Doping dependence of scattering rate for linear-in-temperature resistivity in cuprate superconductors

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The origin of the linear-in-temperature (T-linear) resistivity in cuprate superconductors remains a profound mystery in condensed matter physics. Here, we investigate the dependence of the T-linear resistivity coefficient on doping, i.e., $A_1(p)$, for three typical regions in the temperature versus doping phase diagram of hole-doped cuprates, from which the doping dependence of the scattering rate, i.e., $\alpha_1(p)$, is further derived. It is found that for region I ($p < p^*$ and $T > T^*$), $\alpha_1(p)$ is almost a constant; for region II ($p > p^*$ and $T > T_{\rm coh}$), $\alpha_1(p) \propto p$; for region III ($p > p^*$ and $T < T_{\rm coh}$), $\alpha_1(p) \propto p(p_c - p)$, where T^* is the onset temperature of the pseudogap phase, p^* indicates the doping at which T^* goes to zero, $T_{\rm coh}$ marks the onset of antinodal quasiparticle coherence, and $p_{\rm c}$ is the doping where the low-temperature linear behavior in the overdoped regime vanishes. Moreover, the deduced $\alpha_1(p)$ relations are verified with the experimental data from previous reports. The discovered scattering rate versus doping relationship will shed light on the scattering mechanism underlying the T-linear resistivity in cuprate superconductors.

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I. INTRODUCTION

Deciphering the scattering mechanisms underlying the transport behaviors of materials is a fundamental and essential question in condensed matter physics [1,2]. One effective approach is to study the evolution of the scattering rate γ of charge carriers, which is inversely proportional to the relaxation time τ, across the material phase diagram [3,4]. Generally, the scattering rate could be expressed as

$$\gamma \propto f(T)g(n), \tag{1}$$

where $f(T)$ and $g(n)$ are functions of temperature T and carrier density n, respectively. For instance, when electron-phonon interactions dominate the transport in isotropic metals, it is expected that $f(T) \propto T$ above the Debye temperature and $g(n) \propto N[E_{\rm F}(n)]$ with $N(E_{\rm F})$ the density of states at the Fermi energy $E_{\rm F}$ [5]. For electron-electron scatterings, Landau's Fermi-liquid theory provides $f(T) \propto T^2$ and $g(n) \propto [E_{\rm F}(n)]^{-1}$ [3]. It is obvious that, besides the commonly concerned temperature dependence, the carrier-density dependence of the scattering rate is also crucial to determine the scattering mechanism.

Since the discovery of high-$T_{\rm c}$ superconductivity in cuprates [6], their mysterious transport properties in the normal state have been the subject of intensive research [7,8]. A particularly puzzling example is the linear-in-temperature (T-linear) resistivity over a large temperature range. On one hand, the resistivity can be linear up to a temperature as high as measured [9,10], exceeding the Mott-Ioffe-Regel limit [11]. On the other hand, the linear dependence can persist down to the lowest experimentally accessible temperature [12,13], often termed as "strange metals." It is universally acknowledged that the scattering mechanism underlying the T-linear resistivity is intimately connected with high-$T_{\rm c}$ superconductivity [7,14]. However, the scattering rate versus carrier density in the T-linear regimes has not yet been systematically investigated.

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II. T-LINEAR RESISTIVITY OF CUPRATE SUPERCONDUCTORS

To address this, we explore the carrier-density dependence of scattering rate for the T-linear resistivity across the phase diagram of hole-doped cuprate superconductors. As shown in Fig. 1, a schematic temperature versus doping p phase diagram is depicted, following previous transport studies by

