Spontaneous nemaitc transition within the pseudogap state in cuprates

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Overshadowing the superconducting dome in hole-doped cuprates, the pseudogap state is still one of the mysteries that no consensus can be achieved. It has been shown that the rotational symmetry is broken in this state and may result in a nematic phase transition, whose temperature seems to coincide with the onset temperature of the pseudogap state \( T^* \) around optimal doping level, raising the question whether the pseudogap is resulted from the establishment of the nematic order. Here we report results of resistivity measurements under uniaxial pressure on several hole-doped cuprates, where the normalized slope of the elastoresistivity \( \zeta \) can be obtained as illustrated in iron-based superconductors. The temperature dependence of \( \zeta \) along particular lattice axes exhibits kink feature at \( T_n \) and shows Curie-Weiss-like behavior above it, which suggests a spontaneous nematic transition. While \( T_n \) seems to be the same as \( T^* \) around optimal doping level, they become different in very underdoped \( \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 \). Our results suggest that the nematic order is an electronic phase within the pseudogap state.

Many electronic orders are found in the pseudogap state, such as electronic stripes and charge ordering [1][5], and the nematic order that breaks the in-plane rotational symmetry from \( C_4 \) to \( C_2 \) [6][13]. Previous results from Nernst measurements show two types of nematicity in YBCO within the pseudogap state [8][11][12], the first one tracking the charge-density-wave (CDW) modulations around doping level \( p = 0.12 \) and the second one tracking the pseudogap energy with the onset temperature \( T_{nem} \) much lower than \( T^* \) for \( p < 0.11 \). However, torque-magnetometry measurements in \( \text{YBa}_2\text{Cu}_3\text{O}_y \) (YBCO) \( (p \geq 0.11) \) provide thermodynamic evidence for the rotational symmetry breaking setting in at \( T^* \), suggesting the onset of pseudogap is associated with a second-order nematic phase transition [15]. It is unclear whether these contradictory results come from the different techniques and standards in determining the relevant temperatures. Recently, the studies on the nematic order in iron-based superconductors show that the spontaneous nematic transition can be well studied by measuring the elastoresistivity above the transition temperature [16][19], which suggests that it may also provide key information in understanding the nematicity in cuprates.

Taking a classical magnet as an example, the zero-field magnetic susceptibility should show divergent behavior when approaching the transition temperature from the paramagnetic state. For the nematic order, the conjugated field is the uniaxial pressure or strain [20], so the nematic susceptibility can be obtained from uniaxial pressure or strain dependence of a physical property resembling the nematic order, such as resistivity. Indeed, elastoresistivity measurements on many iron-based superconductors show divergent behavior of nematic susceptibility [16][19], providing thermodynamical evidences for the nematic order. Compared to directly measuring the resistivity anisotropy, measuring nematic susceptibility has a much higher resolution and does not suffer from effect of residual strain from glue, etc. [21], and the external pressure that is typically used in detwinning the sample. Therefore, one may expect that measurement on cuprates may observe similar behavior if the pseudogap state is indeed associated with a nematic phase transition [22].

For this study, we have chosen three classes of hole-doped cuprates, \( \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 \) (LSCO), \( \text{Bi}_{1.74}\text{Sr}_{1.88}\text{Pb}_{0.38}\text{CuO}_{6+\delta} \) (Bi-2201) and \( \text{Bi}_{2-y}\text{Pb}_y\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta} \) (Bi-2212, \( y = 0 \) or 0.7), which were all grown by the traveling solvent floating zone method. The hole concentration \( p \) is determined by the value of \( T_c \) in Bi-2212 and Bi-2201 [23][24], while that in LSCO is determined by the Sr doping level. The orientation of the crystals was determined by the Laue x-ray diffraction, single-crystal x-ray diffraction and transmission electron microscope. The samples were cut into thin rectangular plates along either the Cu-O-Cu or diagonal direction as shown in Fig. 1a. The uniaxial pressure was applied along the length of the rectangle by a home-made device based on the piezo-bender as described previously [18], which is able to avoid the effect of residual strain from glue and measure the resistivity change across zero pressure. The positive and negative pressures correspond to compress and stretch the sample, respectively. The resistivity was measured in a Physical Properties Measurement System (PPMS,
pressure, respectively. We have shown in iron-based superconductors that $\zeta$ may be defined as nematic susceptibility above the transition if the measurement is done along the nematic order direction [18, 19], assuming that the resistivity change is mainly caused by nematic fluctuations.

Figure 1c shows the temperature dependence of $\zeta$ along the Cu-O-Cu direction for the $x = 0.17$ LSCO. The most promising features are the kink at $T_k = 110$ K and the sharp increase of $|\zeta|$ above it. The solid line in Fig. 1c is a Curie-Weiss-like fit of the data as $\zeta = A/(T - T') + y_0$, where $A$, $T'$, and $y_0$ are all temperature-independent parameters [18]. $T'$ is lower than $T_k$, which may be caused by the coupling between the electronic system and the lattice as suggested in iron-based superconductors [16, 18]. Below $T_k$, $\zeta$ becomes independent of temperature. The result along the diagonal direction (Fig. 1d) also shows a kink at the similar temperature. Different from that along the Cu-O-Cu direction, $\zeta$ along the diagonal direction changes little above $T_k$ but dramatically below it. It should be noted that a tetragonal-orthorhombic structural transition happens at about 140 K in this sample [22], but it seems to have no effect on the elastoresistivity data, suggesting that the resistivity difference between the orthorhombic axes can be neglected.

