CHANGE OF CARRIER DENSITY AT THE PSEUDOGAP CRITICAL POINT OF HIGH TEMPERATURE SUPERCONDUCTORS

FOCUS OF STUDY

This study aimed at exploring the nature of the critical point of the pseudogap phase of copper-oxide high-temperature superconductors, in the limit close to absolute zero temperature accessed via the application of a very large magnetic field.

BACKGROUND

Superconductivity is the capacity of some materials to transport electricity without any loss, a spectacular property with transformative potential in areas as diverse as power transmission, communication, and medicine. So far, however, this phenomenon stubbornly appears only at low temperatures, typically tens of degrees above absolute zero. The question is whether room temperature superconductivity is possible. Some copper-oxygen (cuprate) materials are promising candidates, exhibiting superconductivity up to about −100 °C.

In conventional superconductors such as pure aluminum, superconductivity is caused by the ionic lattice, which vibrates in a way that brings the electrons to couple attractively and form pairs. These electron pairs occupy a low-energy state well below their first excited state, and this energy gap forbids the usual scattering mechanisms that give rise to an electrical resistance in metals. Electron pairs are known to also cause high temperature superconductivity in cuprates, but the physical force that binds them is of a different and currently unknown origin.

Identifying this force is largely complicated by the fact that cuprates exhibit a variety of electronic states that are intertwined with each other and with superconductivity, and whose very nature remains a mystery. Chiefly among them is the pseudogap phase, a prominent and universal property of cuprates observed experimentally as a partial suppression of the electronic density of states. The pseudogap phase appears at a characteristic temperature $T^*$ that is initially well above the critical temperature $T_c$ for superconductivity, but is gradually suppressed with doping, falling below $T_c$ typically near the point where it is highest, eventually vanishing entirely at a critical doping $p^*$ (see Fig. 1a).

Because the pseudogap phase and superconductivity coexist and seem so intimately connected, it is widely acknowledged in the community that whatever causes the pseudogap phase must also be actively involved in the electron pairing mechanism. Many scenarios have been proposed, involving either pre-formed electron pairs, or a variety of charge, orbital, or magnetic orders, but none has provided a satisfactory description so far. The pseudogap is also centrally positioned in the phase diagram, bridging the metallic state at high doping and the insulating phase near $p = 0$, so a global and unified understanding of the phase diagram of cuprates certainly requires a solution to the pseudogap problem.

Experimental studies of the pseudogap have been conducted since it was first discovered over two decades ago. But an experiment that would probe in detail what happens at the point where the pseudogap originates at $p^*$, in the zero temperature limit along the doping axis, was missing. This is precisely what the present study achieved.
FINDINGS

Gaining access to the zero temperature limit requires suppressing the superconducting phase and this can be achieved via the application of a magnetic field. But the superconductivity of cuprates is notoriously robust, so fields exceeding a million times the earth’s magnetic fields are necessary, which demands a fully dedicated high-field laboratory like the one in Toulouse, France, where the bulk of the experiments were performed. The magnetic field serves another key purpose: it deflects the electrons in a way that produces an electrical voltage transverse to the direction in which they propagate. This is the Hall effect, which provides a direct measure of the electrons’ density, labelled n_H. By measuring the Hall effect at low temperature in the presence of a large magnetic field on the cleanest specimens of the cuprate YBa_2Cu_3O_y, and repeating the experiment at different doping values p, the CIFAR team observed a sudden and dramatic six-fold drop in n_H at p^*, as shown in Fig. 1b. This is the first clear demonstration that a fundamental electronic phase transition occurs upon entering the pseudogap at p^*. Moreover, it reveals a key relation between the total measured carrier density n_H and the doping p, with n_H going from n_H = 1 + p above p^* to n_H = p below. According to standard theory, n_H = 1 + p is expected in the metallic state of cuprates. That n_H = p inside the pseudogap phase shows that 1 electron per copper atom is lost, which requires a different explanation. An important related finding of the study was to also demonstrate that the pseudogap and charge density-wave occur at markedly distinct dopings (see Fig. 1a), and consequently do not share a common origin.

METHODOLOGY

The study was made possible by recent advances in frontier magnet technology at the Laboratoire National de Champs Magnétiques Intenses (LNCMI), the French national high-field facility in Toulouse, France, where CIFAR Quantum Materials program member Cyril Proust is based. Over the last few years they upped their maximum field from 65 T up to 90 T, precisely the quantum leap required to probe the doping region around p^*. But that is not enough. Such large magnetic fields are not permanent, they are pulsed for about 0.1 second, the time required for a huge capacitor bank to fully discharge into an electro-magnet kept at liquid nitrogen temperatures. This is an extreme environment in terms of vibration and time-scale, which demands sophisticated mechanical decoupling between the experiment and the magnet, and low-noise ultra-fast electronics for data acquisition, while keeping the sample cooled at a few degrees absolute zero.

IMPLICATIONS

The drop in carrier density at p^* indicates a profound transformation in the electronic structure of cuprates. The fact that n_H = p inside the pseudogap phase is a clue that significantly narrows down the possible mechanisms. In the simplest scenario, the pseudogap is a phase of antiferromagnetism where the spins at the copper sites alternate in orientation. This magnetic structure breaks the symmetry of the crystal lattice, folding the electronic energy levels such that 1 electron per copper atom becomes localized. A more exotic scenario involves antiferromagnetically coupled pairs known as resonating valence bonds, a state which does not break translational symmetry but still seem to reproduce the observed drop in carrier density. Other scenarios exist, involving for instance an array of small current loops or some form of orbital ordering, but these will have to be re-examined in the light of the present study. Nevertheless, the window opened up by these results is also providing key insights into some enigmatic physical properties of cuprates, such that their electrical resistivity, previously interpreted as a metal-to-insulator transition whereas in fact it can now be explained as a metal-to-metal transition with differing carrier densities.

RESEARCHERS

Change of carrier density at the pseudogap critical point of a cuprate superconductor
S. Badoux et al., Nature 531, 210 (2016)
Figure 1a: Temperature-doping phase diagram of the cuprate superconductor YBa2Cu3Oy, showing the insulating magnetic phase (AF; dark grey), the pseudogap phase below $T^*$ (PG; light grey), the charge density-wave phase (CDW; pink), and superconductivity below $T_c$ (light yellow). The pseudogap phase terminates at the critical doping $p^*$, denoted by the red dot.

Figure 1b: Hall effect carrier density $n_H$ measured at low temperature in the cuprate superconductor YBa2Cu3Oy (data are red squares), showing a 6-fold drop at $p^*$ from $n_H = 1 + p$ to $n_H = p$. 

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