Pseudogap and Superconducting Gap in High-Temperature Superconductors

Two decades after the discovery of first high temperature superconductors, the microscopic mechanism of high-T_c superconductivity remains elusive. In conventional superconductors, it has been well established that electrons form so-called “Cooper pairs” to give rise to superconductivity. The pair binding manifests itself as an energy gap in many spectroscopic measurements. This energy gap, known as superconducting gap, appears at the superconducting transition temperature T_c where the resistance also vanishes. For high temperature superconductors, the story is more complicated. Over a wide region of compositions and temperatures, there exists an energy gap well above T_c. This energy gap is called pseudogap [1], because there is no direct correlation to the superconducting transition. The origin of this pseudogap and its relation to the superconducting gap are believed to hold the key for understanding the mechanism of high-T_c superconductivity – one of the outstanding problems in condensed matter physics. In this regard, researchers Kiyohisa Tanaka and Wei-Sheng Lee, along with their co-workers in Prof. Zhi-Xun Shen’s group at Stanford University, have recently made an important discovery about the coexistence of two distinct energy gaps that have opposite doping dependence. Their observation not only provides a natural explanation for the contradictory results about the superconducting gap deduced from different experimental techniques, but also has profound implications on the mechanism of high-T_c superconductivity.

In this work published in Science, the authors focused their attention on the evolution of the electronic structure in the highly underdoped cuprate superconductor $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ (Bi2212) with doping level. The technique employed is angle-resolved photoemission spectroscopy (ARPES), a powerful tool in studying the electron structure of complex materials. The significantly improved crystal quality together with the state-of-the-art experimental system at SSRL beamline 5-4 allowed them to address the “pseudogap and superconducting gap” issue in a depth that had not been reached by previous ARPES measurements.

Through a systematic study of heavily underdoped Bi2212 samples with T_c = 30, 40, and 50K, two distinct energy gaps along the Fermi surface were identified in different parts of the momentum space: a small gap along with a sharp coherence peak near the nodal region and a relatively large gap near the antinodal region. Remarkably, these two energy gaps exhibit opposite trends with doping as shown in Fig. 1A & 1B. Panel A displays the data taken at the tip of the “Fermi-Arc” - the region along the Fermi surface where a coherence peak is observed, while panel B shows the data from the antinodal region. As indicated by the shaded area, the gap associated with the Fermi Arc region is reduced as the doping level and T_c decrease, while the gap in the antinodal region increases.

The complete doping evolution of these two energy gaps is summarized in panel C. The doping dependence of the gap magnitude in the antinodal region (black circles and dashed line) is consistent with the well-studied pseudogap behavior. The unexpected doping evolution of the gap in the Fermi Arc region (colored symbols and solid line), on the other hand, is the new discovery of this work. Based on these observations, the Stanford group proposes a picture of two energy gaps coexisting in different regions of the momentum space. The gap associated with the Fermi Arc region is most likely the superconducting gap as evidenced by the existence of a coherence peak in ARPES spectra and a positive correlation between the gap magnitude and T_c. The pseudogap in the antinodal region may, however, arise from another mechanism such as Umklapp scattering by the antiferromagnetic correlations or competing states, such as stripes, polaronic behavior, or a charge-density-wave. This two-gap scenario not only provides natural explanation of the new ARPES results, but also resolves the contradictory results on the superconducting gap deduced from different experimental techniques.

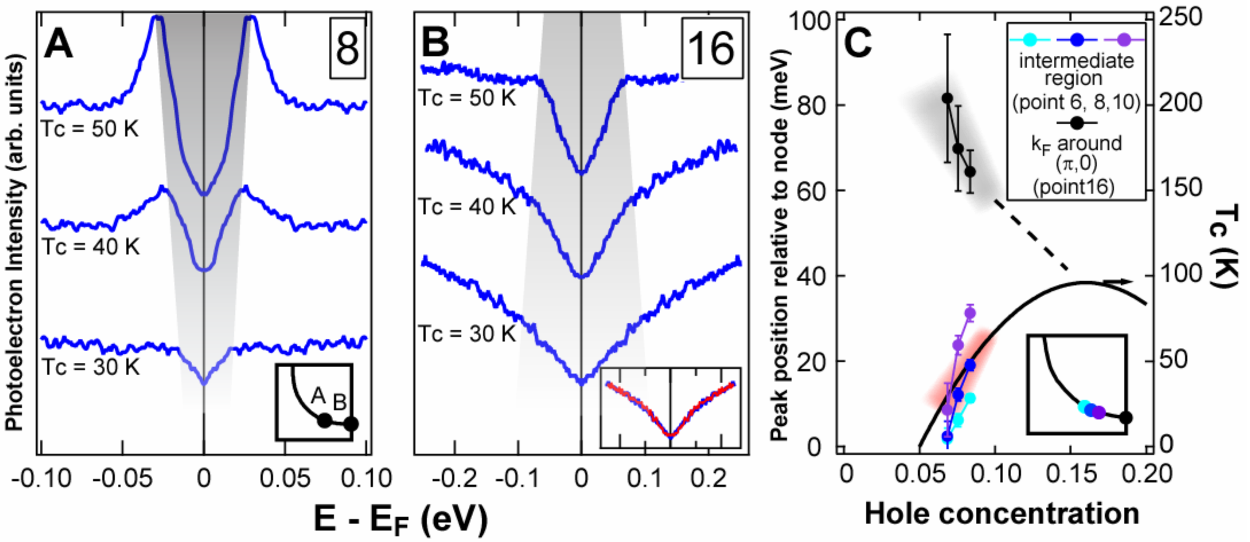

Fig. 1 The symmetrized spectra at (A) the tip of the Fermi Arc region and (B) the antinodal region. Their corresponding locations on the Fermi surface are shown in the inset of (A). The shaded area denotes the region inside the gap. (C) Doping dependence of the gap magnitude on various locations along the Fermi Arc region and in the antinodal region with their locations shown in the inset together with T_c. The dashed line indicates the pseudogap at the antinodal region reported by previous ARPES studies on Bi2212 system.

This two-gap scenario has two important implications that could be important for developing a microscopic theory of high-T_c superconductivity. First, the pseudogap near the antinodal region in these deeply underdoped samples is unlikely a precursor state of the superconducting state, as had been suggested previously [2,3]. Instead, it is more likely a state that competes with the superconducting state [4,5]. Second, these data suggest that the weakened superconductivity in the underdoped regime arises not only from the loss of phase coherence associated with the decrease in the superfluid density but also due to the weakening of the pairing amplitude. In this case, a mechanism for the superconducting gap reduction could be related to the shrinkage of the coherent Fermi surface with less doping, leading to a smaller phase space for pairing.

Primary Citation

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