The enigmatic normal state of high temperature superconductors

Superconductivity is a macroscopic quantum state characterized by the total absence of electrical resistance and the ability to fully expel an applied magnetic field. However, these fascinating properties show up only below some characteristic (critical) temperature which, for conventional superconductors, usually does not exceed a few degrees, or a few tens of degrees. So the completely unexpected discovery, in 1986, of new materials where this critical temperature can rise to well above 100 K triggered huge interest. But, despite three decades of intensive studies, understanding the microscopic mechanism at the origin of this unconventional high temperature still remains one of the most challenging issues of solid-state physics.

The main problem is that the fascinating properties of superconductors are also major obstacles to investigation of their physical properties. Indeed, superconductors behave as "black boxes" expelling all electromagnetic probes, hence hindering the investigation of the state that is the immediate precursor to superconductivity. Therefore, it is essential to characterize their non-superconducting state, the so-called "normal" state. But, it appears that the precursor state of the high temperature conductors is far from normal! One of the main ingredients of the standard theory of superconductivity in conventional superconductor systems is the existence of an underlying "good metal" where electrons form a so called "simple" Fermi sea, in which they will be able to form the Cooper pairs that give rise to superconductivity, thanks to their interactions with the lattice vibrations. However, in high temperature superconductors, this calm (Fermi) sea transforms into an extremely rough storm and the nature of the electronic state hiding behind this unconventional superconductivity is still highly debated.

To get access to the precursor normal state it is hence necessary to destroy the superconducting state. This can be done by raising the temperature above the critical temperature (T_c). However, the main difficulty encountered in high temperature superconductors is the presence of several competing magnetic and electronic states. Most of these states are still badly understood (as for instance the mysterious "pseudo-gap" state) and some might yet be discovered. The origin of the high critical temperature is probably ineluctably related to the complexity of their phase diagram, but determining which of these states is essential to the onset of superconductivity or which is, on the contrary detrimental, is an essential – and still extremely debated – step towards our understanding of the mechanism leading to this unconventional superconductivity.

The second way to destroy the superconducting state is to apply a strong magnetic field, while keeping $T < T_c$. Unfortunately in most of the high temperature superconductors the field required to completely destroy superconductivity (called the upper critical field) exceeds 100 Tesla (at zero temperature), much larger than any practically reachable magnetic field. However it has been found recently that, surprisingly, this critical field drops to ~20 T for certain well-defined compositions ("underdoped" non-stoichiometric compositions) of the high-temperature superconductor material YBCO (Yttrium Barium Copper Oxide). This provides the opportunity to destroy the superconducting state in fields available at high magnetic field facilities. The lowering of the upper critical field for this specific material is accompanied by a drastic reconstruction of the electronic structure associated with the formation of an unexpected charge-ordered phase (the electron density becomes inhomogeneous, but with a spatial ordering).

Several probes have been used to investigate the nature of this new charge-ordered state but the most efficient technique to study phase transitions is probably the specific heat (C_p). Indeed, this thermodynamic quantity is directly related to the temperature derivative of the entropy and is expected to present a clear anomaly at any phase transition.

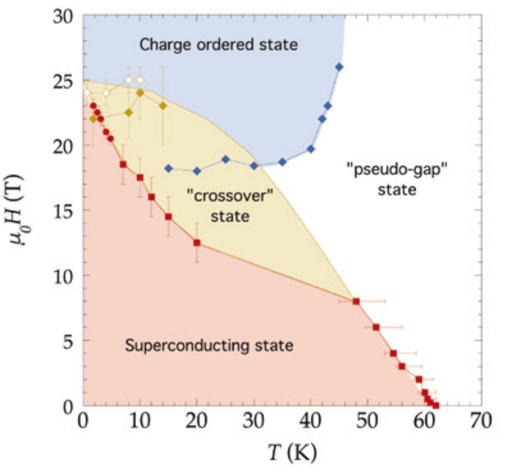

***Fig. 1**: The Magnetic field - Temperature (H-T) phase diagram of underdoped YBa$_2$Cu$_3$O$_{6.54}$ single crystals deduced from our specific heat measurements (red symbols) as compared to characteristic phase boundary lines deduced from other experimental probes, namely thermal conductivity (brown symbols) and sound velocity measurements (blue symbols).*

There is clearly an inflection in the specific heat line around 30-40 K highlighting the existence of a broad "crossover" state arising from the competition between the superconducting and the charge-ordered states.

We have developed a high-sensitivity modulation technique that enabled us to study the calorimetric properties of very small single crystals. Specific heat measurements were performed at up to 36T and down to 1.5K at the French National High Magnetic Field Laboratory, Grenoble. A well-defined anomaly could be identified in both the magnetic field and the temperature dependence of C_p. This anomaly (the field where the specific heat deviates from its standard dependence in the superconducting state) is plotted in Fig. 1 (red points). As is seen, the corresponding boundary line in the *H-T* phase diagram differs strongly from those deduced from other experimental probes such as thermal conductivity (brown symbols) and sound velocity measurements (blue symbols).

Below 20 K, our boundary line has also clearly deviated from the standard upper critical field (the line between the brown and blue regions in Fig. 1 which would mark the onset of superconductivity in a conventional superconductor.

This highlights the presence of a large "crossover" state separating the superconducting state and a charge-ordered, normal state in this material. It most probably originates from the competition between these two states. Our future research will be directed to understanding the significance of this newly discovered crossover-state, in view of solving the enigma of the normal state of high temperature superconductors.

CONTACT

Thierry KLEIN
thierry.klein@neel.cnrs.fr

PhD student:
Bastien MICHON

FURTHER READING...

"Calorimetric determination of the magnetic phase diagram of underdoped ortho II YBa$_2$Cu$_3$O$_{6.54}$ single crystals"
C. Marcenat, A. Demuer, K. Beauvois, B. Michon, A. Grockowiak, R. Liang, W. Hardy, D.A. Bonn and T. Klein
***Nature Commun.* 6**, 7927 (2015).