Figure 1e and 1f shows the same measurements on the overdoped $x = 0.21$ LSCO. No temperature dependence of $\zeta$ can be seen and all the features in the $p = 0.17$ sample disappear.

For the underdoped $x = 0.07$ and 0.08 LSCO samples, similar divergent behavior of $\zeta$ and kink feature are also observed along the diagonal direction, as shown in Fig. 1g-1h. At lower temperatures, we can find additional kink features, whose origin is currently unknown. The changes of $\zeta$ in these two samples are much larger than that in the $x = 0.17$ LSCO. In previous results of lower doping samples ($x \leq 0.04$), the resistivity along the orthorhombic b direction is smaller than that along the orthorhombic a direction at high temperature, i.e., $\rho_b < \rho_a$ [6], which suggests that the positive value of $\zeta$ at high temperature in the $x = 0.07$ and 0.08 samples may be resulted from the domain change under pressure. Interestingly, $\rho_b/\rho_a$ quickly increases with decreasing temperature and becomes larger than 1 at low temperature [6], which is also consistent with the sign change of $\zeta$ in our samples.

Figure 2a and 2b show results of the Bi-2212 samples, where again the kink feature is found in the $p = 0.134$ sample, but the direction showing the kink is along the diagonal direction. Moreover, $|\zeta|$ decreases with decreasing temperature below $T_k$ (Fig. 2a). For Bi-2201, we found the kink feature along the Cu-O-Cu direction, as shown in Fig. 2d. The increase of $\zeta$ with decreasing temperature is not as dramatic as those in LSCO and Bi-2212, so it cannot be fitted by the Curie-Weiss-like function. Interestingly, $\zeta$ along the diagonal direction shows different
FIG. 2. Elastroresistivity results of the Bi-2212 and Bi-2201 samples. a & b, Temperature dependence of $\zeta$ for the Bi-2212 samples along the diagonal and Cu-O-Cu directions, respectively. The black line in (a) is a Curie-Weiss-like fit with $T'_\text{C-W} = 135$ K.
c & d, Temperature dependence of $\zeta$ for the Bi-2201 samples along the diagonal and Cu-O-Cu directions, respectively.

There results suggest that nematicity may present in these three classes of hole-doped cuprates as shown in iron-based superconductors [16–19], but very different behaviors of elastroresistivity are found among different materials. First, the direction above $T_k$ along which the divergent behavior of $\zeta$ presents is the Cu-O-Cu direction in x = 0.17 LSCO and Bi-2201, but it is the diagonal direction in Bi-2212 and very underdoped LSCO (x = 0.07 and 0.08). These directions may be called as the nematic direction where the nematic order should point to. This may be related to the crystal structure since both Bi-2212 and very underdoped LSCO are in the orthorhombic structure at room temperature [26, 27]. It is consistent with the fact that the nematic direction may be affected by the crystal structure as shown in both iron-based superconductors [20] and cuprates [14]. It should be noted that the nematicity in Bi-2212 observed in the scanning tunneling microscope (STM) experiments is along the Cu-O-Cu direction [9], which is different from our observations here and has been explained otherwise [28]. Second, the elastroresistivity below $T_k$ also behaves dramatically different. The absolute value of $\zeta$ along the nematic direction decreases slowly with decreasing temperature in Bi-2212 and Bi-2201, but is unchanged in the x = 0.17 LSCO. In both x = 0.07 and 0.08 LSCO, additional kink features are observed below $T_k$. Third, the transition in Bi-2201 is not as sharp as those in LSCO and Bi-2212, probably due to the presences of very strong disorders [24].

Despite the above differences, there are two common features of nematicity for these materials, i.e., the kink feature of $\zeta$ at $T_k$ and the quick increase of $\zeta$ with decreasing temperature along the nematic direction. Figure 3 gives the phase diagram of these three classes of cuprates, where $T_k$ is the same as $T^*$ around the optimal doping level and in the overdoping regime. In both LSCO and Bi-2212, $\zeta$ above $T_k$ can be described by the Curie-Weiss-like function, suggesting that it shows divergent behavior as in iron-based superconductors [16, 18]. It seems to be consistent with the suggestion that the onset of the pseudogap state in hole-doped cuprates is associated with a spontaneous nematic transition [15]. However, this picture is not valid if we consider the data of the underdoped LSCO (x = 0.07 and 0.08), where $T_k$ is much lower than $T^*$, as shown in Fig. 3. Moreover, $\zeta$ shows no feature around $T^*$ (~ 200 K) as shown in Fig. 1g and 1h. Our results is consistent with previous Nernst measurements, where the nematic temperature has been shown to be significantly lower than $T^*$ in very underdoped YBCO [11].

Our results provide thermodynamical evidence that an electronic nematic order presents within the pseudogap state. While the nematic transition may happen at $T^*$ around optimal doping level, it becomes significantly lower than that in the very underdoped regime. Therefore, the nematic order in cuprates is just another phase within the pseudogap state, such as the stripes and CDW [1–5], which makes it as one of the competing or intertwined orders [29, 30]. Compared to CDW, the nematic phase can exist at much higher temperature and lower
doping at least in LSCO and YBCO, which suggests a very close relationship between these two orders [10].

Recently, nematicity has been observed in a wide doping range and up to room temperature in LSCO films by measuring the angle resolved transverse resistivity [11]. Besides that we measured the nematic susceptibility, we note the films are constrained on the substrates while the single crystals are in the freestanding condition. Further studies are needed to understand whether these are two kinds of nematicity or just one.

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