Spectroscopic Signature of Electronic Pairing in the Normal State of Cuprate Superconductors

Cuprate superconductors have been intensely studied as a prototypical system exhibiting strong electron-electron correlations driving the formation of intertwined emergent phases. These phases include high-transition-temperature unconventional superconductivity, tendencies toward magnetic and charge-ordering, and a mysterious "pseudogap" phase that is still not well understood after many decades of research. Understanding these strongly correlated phases and their role in superconductivity is one of the major open questions in modern condensed matter physics.

These intertwined phases exist and are usually investigated in the context of doping electrons (n-type) or holes (p-type) into the copper oxide plane. Historically, p-type cuprates have been studied more extensively as they host the highest superconducting transition temperatures. One possible explanation for the pseudogap phase in the p-type cuprates is the preformed pairs without global coherence. This is an exciting prospect that may allow us to engineer much higher superconducting transition temperatures. However, investigations of the pseudogap are difficult because spectroscopic signatures of the various intertwined orders are expected to be similar in momentum space.

Compared to the p-type cuprates, the n-type cuprates have a much smaller superconducting region with a lower maximum superconducting transition temperature. Instead, much of the underdoped regime – with a small number of doped electrons – is dominated by strong antiferromagnetism where the spins are aligned in an alternating fashion. A consequence of the long-range antiferromagnetism is that the electron Fermi surface, or the distribution of the electrons in momentum space, is reconstructed from a large Fermi surface to a small Fermi pocket. It was previously thought that the ground state of the n-type cuprate is a simple antiferromagnetic metal with small pockets.

In this work, researchers at Stanford University and SLAC performed a detailed systematic study on a prototypical n-type cuprate $Nd_{2-x}Ce_xCuO_4$ using angle-resolved photoemission spectroscopy at SSRL beam line 5-4. Using a state-of-the-art high-energy resolution spectrometer, the researchers found that

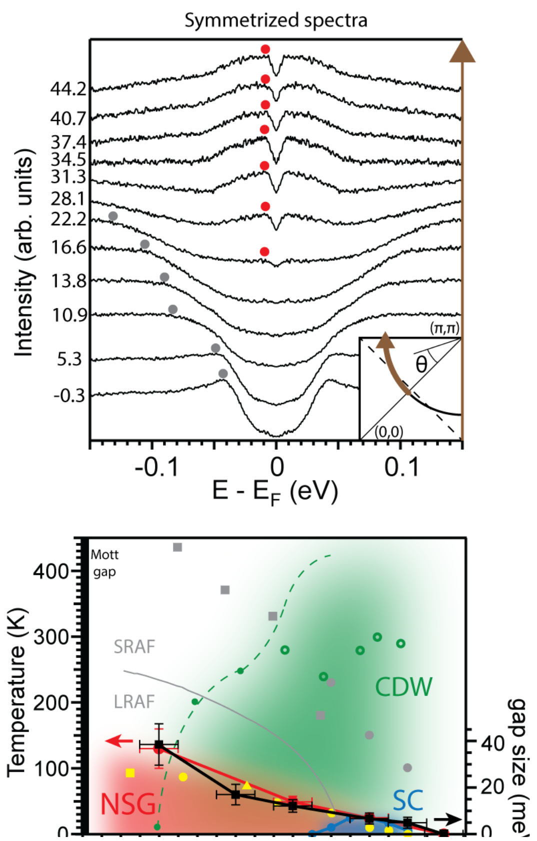

Figure 1. Observation of an anomalous normal state gap in n-type cuprates. Top: momentum distribution of the symmetrized energy distribution curves showing a low energy gap. Numbers to the left indicate the Fermi surface angle θ along the brown arrow indicated in the inset. Grey dots highlight the antiferromagnetic gap edge. Red dots highlight the normal state gap. Bottom: revised doping-temperature phase diagram of the n-type cuprates, showing antiferromagnetism in grey data points and line; charge density wave in green; bulk superconductivity in blue; anomalous normal state gap phase in red.

the small Fermi pockets in the underdoped n-type cuprates host an energy gap near the Fermi level (Fig. 1 Top), inconsistent with a simple antiferromagnetic metal picture. Comprehensive measurements of doping, momentum, and temperature dependences on this newly observed “normal state gap” reveal incompatibility with known magnetic and charge ordering tendencies as summarized in Fig. 1 Bottom. These observations suggest that this normal state gap likely originates from the pairing of electrons, which do not yet form a bulk superconducting phase due to lack of coherence. Remarkably, the normal state gap persists up to 150 K, a temperature much higher than the highest bulk transition temperature of 25 K in this material system. While complementary studies are required to confirm the nature of this putative superconducting state in the underdoped n-type cuprates, these results spur the tantalizing possibility of engineering higher transition temperatures in cuprate superconductors.

Leveraging collaborations with expert theorists at the University of California, Berkeley, the researchers were also able to reconcile the observed isotropic gap symmetry with the expected *d*-wave symmetry of the superconducting order parameter. Surprisingly, due to the coexistence of long-ranged antiferromagnetic order with the putative superconductivity, the nodes of the *d*-wave order parameter are nullified. Such a result has important implications for power transmission, where significant losses occur along the *d*-wave node direction, as well as quantum computing, where the *d*-wave node hosts low energy excitations that induce decoherence.

Primary Citation

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