Experimental investigation of the asymmetric spectroscopic characteristics of electron- and hole-doped cuprates

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Abstract

Quasiparticle tunneling spectroscopic studies of electron- (n-type) and hole-doped (p-type) cuprates reveal that the pairing symmetry, pseudogap phenomenon and spatial homogeneity of the superconducting order parameter are all non-universal. We compare our studies of p-type $YBa_2Cu_3O_{7-\delta}$ and n-type infinite-layer $Sr_{0.9}Ln_{0.1}CuO_2$ (Ln = La, Gd) systems with results from p-type $Bi_2Sr_2CaCu_2O_x$ and n-type one-layer $Nd_{1.85}Ce_{0.15}CuO_4$ cuprates, and attribute various non-universal behavior to different competing orders in p-type and n-type cuprates.

Keywords: Quasiparticle spectra; pseudogap; pairing symmetry; competing orders

1. Introduction

The presence of competing orders in the ground state of cuprate superconductors [1] results in rich phenomena and complications for unraveling the pairing mechanism. Recent experimental development [1-3] reveals significant non-universal phenomena and asymmetric characteristics between n-type and p-type cuprates as the consequences of competing orders. In particular, the asymmetric characteristics among n-type and p-type cuprates may be attributed to the differences in their low-energy spin excitations [1,2]. We suggest that the *incommensurate* spin excitations associated with charge modulations in *p-type* cuprates may result in a charge nematic (CN) phase that competes with superconductivity (SC), yielding pseudogap phenomena and nano-scale phase separations in two-dimensional (2D) cuprates and long-range SC order in 3D cuprates [1,2]. In contrast, *commensurate* spin excitations in *n-type* cuprates, as manifested by neutron scattering [4] and implied by quasiparticle spectra [2,3], are indicative of the coexistence of antiferromagnetism (AFM) with SC.

2. Competing orders and pseudogap in p-type cuprates

The doping of holes into the CuO_2 planes of cuprates is known to induce gapped spin excitations in the CuO_2 plane. One of the possible ground states of the hole-doped CuO_2 plane is the stripe phase which accommodates gapped spin excitations via charge modulations [1]. However, a charge stripe phase with long-range order is energetically very costly. A compromised competing ground state phase in the presence of disorder could be a CN phase that involves local charge modulations while evading strong Coulomb repulsion. In general, the competition between two order parameters can result in three possible phase diagrams as a function of the chemical potential [1-3]: 1) nano-scale phase separations of the two phases, 2) coexistence of the two phases, and 3) disorder intermediate between the two phases. For highly 2D p-type cuprates such as $Bi_2Sr_2CaCu_2O_x$ (Bi-2212), the resulting ground state could reflect either Case 1) or Case 2), because SC involving continuous U(1) symmetry breaking cannot sustain long-range homogeneity in 2D [2], and also because the CN

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phase could be better stabilized by local disorder in 2D [8]. The CN phase may extend above T_c and yield the pseudogap (PG) phenomenon. In contrast, highly 3D p-type cuprates like $YBa_2Cu_2O_{7-\delta}$ (YBCO) may belong to Case 2), with homogeneous SC manifested by scanning tunneling spectroscopy [1], NMR [5] and microwave [1] studies.

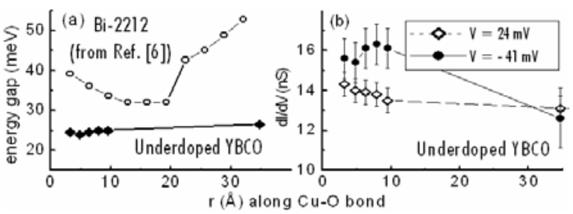

Figure 1 compares the spatial evolution of quasiparticle spectral characteristics between YBCO and Bi-2212.

Fig.1 Spatial evolution of quasiparticle spectral features along the Cu-O bonding direction: (a) energy gap of underdoped YBCO ($T_c \approx 60$ K) [1] and Bi-2212 ($T_c \approx 79$ K) [6]; (b) differential conductance (dI/dV) of underdoped YBCO at bias voltages V = 24 mV and –41 mV.

