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$_2$Cu$_3$O$_{7-\delta}$ and n-type infinite-layer Sr$_{0.6}$La$_{0.1}$CuO$_2$ (Ln = La, Gd) systems with results from p-type Bi$_2$Sr$_2$CaCu$_2$O$_x$ 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. © 2001 Elsevier Science. All rights reserved

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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$_2$Sr$_2$CaCu$_2$O$_x$ (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 \( \text{YBa}_2\text{Cu}_3\text{O}_7 \) (YBCO) may belong to Case 2, with homogeneous SC manifested by scanning tunneling spectroscopy [1], NMR [5] and microwave [1] studies.

We have included 24 randomly distributed defects in an quasiparticle FT-LDOS are shown in Figs. 2(a)-(c), where and spin-dependent (\( 3\)).

implying that pinned CN could coexist with SC in Bi-2212. seem to agree better with experimental observation [7,8], combined spectra of both point- and 1D-scattering centers due to point and edge defects in Figs. 2(a) and 2(c). The transformed local density of states (FT-LDOS) first-order T-matrix approximation [8], we find that regions. Assuming weak scattering potentials and using the elastic scattering matrix in the Born approximation, and

\[
\rho(F±(k,E)) \propto |V(F±)| \rho(\delta E-E_k+q) \delta(E-E_k-q)|F±(k,E)|.
\]

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 \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \) and \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \) suggest excess pinning effects due to the magnetic moments of Gd.

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 (\( q \)) dependence of the tunneling conductance \( \delta G(E,q) \), which is proportional to the Fourier-transformed local density of states (FT-LDOS) \( \rho_q(E) \) [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

\[
\rho_q(E) \approx \int d\mathbf{k} \delta(E-E_k) \delta(E-E_k+\mathbf{q}) |V(q)| F_q(k,q),
\]

where \( |V(q)| \) is the elastic scattering matrix in the Born approximation, and \( F_q(k,q) \) 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 \((\pi,0)\) and \((0,\pi)\) 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 \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \). For small tunneling currents (< 20 nA), similar spectral characteristics with \( \Delta_{\text{sc}} = 13 \text{ meV} \) prevail, whereas for large tunneling currents (> 80 nA), a different large-gap spectrum (\( \Delta_{\text{afm}} \sim 25 \text{ meV} \) emerges. The field-induced pseudogap below \( T_c \) and above the upper critical field \( B_{c2}(T) \) for one-layer n-type cuprates [9] also suggests 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 \( \text{Sr}_{0.9}\text{Gd}_{0.1}\text{CuO}_2 \) and \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \) suggest excess pinning effects due to the magnetic moments of Gd.

![Figure 2](image2.png)

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

![Figure 3](image3.png)

**Figure 3** (a) Quasiparticle tunneling spectra of \( \text{Sr}_{0.9}\text{La}_{0.1}\text{CuO}_2 \) at 4.2 K taken with tunneling currents of \( I = 6.25 \text{ nA} \) and 100 nA. (b) Magnetic phase diagram of n-type cuprates: infinite-layer (main panel) and one-layer (inset). In the inset \( B_{c2}(T) \) refers to a spin-flop phase for \( H \parallel c\)-axis.

### References