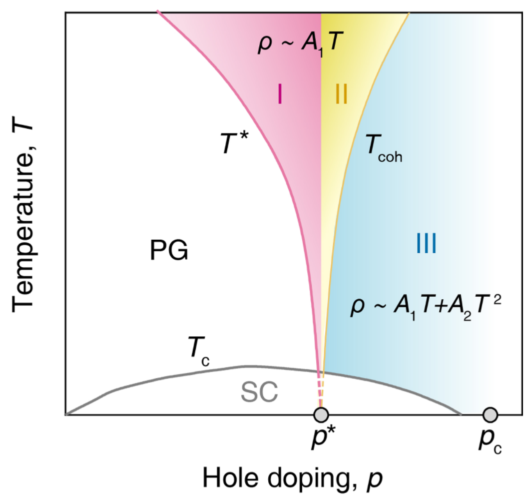

FIG. 1. Schematic temperature vs hole doping phase diagram of cuprates. T_c and T^* refer to the onset temperature of the superconducting (SC) phase and the pseudogap (PG) phase, respectively. p^* ($\approx$0.19) indicates the doping at which T^* goes to zero. The purely T-linear resistivity is observed in the funnel-shaped region opening up from p^*, which can be divided into region I ($p < p^*$ and $T > T^*$, indicated in magenta) and region II ($p > p^*$ and $T > T_{coh}$, indicated in yellow). For region III ($p > p^*$ and $T < T_{coh}$, indicated in blue), the resistivity is found to be composed of both T and T^2 terms, of which the former vanishes at p_c ($\approx$0.31).

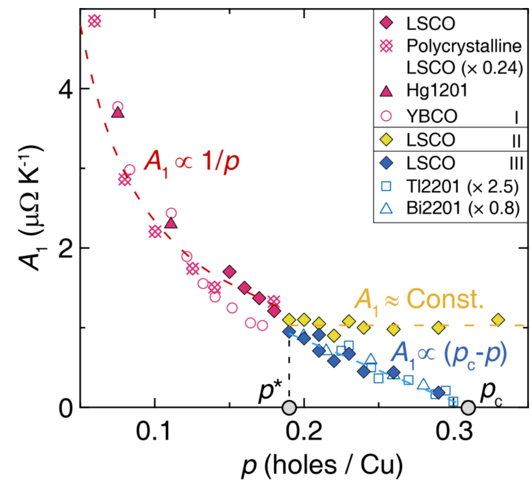

FIG. 2. Doping dependence of the T-linear resistivity coefficient in hole-doped cuprates. The A_1 data were obtained by fitting the resistivity vs temperature curves. For region I, the data of $La_{2-x}Sr_xCuO_4$ (LSCO) [12], polycrystalline LSCO, $HgBa_2CuO_{4+\delta}$ (Hg1201), and $YBa_2Cu_3O_{7-\delta}$ (YBCO) [22] are in accordance with $A_1 \propto 1/p$ (the magenta dashed line). For region II, the A_1 of LSCO [15] is insensitive to doping (the yellow dashed line). For region III, the data of LSCO [12], $Tl_2Ba_2CuO_{6+\delta}$ (Tl2201), and (Pb/La)-doped $Bi_2Sr_2CuO_{6+\delta}$ (Bi2201) [24] can be fitted with $A_1 \propto (p_c - p)$ (the blue dashed line). The data for polycrystalline LSCO, Tl2201, and Bi2201 are rescaled by factors of 0.24, 2.5, and 0.8, respectively.

Hussey *et al* [15]. With an increase of the doping level, the superconducting (SC) phase emerges as a dome shape below the critical temperature T_c. The opening temperature of the pseudogap (PG) T^* [16] cuts the top of the SC dome and tends to zero at p^* ($\approx$0.19). The coherent temperature T_{coh}, which marks the onset of antinodal quasiparticle coherence, appears beyond p^* [17,18]. For $p < p^*$ and $T > T^*$ (labeled as region I), the in-plane resistivity exhibits a T-linear dependence, i.e.,

$$\rho_{ab} = \rho_0 + A_1 T, \tag{2}$$

where ρ_0 is the residual resistivity and A_1 is the coefficient of the T-linear term [19]. Beyond p^*, the purely T-linear behavior persists for $T > T_{coh}$ (region II), while the resistivity for $T < T_{coh}$ (region III) is found to be fitted to $\rho_{ab} = \rho_0 + A_1 T + A_2 T^2$ with A_2 the coefficient of the quadratic term [12,20–22]. Note that the low-temperature linear term extends over a wide doping range and vanishes at a critical doping p_c ($\approx$0.31) [23,24]. The T-linear components of resistivity in these three regions are the focus of this paper. According to the Drude model, the resistivity is expressed as

