Spectroscopic Evidence for Competing Order-Induced Pseudogap Phenomena and Unconventional Low-Energy Excitations in High-T_C Cuprate Superconductors

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Abstract The low-energy excitations of cuprate superconductors exhibit various characteristics that differ from those of simple Bogoliubov quasiparticles for pure $d_{x^2-y^2}$-wave superconductors. Here we report experimental studies of spatially resolved quasiparticle tunnelling spectra of hole- and electron-type cuprate superconductors that manifest direct evidences for the presence of competing orders (COs) in the cuprates. In contrast to conventional type-II superconductors that exhibit enhanced local density of states (LDOS) peaking at zero energy near the centre of field-induced vortices, the vortex-state LDOS of $YBa_2Cu_3O_{7-\delta}$ (Y-123) and $La_{0.1}Sr_{0.9}CuO_2$ (La-112) remains suppressed inside the vortex core, with pseudogap (PG)-like features at an energy larger (smaller) than the superconducting (SC) gap Δ_{SC} in Y-123 (La-112). Energy histograms of the SC and PG features reveal steady spectral shifts from SC to PG with increasing magnetic field H. These findings may be explained by coexisting COs and SC: For hole-type cuprates with PG above T_c, the primary CO gap (V_{CO}) is *larger* than Δ_{SC} and the corresponding COs are charge/pair-density waves with wave-vectors parallel to (π,0)/(0,π). For electron-type cuprates without PG above T_c, V_{CO} is *smaller* than Δ_{SC} and the CO wave-vector is along (π,π). This CO scenario may be extended to the ARPES data to consistently account for the presence (absence) of Fermi arcs in hole- (electron)-type cuprates. Fourier transformation of the vortex-state LDOS in Y-123 further reveals multiple sets of energy-independent wave-vectors due to field-enhanced pair- and spin-density waves. These results imply important interplay of SC with low-energy collective excitations.

Keywords Local density of states; competing orders; Fermi arcs; pseudogap; cuprate superconductivity.

1 Introduction: Competing Orders in Doped Mott Insulators

High-temperature superconducting cuprates are doped Mott insulators with strongly correlated electronic ground states [1]. The complexity of these materials and the strong electronic correlation gives rise to various competing orders (COs) in the ground state besides superconductivity (SC), as manifested by such experimental evidences as x-ray and neutron scattering, μSR, NMR, Raman scattering, ARPES, STM [2-15] and further confirmed by theoretical modeling/simulations [16-25]. The occurrence of specific types of COs such as the charge-density waves (CDW) [16,17], pair-density waves (PDW) [21,22], or spin-density waves (SDW) [18-20] depends on the microscopic properties of a given cuprate, which include: electron or hole-doping, doping level (δ), number of CuO_2 layers per unit cell (n), and electronic anisotropy (γ). Although the relevance of COs to cuprate SC remains unclear, the existence of COs has a number of important physical consequences. First, quantum criticality naturally emerges as the result of competing phases in the ground state [5,18,25,26]. Second, strong quantum fluctuations are expected as the result of proximity to quantum criticality [5,14,27]. Third, the low-energy excitations are unconventional as the result of redistributions of the spectral weight between SC and COs [11-15,28-30]. The unconventional phenomena include: satellite features [3,5,14,28-30] and periodic LDOS modulations in the quasiparticle spectra of hole-type cuprates [11-13,30]; the excess sub-gap DOS in electron-type cuprates below T_c [5,14]; "dichotomy" in the momentum dependence of quasiparticle coherence [2,28,31,32]; and PG-like

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vortex-core states [15,29,30]. Fourth, the exact CO phase and the energy scale may differ amongst the cuprates, leading to various non-universal phenomena [5,14] such as the presence or absence of the low-energy PG [2,3,28,29], anomalous Nernst effect [33] and Fermi arcs [2,10,34]; the varying spatial homogeneity and modulations in the quasiparticle spectra [15,30,31,35-37]; and the characteristics of magnetic excitations [38-40]. Finally, The presence of COs and strong quantum fluctuations naturally lead to weakened superconducting stiffness upon increasing T and H [5,27,41,42] and may be responsible for the extreme type-II nature [43]. Hence, COs may be highly relevant to the strong fluctuations and novel vortex dynamics in cuprate superconductors [5,27].

For comparison, an alternative theoretical viewpoint commonly referred to as the "preformed pair" model or the "one-gap" model assumes that the low-energy PG temperature T^* is the onset of Cooper pairing and the superconducting transition T_c is the onset of phase coherence [41,44-47]. However, the phenomenology associated with the one-gap scenario is only partially applicable to the hole-type cuprates. Additionally, the one-gap notion cannot account for either the appearance of energy-independent wave-vectors or charge modulations that are doping-dependent in the SC state of hole-type cuprates [13]. In contrast, the CO scenario, or the "two-gap" model, is not exclusive of the possibility of preformed pairs: COs represent additional phase instabilities in the cuprates that are neglected in all one-gap models, and they may coexist with preformed pairs above T_c if they already coexist with coherent Cooper pairs at low temperatures.

