameter, $\lambda(T)$, determined from the gradient of the real part of the self-energy at the Fermi level, as shown in Fig.1(a). One can see that $\lambda_{\mathrm{tot}} \sim 1$ at 300 K, indicating that the normal state is strongly correlated. Since Σ_{HEA} is dominant at 300 K, Σ_{HEA} should correspond to the self-energy in the strange metal state. On the other hand, we found that $\lambda_{\mathrm{LEK}}(T) = \lambda_{\mathrm{tot}}(T) - \lambda_{\mathrm{HEA}}$ deviates from the theoretical calculation based on the temperature-independent Eliashberg function of the electron-phonon interaction [7], revealing that the LEK is remarkably enhanced at low temperatures. 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.

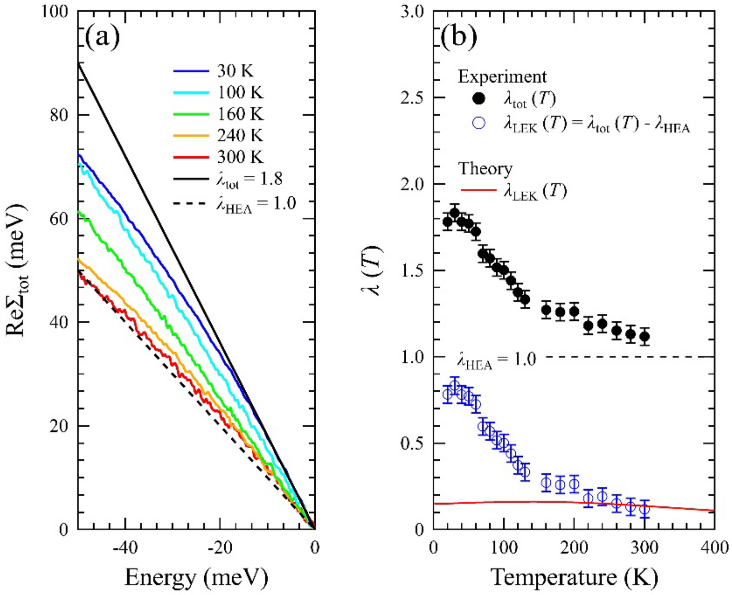

Figure 1 (a) The real part of the self-energy, $\mathrm{Re}\Sigma_{\mathrm{tot}}(\omega)$, for some representative temperatures. Black solid line indicates the magnitude of the coupling parameter calculated from $\mathrm{Re}\Sigma_{\mathrm{tot}}(\omega)$ at 300 K, while the black dashed line corresponds to the real part of the model self-energy for HEA, $\mathrm{Re}\Sigma_{\mathrm{HEA}}(\omega)$. (b) The temperature dependence of the coupling parameter. Black and blue dots indicate the total coupling parameter, $\lambda_{\mathrm{tot}}(T)$, and the coupling parameter for the LEK, $\lambda_{\mathrm{LEK}}(T) = \lambda_{\mathrm{tot}}(T) - \lambda_{\mathrm{HEA}}$, respectively, where λ_{HEA} denotes the coupling parameter for the HEA (black dashed line). The red curve shows the theoretical temperature dependence of the coupling parameter for LEK using the Eliashberg function in Ref.[7].

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