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Transport anomalies and quantum criticality in electron-doped cuprate superconductors

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ABSTRACT

Superconductivity research is like running a marathon. Three decades after the discovery of high-T_c cuprates, there have been mass data generated from transport measurements, which bring fruitful information. In this review, we give a brief summary of the intriguing phenomena reported in electron-doped cuprates from the aspect of electrical transport as well as the complementary thermal transport. We attempt to sort out common features of the electron-doped family, e.g. the strange metal, negative magnetoresistance, multiple sign reversals of Hall in mixed state, abnormal Nernst signal, complex quantum criticality. Most of them have been challenging the existing theories, nevertheless, a unified diagram certainly helps to approach the nature of electron-doped cuprates.

Contents

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1. Introduction

In last several decades, the developments in advanced scientific instruments have brought great convenience to condensed matter physics. One paradigm is probing the electronic states and electronic structures of strongly correlated electron systems. Remarkably in high-T_c superconductors, tools such as scanning tunneling microscope (STM) [1] and angle-resolved photoemission spectroscopy (ARPES) [2] have been exhibiting the power to discern complex density states and topology of Fermi surface. Nevertheless as an utmost used method, transport probe is unique for discovering new materials and novel properties, as well as a necessary complement to advanced probes in unraveling electron correlations, phase diagrams and so on. For instance, a panoply of discoveries, such as superconductivity [3], Kondo effect [4], integer and fractional quantum Hall effects [5,6] and giant magnetoresistance effect [7,8] were first witnessed by transport measurements.

Since the discovery of first superconductor, i.e. the element mercury in 1911 [3], the milestones of searching for new materials in this field leastwise include the heavy fermion superconductor $CeCu_2Si_2$ in 1978 [9], the organic superconductor $(TMTSF)_2PF_6$ in 1980 [10], the copper-oxide perovskite superconductor (cuprate) $La_{2-x}Ba_xCuO_4$ in 1986 [11], the iron-based superconductor LaOFeP in 2006 [12, 13]. The cuprates keeping the record of T_c at ambient pressure (∼134 K) have been of greatest concern to the superconductivity community. For the cuprates, there is a common feature in crystal structures, that is, the copper–oxygen blocks separated by charge reservoir blocks which donate charge carriers to the CuO_2 planes. Nominally, the cuprate superconductors can be categorized into types of hole doping and electron doping according to the sign of doped carriers. Soon after the discovery of hole-doped La_{2-x} Ba_xCuO_4, the first electron-doped Nd_{2-x} Ce_xCuO_4 was reported in 1989 [14, 15].

The distinction between these “214-type” La_{2-x} Ba_xCuO_4 and $Nd_{2-x}Ce_xCuO_4$ is the apical oxygen, where one copper atom and six oxygen atoms form a CuO_6 octahedron in the former but only a Cu–O plane in the latter as shown in Fig. 1. For convenience, the community abbreviates the hole- and electron-doped 214 types as *T* and *T*', respectively. There are only two branches in electron-doped family: the aforementioned T' superconductor (point group D_{4h}^{17}, space group I4/mmm) and infinite-layer superconductor (point group D_{4h}^{1}, space group P4/mmm). Owing to a limited number of electron-doped cuprates and their complicated synthesis procedures compared to the hole-doped ones, heretofore, researches were addressed mostly on the hole-doped family and rarely on electron-doped counterparts. However, it is undoubtedly that exploring the nature of electron-doped cuprates is indispensable for approaching the mechanism of high-T_c superconductors.

Not expected to recall the whole achievements on electron-doped cuprates in last 27 years, instead this short review centers on intriguing transport anomalies and quantum criticality. To provide a profile of electron-doped cuprates from the aspect of transport, we select the following topics, i.e. electrical transport anomalies (Section 2), two-band feature in both normal and mixed states (Section 3), the complementary thermal transport behavior (Section 4), and quantum phenomena in extreme conditions (Section 5). One can refer to other nice reviews published recently for an overall view on structures, properties and applications [16–18].

2. Electrical transport anomalies

A characteristic of all superconductors is zero electrical resistance below the critical superconducting transition temperature (T_c) and fully expulsion of magnetic field known as Meissner effect. For type-I superconductors, transition width of $R(T)$ curve, i.e. the temperature from normal state to Meissner state, is typical of 0.1 K or less. For type-II layered cuprate superconductors (high-T_c cuprates), the transition is usually broadened by an order of magnitude, due to Kosterlitz–Thouless transition where vortex pairs with opposite sign unbind with lifting up the temperature. When applying magnetic field, there is a mixed state located between the normal state and the Meissner state. In this state, vortices with normal core coexist with the superconducting area. Consequently, the resistance behavior becomes more complicated, since both intrinsic properties of the vortex and pinning effects play roles in fruitful vortex states [19]. From the aspect of electrical transport, once entering the mixed state rich phenomena can be observed in Hall signal (reviewed in Section 3), compared to the rare from resistance signal. However, a numbers of well-known anomalies were first uncovered from the resistance measurements in the normal state when tuning chemical doping, defects, temperature, magnetic field, and so on. Fig. 2 exhibits a typical Hall-bar configuration to measure voltages of both Hall (**V** // *y*, **I** // *x*, **B** // *z*) and resistance (**V** // **I** // *x*, **B** // *z*).

In this section, we hash over resistance anomalies in electron-doped cuprates, e.g. low temperature metal–insulator transitions, linear-in-temperature resistivity (the ‘strange metal’ behavior), negative magnetoresistance, anisotropic in-plane angular dependent magnetoresistance (AMR), and linear-in-field magnetoresistance. Although these intriguing phenomena are present in the normal state, their underlying physics is crucial to the understanding of high-T_c superconductivity.

2.1. Metal–insulator transitions

Metal–insulator transitions (MITs) mean huge change in resistivity, by even tens of orders of magnitude, which have been widely observed in correlated electron systems [20]. On the basis of different driving forces, the MITs are sorted into several types and named after a few memorable physicists like Wilson, Peierls, Mott, and Anderson. In this sense, unveiling the nature of MITs has profound influence on condensed matters. In electron-doped cuprates, MITs have been inevitably observed by tuning chemical doping [21–25], sample annealing process (adjusting oxygen concentration in the samples) [26–29], magnetic field [30] and disorder [31–34]. Acquainted with the MITs in electron-doped cuprates, we first look through two key elements, i.e. crossover from metallic-to-insulating behavior by tuning temperature and superconductor–insulator transitions by tuning nonthermal parameters.

(1) **Crossover from metallic- to insulating-behavior.** In $Ln_{2-x}Ce_xCuO_{4\pm\delta}$ (Ln = Nd, Pr, La…), the slightly Ce-doped or heavily oxygen-off-stoichiometric samples show insulating (or semiconducting) behavior with the residual resistivity in the range from mΩ·cm to Ω·cm. In contrast, the optimally- or over-doped sample has a residual resistivity of tens of μΩ·cm. Most of the time, the $R(T)$ curve displays a crossover from metallic behavior (higher *T*) to insulating-like behavior (lower *T*) as seen in Fig. 3. In this case, the ground state is not exactly an insulating (or semiconducting) state, whereas literature still prefers to use MIT (we will not stick to this issue in the following part). The origin of crossover from metallic-to-insulating-behavior, (i.e. upturn of resistivity) is still in debate, which may be subject to two-dimensional (2D) weak localization [35,36], Kondo-like scattering [37], additional scattering by magnetic droplets trapped at impurity sites [38,39], or a link to antiferromagnetism [40].