In this work, we describe our scanning tunneling spectroscopic (STS) studies of quasiparticle spectra of various cuprates as functions of temperature (T) and magnetic field (H). We also present our own theoretical analyses based on the CO scenario for the quasiparticle tunneling spectra and ARPES data of both electron- and hole-type cuprates with varying doping levels, and find that a unified phenomenology emerges. These studies therefore suggest an important interplay between collective low-energy bosonic excitations and cuprate superconductivity.

2 Scanning Tunneling Spectroscopic Studies of the Low-Energy Quasiparticle Excitations

The spatially resolved tunneling conductance (dI/dV) versus energy (ω = eV) spectra for the quasiparticle LDOS maps were obtained with our homemade cryogenic scanning tunneling microscope (STM). Our STM has a base temperature of 6 K, variable temperature range up to room temperature, magnetic field range up to 7 Tesla, and ultra-high vacuum capability down to a base pressure < 10^{-9} Torr at 6 K. For each constant temperature (T) and magnetic field (H), the experiments were conducted by tunneling currents along the crystalline c-axis under a range of bias voltages at a given location. The typical junction resistance was ~ 1 GΩ. Current (I) vs. voltage (V) measurements were repeated pixel-by-pixel over an extended area of the sample. To remove slight variations in the tunnel junction resistance from pixel to pixel, the differential conductance at each pixel is normalized to its high-energy background. More details of our experimental setup, surface preparation and tunneling conditions have been described elsewhere [15,30,35]. The cuprates in our spatially resolved tunneling spectra study include optimally doped hole-type $YBa_2Cu_3O_{7-\delta}$ (Y-123) with T_c = 93 K and optimally doped electron-type $La_{0.1}Sr_{0.9}CuO_2$ (La-112) with T_c = 43 K. For analysis, we apply Green function techniques based on the CO scenario [28,29] to our tunneling spectra as well as to spectra taken by others on such systems as hole-type $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) [31] and $Bi_2Sr_2CuO_{6+x}$ (Bi-2201) [13] and electron-type $Pr_{1.85}Ce_{0.15}CuO_{4-x}$ (PCCO) [48] of various doping levels in zero-field for self-consistent comparison.

2.1 Temperature-Dependent Tunneling Spectra in Zero Fields

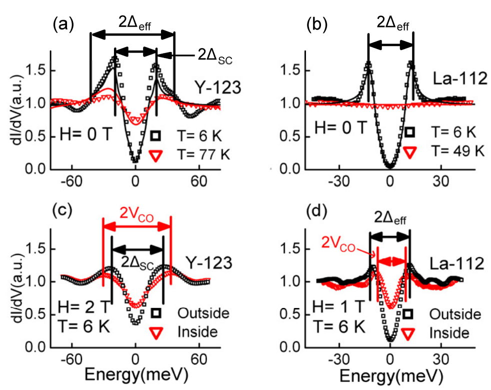

Fig. 1 Implication of CO from zero- and finite-field STS in Y-123 and La-112: **(a)** Normalized zero-field tunneling spectra of Y-123 taken at T = 6 K (black) and 77 K (red). The solid lines represent fittings to the T = 6 and 77 K spectra by assuming coexisting SC and CDW, with fitting parameters of Δ_{SC} = 20 meV, V_{CDW} = 32 meV and Q_{CDW} = (0.25π ± 0.05π, 0) / (0, 0.25π ± 0.05π), following Refs. [28,29]. **(b)** Normalized zero-field tunneling spectra of La-112 taken at T = 6 K (black) and 49 K (red). The solid lines represent fittings to the T = 6 and 49 K spectra by assuming coexisting SC and SDW, with fitting parameters Δ_{SC} = 12 meV, V_{SDW} = 8 meV, and Q_{SDW} = (±π, ±π), following Refs. [28,29]. **(c)** Spatially averaged intra- and inter-vortex spectra of Y-123 for T = 6 K and H = 2 T, showing PG features inside the vortex, with a PG energy *larger* than Δ_{SC} and consistent with the V_{CDW} value derived from fitting the zero-field spectra in (a). **(d)** Spatially averaged intra- and inter-vortex spectra of La-112 for T = 6 K and H = 1 T, showing PG features inside the vortex, with a PG energy *smaller* than Δ_{SC} and consistent with the V_{SDW} value derived from fitting the zero-field spectra in (b).