$$\rho = 4\pi\omega_p^{-2}\gamma, \tag{3}$$

where ω_p ($\propto\sqrt{n/m^*}$ with m^* the effective mass of charge carriers) is the plasma frequency. As the temperature is much less than the chemical potential, a strong temperature dependence of ω_p would be unnatural [25]. This implies that the scattering rate γ governs the temperature dependence of resistivity, as discussed in Refs. [26,27]. Thus, for the T-linear resistivity, $f(T) \propto T$ [see Eq. (1)], and $g(n)$ is proportional to the T-linear coefficient of scattering rate, defined as

$$\alpha_1 \equiv \gamma/T. \tag{4}$$

Then it could be deduced from Eqs. (2)–(4) that

$$\alpha_1 = (4\pi)^{-1}\omega_p^2 A_1 \propto (n/m^*)A_1. \tag{5}$$

A recent optical study by van Heumen *et al.* [26] demonstrates that the Drude weight n/m^* is proportional to the doping p across the phase diagram, which points to $n \propto p$ assuming that m^* is doping independent. In light of these, Eq. (5) could be rewritten as

$$\alpha_1(p) \propto pA_1(p), \tag{6}$$

which allows us to track the scattering rate versus carrier density for the T-linear resistivity in cuprates.

III. DOPING DEPENDENCE OF SCATTERING RATE FOR T-LINEAR RESISTIVITY

Figure 2 shows the dependences of A_1 on p for the three regions in Fig. 1, of which the data are collected from various cuprate systems. Notably, the $A_1(p)$ relation in each region is universal, despite substantial differences of the tested materials, indicating a common mechanism responsible for the T-linear resistivity. In region I, A_1 decreases rapidly with increasing p, and is, to a good approximation, proportional to the inverse doping, i.e., $A_1 \propto 1/p$ [22]. In region II, A_1 attains a constant value [15], strikingly different from the doping dependence in region I. In region III, A_1 decreases faster than $1/p$, and the data could be fitted to $A_1 \propto (p_c - p)$ with $p_c \approx 0.31$ [23]. Intriguingly, the linear dependence of A_1 on p has also been uncovered in the overdoped regime of the electron-doped cuprates $La_{2-x}Ce_xCuO_4$ by a composition-spread film fabrication technique [28]. It is noteworthy that

TABLE I. Range, doping dependence of the T-linear resistivity coefficient, and doping dependence of the T-linear scattering rate coefficient for three regions in Fig. 1. Definitions of p^*, T^*, $T_{\rm coh}$, and p_c could be found in Fig. 1.

	Range	$A_1(p)$	$\alpha_1(p)$
I	$p < p^*$ and $T > T^*$	$1/p$	const
II	$p > p^*$ and $T > T_{\rm coh}$	const	p
III	$p > p^*$ and $T < T_{\rm coh}$	$p_c - p$	$p(p_c - p)$

the high-temperature and low-temperature A_1 merge at p^*. Nonetheless, this does not imply that the scattering mechanisms in different temperature regions are identical at this critical doping, as unveiled by the thermal diffusivity measurements [29]. Table I displays the functional expressions of $A_1(p)$ for three regions. This is a summary of $A_1(p)$ for different T-linear regimes across the phase diagram of hole-doped cuprates. With the $A_1(p)$ relations, the dependences of α_1 on p are further obtained according to Eq. (6), which are also listed in Table I.

