Addressing the Mechanism of High-Temperature Superconductivity

Background

If a "room-temperature superconductor" (a material which conducts electrical current without any loss at room temperature) is discovered, it will revolutionize a wide range of industries, including the electric power industry. Hence, CRIEPI has been actively advancing the basic research of high-temperature superconductivity (HTS) to elucidate its mechanism, with the ultimate goal of finding a *recipe* for synthesizing a room-temperature superconductor.

Objectives

Currently, the group at CRIEPI is leading the HTS research community in terms of producing high-quality single crystals of high-temperature superconductors and making best measurements of their electrical transport properties; at the same time, a worldwide network of collaborations has been established, placing CRIEPI at the "hub" of the network, to employ various experimental tools to study the HTS from all possible aspects. Here, as examples of such collaborations, we present (i) ultra-low-temperature measurements of the Hall coefficient under very high magnetic fields, done in collaboration with the National High Magnetic Field Laboratory of the United States, and (ii) scanning-tunneling-microscopy (STM) experiments to directly observe the electronic states, done in collaboration with Prof. Yazdani's group at University of Illinois at Urbana-Champaign.

Principal Results

(1) The Hall coefficient, R_H, reflects the collective state of electrons in materials. We measured the R_H in a series of Bi-based high-temperature superconductors by applying very high magnetic field of 550,000 Gauss (about a million times larger than the geomagnetic field) to suppress superconductivity down to ultra-low temperatures below 1 K. We discovered that at low temperatures the doping dependence of R_H presents a sharp cusp at the optimum doping level (15%), where the superconducting transition temperature is maximal (Fig. 1). This result indicates that the electronic states to host the superconductivity are of different nature across the optimum doping. Since collective electron systems are known to become unstable near a "quantum critical point" (QCP) where two different ground states meet, the present result suggests that the quantum fluctuations associated with a QCP are the driving force of the high-temperature superconductivity. This result was published in Nature[1)].

(2) By directly observing the spatial arrangement of the electronic density at the surface of a Bi-based high-temperature superconductor above the superconducting transition temperature, we discovered that the electrons self-organize into a peculiar ordered state (Fig. 2) before the superconductivity sets in. Normally, the flow of the electrical current is hindered when the electrons are ordered, but the present result suggests that in high-temperature superconductors an ordered state of electrons is a *precursor* to superconductivity and leads to the state where the current flow becomes the easiest. This result demonstrates an unexpected intimacy between the electron self-organization and the superconductivity, and was published in Science[2)].

Future Developments

Now that such peculiar phenomena as the quantum fluctuations and the electron self-organization are found to be fundamentally related to the occurrence of the superconductivity, we will sort out the exact role of these phenomena and elucidate the mechanism of the HTS.

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References

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2) M. Vershinin, S. Misra, S. Ono, Y. Abe, Y. Ando, and A. Yazdani, 2004, "Local Ordering in the Pseudogap State of the High-T_c Superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$", Science 303, 1995.

