Particle-hole Symmetry Broken Pseudogap in High Temperature Superconductors

High-temperature (T_c) superconductivity is one of the most important topics in condensed matter physics. Despite extensive studies over more than two decades, the microscopic mechanism of high temperature superconductivity still remains elusive due to many unconventional properties that are not well understood. Among them, the most mysterious behavior of high-T_c superconductor is the nature of so called "pseudogap", which has been a focus of the field for many years. In conventional superconductors, a gap exists in the energy absorption spectrum only below T_c, corresponding to the energy price to pay for breaking a Cooper pair of electrons. In high-T_c cuprate superconductors, an energy gap called the pseudogap exists above T_c but below T^*, and is controversially attributed either to pre-formed superconducting pairs or to competing phases. Recently, by carefully studying the "symmetry" of the gap, researchers Makoto Hashimoto and Rui-Hua He, along with their co-workers in Prof. Zhi-Xun Shen's group at Stanford University, have found crucial evidence suggesting that the particle-hole symmetry required by superconductivity is broken in the pseudogap state.

The measurements were performed at SSRL Beam Line 5-4 using the state-of-the-art angle-resolved photoemission spectroscopy (ARPES) system with excellent beam and endstation stability. With this incomparable experimental setup, Hashimoto and He *et al* successfully obtained a high quality data set of the detailed temperature dependence of the pseudogap in a high-temperature cuprate superconductor Bi2201. By covering a wide temperature range from below T_c (34 K) to above T* (125 K) in the antinodal region close to the Brillouin zone boundary where the pseudogap reaches its maximum value, many important insights on the nature of the pseudogap were revealed which have not been achieved by previous ARPES studies.

In this work published in *Nature Physics*, the "symmetry" of the pseudogap was explored by examining the dispersion of the occupied electronic states measured by ARPES. As shown in Fig. 1m, when a particle-hole symmetric gap opens from the normal state dispersion (red curve) due to superconductivity, one always expects an alignment between the Fermi momentum k_F and the "back-bending" (green arrows) of the dispersion in the gapped states (weighted blue curve). Because of this strong constraint, the observation of back-bending away from k_F in a gapped state can be taken as conclusive evidence for a broken particle-hole symmetry nature of the gap, even though the information on the unoccupied state is absent in ARPES spectra. Therefore, a close examination of the symmetry of the gap may help us to identify the origin of the pseudogap: whether is due to pre-formed superconducting pairs or competing phases.

As shown in Fig. 1, the spectra in the true normal state above T^* (~125 K) exhibit a parabolic dispersion with two well-defined Fermi level crossings (Fig. 1a,1g & 1n), similar to that of ordinary metal. In the pseudogap state, despite the broadness of the spectra, the extracted dispersion becomes stronger towards lower temperatures with the band bottom at (π, 0) being pushed far away from the true normal state one, as summarized in Fig. 1n. Well below T^*, no dispersion saturation or back-bending is observed at k_F. Instead, while approaching E_F, the dispersion bends back at momenta (green arrows) markedly away from k_F (See also Fig. 1i-1l). Contrasting to what is shown in Fig. 1m, the behavior below T^* is completely different from the expectation for the superconducting state, suggesting that the transition from the true normal state above T^* to the pseudogap state has a different origin.

As also described in this paper, further analysis of these new data revealed that this symmetry breaking has its onset at T*, accompanied with anomalous spectral broadening indicative of spatial symmetry breaking without long-range order. These results improve the understanding of their previous work on Bi2212 system published in Science and Nature [1, 2] and the STM proposal that the pseudogap state is a broken-symmetry state, both suggesting that the pseudogap state is distinct from simple superconducting state. As such, their finding depicts a coherent picture for an understanding of the pseudogap as a broken-symmetry state that emerges from a simple normal state above T^* and most likely competes with superconductivity.

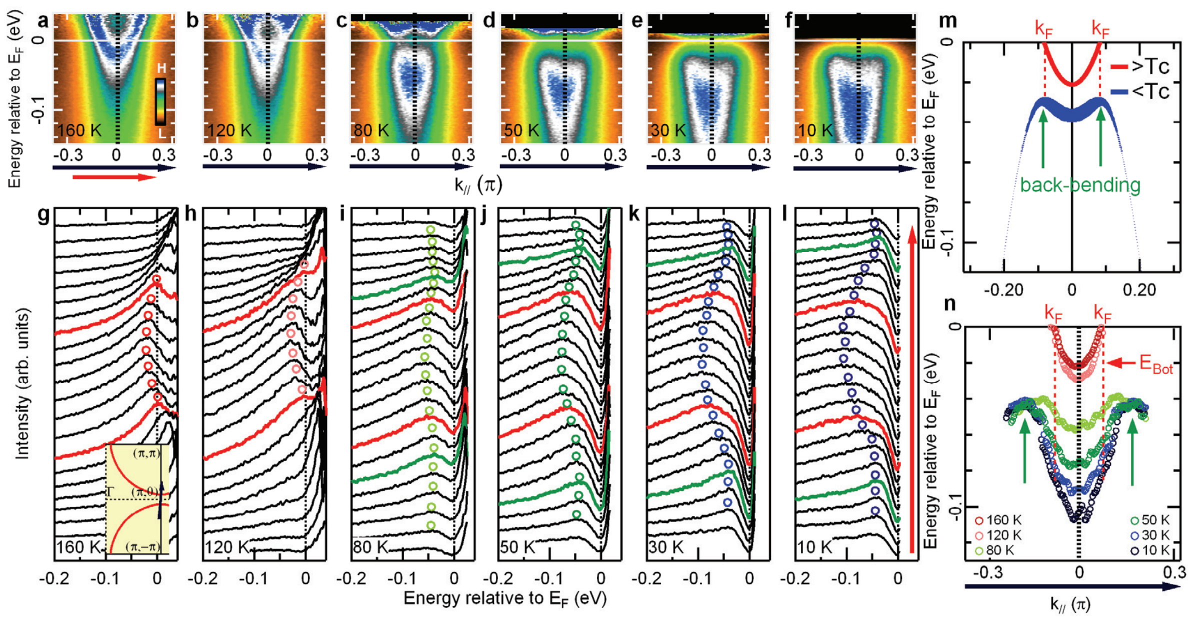

Figure 1 Particle-hole symmetry breaking in the antinodal dispersion of pseudogapped Pb-Bi2201. T_c = 34 K, T^* = 125 ± 10 K. **a-l,** Fermi-Dirac function (FD) divided image plots (upper panels) and corresponding spectra as a function of parallel momentum (lower panels) taken along the antinodal cut shown in the inset of **g** at selected temperatures. The intensity maximum of each spectrum is marked by circle. Spectra in red and green are at k_F and back-bending momenta of the dispersion, respectively (Supplementary Figs. 1 and 2). **m,** Simulated dispersion for *d*-wave homogeneous superconductivity with order parameter V = 30 meV. Cuts are along (π, - π)-(π, 0)-(π, π). The red (blue) curve is for the true normal (gapped) state. Spectral weight is indicated by the curve thickness. The back-bending (or saturation) of the dispersion and k_F are indicated in the panel. Note that the back-bending momentum in the gapped state remains aligned with k_F. **n,** Summary of the intensity maximum dispersions at different temperatures.

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