In order to verify the derived $\alpha_1(p)$ relations, we extract α_1 from the experimental data in the literature, shown in Fig. 3. For $p < p^*$, a previous study on underdoped YBCO has shown that the high-temperature A_1^{-1} tracks closely with the ω_p^2 [30], thus the value of α_1 calculated using Eq. (5) is nearly doping independent [Fig. 3(a)]. The high-temperature scattering rate data of Pr-doped $YBa_2Cu_3O_{7-\delta}$ (Pr-YBCO), (Y/Pb)-doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Y/Pb-Bi2212) have been obtained by tracing the Drude width of the optical conductivity [31], and the corresponding α_1 also exhibits weak doping dependence [Fig. 3(a)]. These results are in line with the constant $\alpha_1(p)$ of region I, which is also observed in the transition metal oxides [32,33]. For $p > p^*$, the temperature dependence of scattering rate of (Pb/La)-doped $Bi_2Sr_2CuO_{6+\delta}$ (Pb/La-Bi2201) has been systematically measured by optical methods [26], enabling us to extract the α_1 in different temperature regions using Eq. (4). It is found that α_1 of high temperatures ($T > 250$ K) satisfies the $\alpha_1(p) \propto p$ relation of region II [Fig. 3(b)], and α_1 of low temperatures ($T_c < T < 100$ K) coincides with the $\alpha_1(p) \propto p(p_c - p)$ relation of region III [Fig. 3(c)]. Figure 3(c) involves the low-temperature α_1 of heavily overdoped Tl2201 inferred from transport data [34], which also shows a good agreement with the expected $\alpha_1(p) \propto p(p_c - p)$ relation.

IV. DISCUSSIONS

Overall, the experimental data measured on various cuprate systems by different techniques are consistent with the deduced $\alpha_1(p)$ relations in Table I. This implies that the $A_1(p)$ relations obtained from Fig. 2 are persuasive and the premises of Eq. (6) are rational. In particular, the $n/m^* \propto p$ assumption accords with the experimental observations that the optical carrier density varies almost linearly with doping and the effective mass enhancement is doping independent [35,36]. It is worth mentioning that $n \propto p$ throughout the phase diagram is in stark contrast with the sudden slope change of $n(p)$ around p^* obtained by Hall effect measurements [19,24]. However, the $\alpha_1(p)$ relation obtained from the Hall number provides a