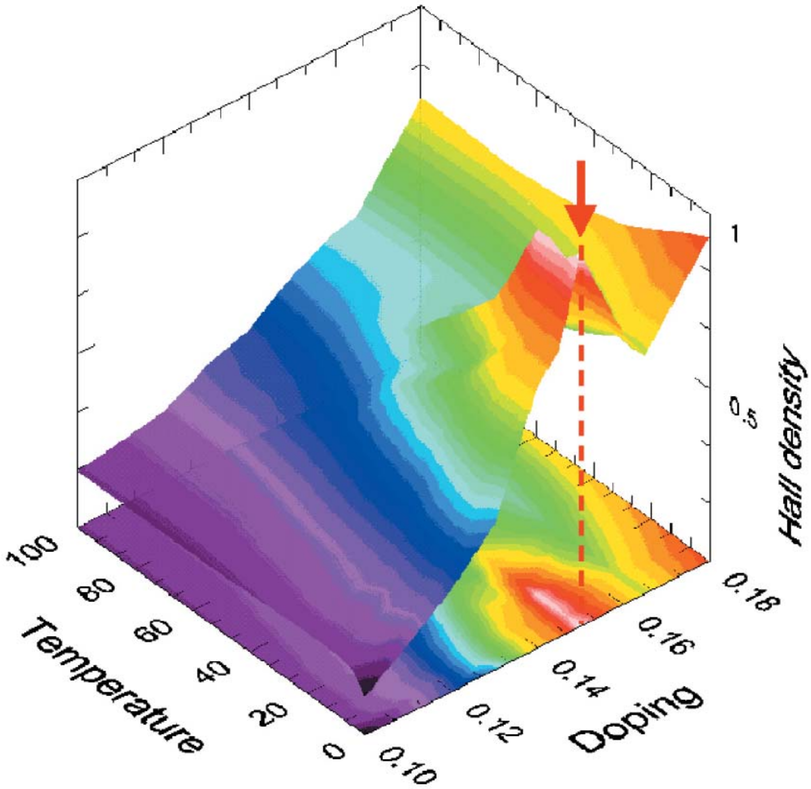

Fig.1 3D plot of the temperature and carrier-doping dependences of the Hall density, which is essentially an inverse of the R_H and reflects the collective state of electrons, measured under very high magnetic field of 550,000 Gauss that is strong enough to destroy the superconducting state. The carrier doping of 0.15 (i.e., 15% per Cu) corresponds to the optimum doping level where the superconductivity becomes the strongest. As a result of a competition between two different collective states of electrons that alternate across the optimum doping, the Hall density shows a sharp cusp (red arrow) near absolute-zero temperature.

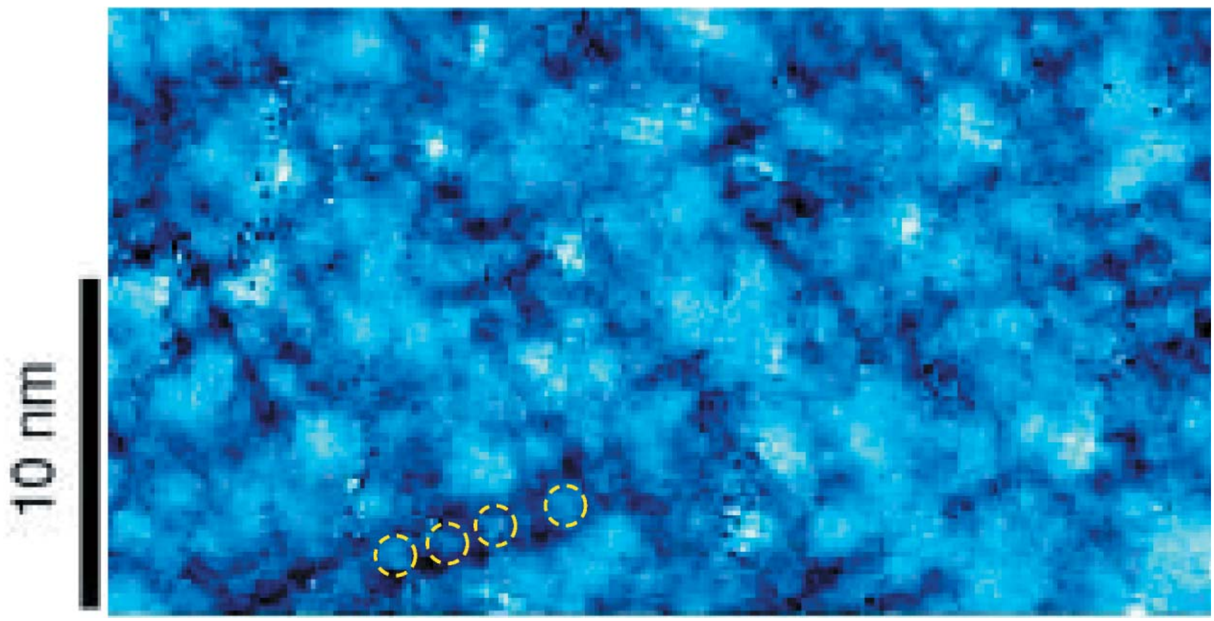

Fig.2 Spatial distribution of the electronic density of a Bi-based high-temperature superconductor measured at -173℃, which is *above* the superconducting transition temperature, using a scanning tunneling microscope (STM). In this measurement, the change of the tunneling current is registered while keeping the distance between the STM tip and the specimen, so that the regions with higher electronic density show up as bright spots. As is enclosed by yellow dashed circles in the figure, the electrons in this material appear to form “blobs” of about 1 nm in diameter and line up into a two-dimensional ordered state.