To investigate the possibility of locally pinned CN coexisting with SC in Bi-2212, we consider the effects of three sources of elastic scattering on the energy (E) and momentum transfer ($\boldsymbol{q}$) dependence of the tunneling conductance $\Delta G(\boldsymbol{q},E)$, which is proportional to the Fourier-transformed local density of states (FT-LDOS) $\rho_{\boldsymbol{q}}(E)$ [7,8]: point defects in the SC region, stripes in the pinned CN region, and 1D "edge states" separating the CN and SC regions. Assuming weak scattering potentials and using the first-order T-matrix approximation [8], we find that $\rho_{\boldsymbol{q}}(E) \propto \int d^3k\ \delta(E-E_k)\ \delta(E-E_{k+q})\ |V(\boldsymbol{q})|\ F_{\pm}(k,\boldsymbol{q})$, where $|V(\boldsymbol{q})|$ is the elastic scattering matrix in the Born approximation, and $F_{\pm}(k,\boldsymbol{q})$ are the coherence factors for spin-independent (+) and spin-dependent (−) interactions [8]. Examples of the quasiparticle FT-LDOS are shown in Figs. 2(a)-(c), where we have included 24 randomly distributed defects in an area of $(200a_0 \times 200a_0)$. We note that the FT-LDOS in Fig. 2(b) due to CN scattering of quasiparticles reveals more intense features along the (π,0)/(0,π) directions than those due to point and edge defects in Figs. 2(a) and 2(c). The combined spectra of both point- and 1D-scattering centers seem to agree better with experimental observation [7,8], implying that pinned CN could coexist with SC in Bi-2212.

3. Coexisting AFM and SC in n-type cuprates

The presence of commensurate spin excitations in one-layer n-type cuprates, as revealed from neutron scattering data [4], is consistent with the coexistence of a long-range AFM order parameter in the SC state, and the absence of charge modulations may account for the absence of PG above T_c [9]. Further evidence for coexisting AFM and SC is provided by our quasiparticle spectra of the n-type infinite-layer cuprate $Sr_{0.9}La_{0.1}CuO_2$: For small tunneling currents (< 20 nA), similar spectral characteristics with Δ_{SC} = 13 meV prevail, whereas for large tunneling currents (> 80 nA), a different large-gap spectrum (Δ_{AFM} ~ 25 meV) emerges. The field-induced pseudogap below T_c and above the upper critical field $B_{c2}(T)$ for one-layer n-type cuprates [9] is also suggestive of remnant AFM or a spin-flop (SF) phase upon the suppression of SC at $B > B_{c2}(T)$. In Fig. 3 we compare the phase diagram of the n-type infinite-layer (from our magnetization measurements) with that of the one-layer cuprates [9]. The different vortex phase boundaries of $Sr_{0.9}Gd_{0.1}CuO_2$ and $Sr_{0.9}La_{0.1}CuO_2$ suggest excess pinning effects due to the magnetic moments of Gd.

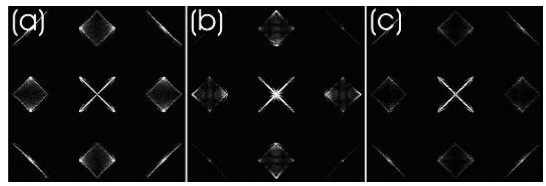

Fig.2 Quasiparticle FT-LDOS associated with (a) non-magnetic point defects, (b) stripes in CN, and (c) edge states for $(q_x,q_y) = (\pm\pi/a_0,\pm\pi/a_0)$, Δ_d = 40 meV and E = 20 meV. The sharper contrast represents stronger interference intensity.

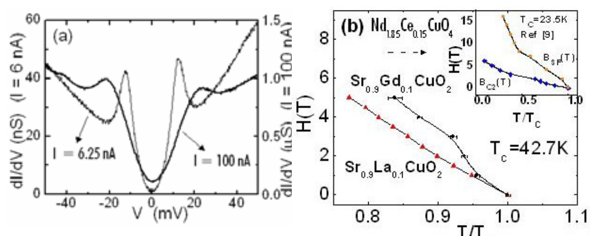

Fig.3 (a) Quasiparticle tunneling spectra of $Sr_{0.9}La_{0.1}CuO_2$ at 4.2 K taken with tunneling currents of I = 6.25 nA and 100 nA. (b) Magnetic phase diagram of n-type cuprates: infinite-layer (main panel) and one-layer (inset). In the inset $B_{SF}(T)$ refers to a spin-flop phase for H || c-axis.

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