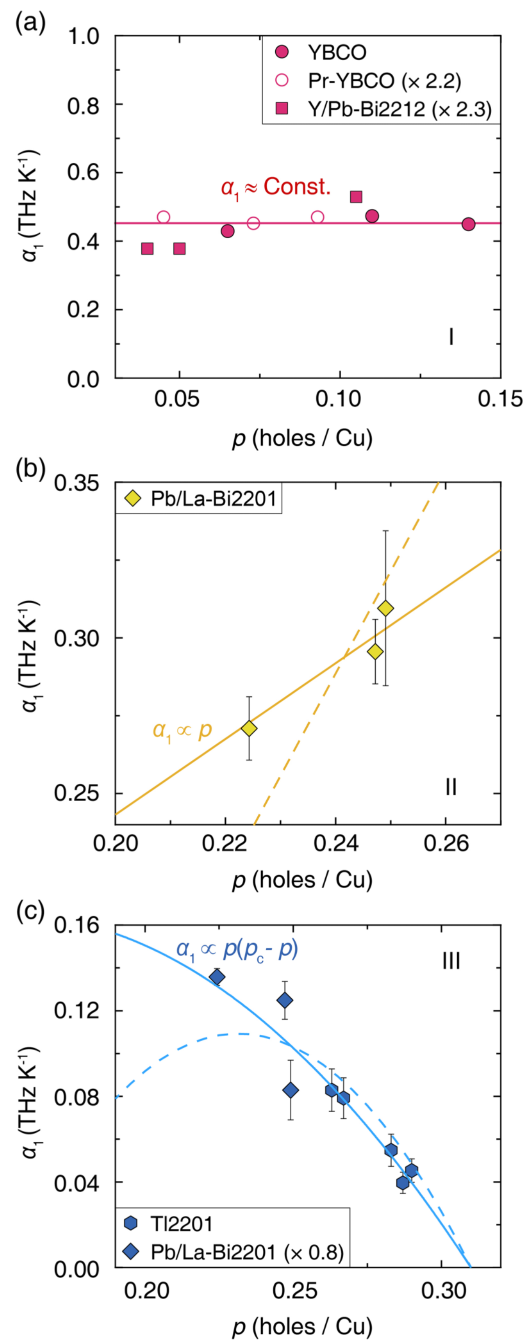

FIG. 3. Evolution of the T-linear scattering rate coefficient with doping for (a) region I, (b) region II, and (c) region III. The data of YBCO are calculated using Eq. (5), where ω_p^2 was extracted from the optical conductivity spectra [30,37]. The data of Pr-doped $YBa_2Cu_3O_{7-\delta}$ (Pr-YBCO), (Y/Pb)-doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Y/Pb-Bi2212) [31], and (Pb/La)-doped $Bi_2Sr_2CuO_{6+\delta}$ (Pb/La-Bi2201) [26] are extracted by fitting the reported Drude width vs temperature curves to a linear function. The data of Tl2201 are calculated using the average value of the momentum-dependent scattering rate, obtained by the angle-dependent magnetoresistance [34] and the quantum oscillation [38] measurements. The solid lines are the best fits of the data to the $\alpha_1(p)$ relations shown in Table I. The dashed lines are the fits to $\alpha_1(p)$ relations obtained with the Hall number $n = 10.08p - 1.54$ [23]. The data for Pr-YBCO, Y/Pb-Bi2212, and Pb/La-Bi2201 in (c) are rescaled by factors of 2.2, 2.3, and 0.8, respectively.

worse fit to the available data, as shown by the dashed lines in Figs. 3(b) and 3(c). The discrepancy may be attributed to that the Hall coefficient does not directly reveal the carrier density in some cases, as discussed in Ref. [26].

Moreover, the good fits in Fig. 3 indicate that the $\alpha_1(p)$ relationship summarized in Table I captures the intrinsic doping dependence of scattering rate, which helps us to understand the T-linear resistivity in cuprates. Regions I and II seem to be located in one quantum critical region associated with p^*, but they exhibit different $\alpha_1(p)$ relations. This suggests a switch of scattering mechanism upon doping, which contrasts with the scenario that the funnel-shaped region in Fig. 1 is dominated by quantum critical fluctuations [14,39,40]. Interestingly, for region I, the recent resonant inelastic x-ray scattering experiment shows a clear correlation between the charge order and the T-linear resistivity [41]; for region II, the scattering of electrons by classical phonons has been detected by the thermal transport [29]. However, whether such mechanisms are compatible with the $\alpha_1(p)$ relations uncovered in this paper remains to be discussed.

Region III, the so-called strange-metal regime [42], displays the T-linear resistivity at low temperatures, in sharp contrast with the T^2 dependence in conventional metals. Importantly, the T-linear resistivity in this region is intimately connected with the unconventional superconductivity in cuprates [8,39]. It has been observed that A_1 scales with T_c in the strange-metal regime [20,43,44]. Recently, a quantitative relation of $T_c \sim A_1^{0.5}$ has been revealed through the combinatorial material engineering [28]. Furthermore, A_1 is found to be correlated with the zero-temperature superfluid density, a key parameter determining the properties of superconducting state [45–47]. These results strongly suggest that the interaction causing the strange-metal transport is also involved in the superconducting pairing [48].

Despite enormous theoretical efforts over the past decades (see, e.g., Refs. [45,49,50] and references therein), the mechanism underlying the strange metallicity is still hotly debated. One conjecture drawing much attention is that the scattering rate obeys the so-called Planckian limit [51–54], i.e., $\hbar/\tau = \alpha k_B T$, where α is a constant of order unity, $\hbar$ is the reduced Planck constant, and k_B is the Boltzmann constant. In an attempt to prove this empirical relation, a universal $\alpha \approx 1$ was obtained by assuming the scattering rate is doping independent [55], which is oversimplified since our finding explicitly points out that α $(=\hbar\alpha_1/k_B)$ rapidly decreases with doping [see Fig. 3(c)]. Hence, whether, where, and why the Planckian limit exists require future studies. Moreover, a very recent work proposed a theory of strange metals from spatially random Yukawa interactions [56]. We emphasize that any theoretical model put forward to explain the strange-metal behavior should account for the $\alpha_1(p) \propto p(p_c - p)$ relation, which unveils a scattering rate that fades away with increasing the doping level and vanishes at $p_c \approx 0.31$.

V. CONCLUSION

In summary, we explore the dependence of the T-linear resistivity coefficient on doping for three typical regions in the phase diagram of hole-doped cuprates, from which the doping dependence of the scattering rate is derived. Further, the scattering rate versus doping relations are confirmed with the optical and transport data in previous reports. Such relations place a different constraint on the development of theoretical models proposed to explain the T-linear resistivity in cuprate superconductors.

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