PULSED FIELD USERS PROGRAM

ATTENTION USERS: Chuck Mielke, Head

The measurement techniques that the NHMFL has developed over the years have contributed to making our facilities not only a great asset to the user community but to scientific endeavors globally. A summary of the work by F. Balikirev, *et al.* is a crystal clear example of how excellence in science and instrumentation has had a major impact on our community. The pulsed field Hall resistivity measurements took years to develop and perfect; Balikirev and co-workers are recognized for their significant contributions to this exceptionally challenging series of experiments. To read more about this impressive experimental accomplishment, see the 21 August, 2003 issue of *Nature* (Volume 424, page 912).

Signature of Optimal Doping in Hall-Effect Measurements on a High Temperature Superconductor

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After over a decade of research since the discovery of high temperature superconductivity, the mechanism of this phenomenon is yet to be established. There is a strong belief in the scientific community, however, that the elusive cause of superconductivity can be found through studying high temperature superconductors in their "normal" state (the state when superconductivity is "lifted" by a magnetic field or temperature). Among the various abnormal normal state properties, the Hall effect has been notoriously difficult to understand.

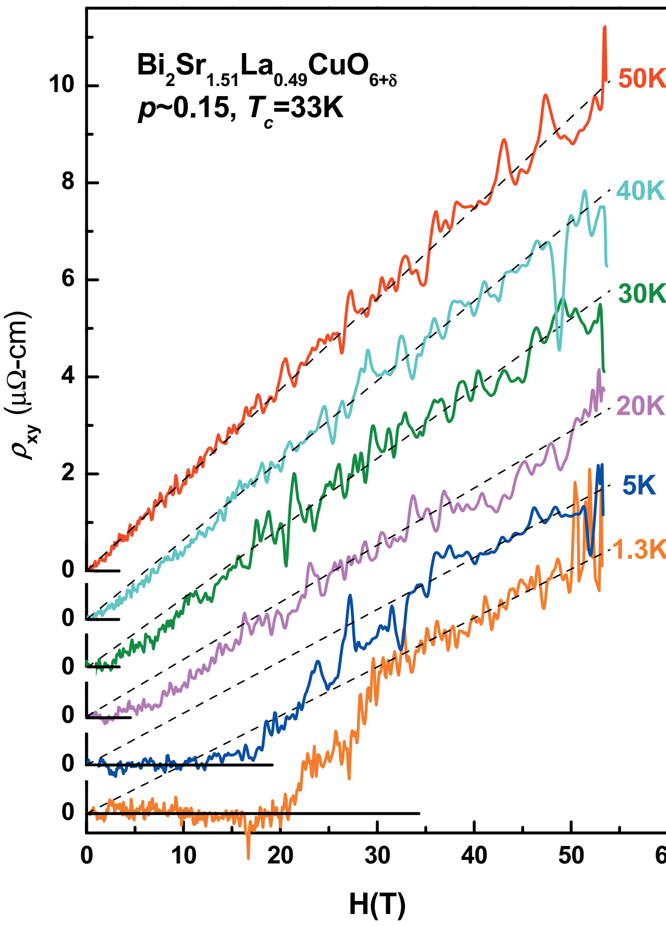

Figure 1. Hall signal as a function of magnetic field in a $Bi_2Sr_{0.51}La_{0.49}CuO_{6+\delta}$ superconducting sample (T_c=33 K, hole doping p~0.15) obtained using a high resolution, low noise, synchronous lock-in technique developed at the NHMFL. Hall coefficient, R_H, is determined with best linear fit, $\rho_{xy}(H) = R_H H$, at high fields (dashed lines), where superconductivity is suppressed by high magnetic field.

NHMFL Pulsed Field Facility scientists, in collaboration with Y. Ando group (CRIEPI, Japan), uncovered a startling evolution of the low-temperature Hall coefficient in the normal state of the high temperature superconductor $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (BSLCO) as a function of temperature and hole doping, p, by suppressing high temperature superconductivity with an intense magnetic field. The Hall number per unit cell, $n_{Hall} \equiv V_{cell}/eR_H$, is found to increase rapidly from nearly zero value at the onset of the high temperature superconducting state (p=0.10) to approximately one

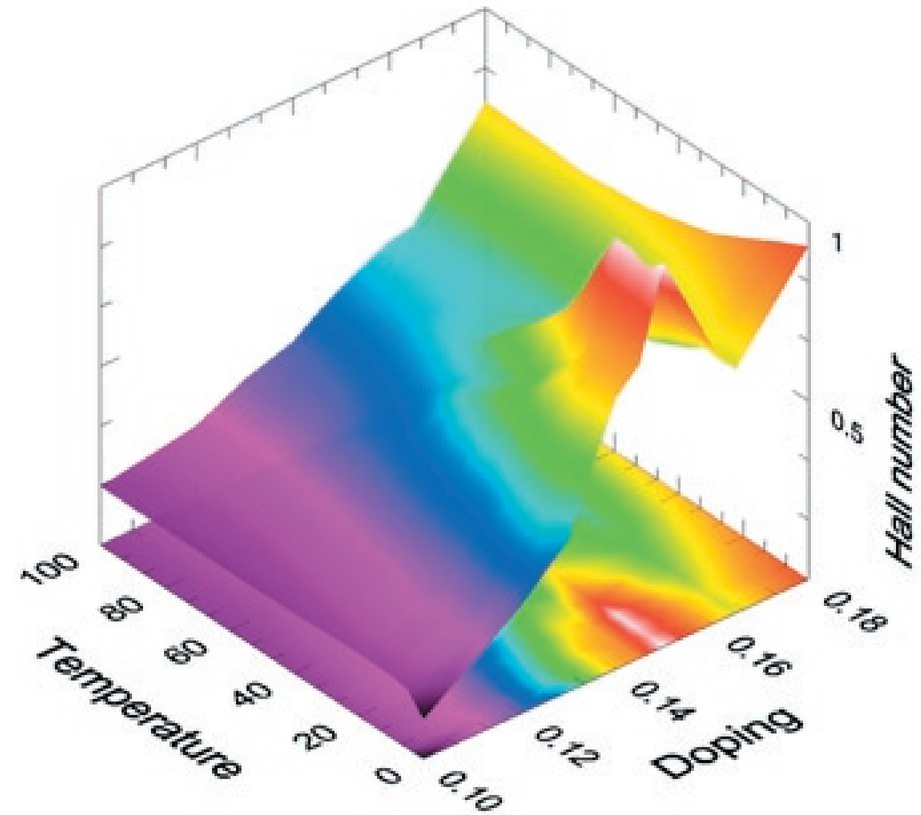

Figure 2. 3D color map plot of the Hall number, n_{Hall}=V_{cell}/eR_H, as a function of temperature and doping. n_{Hall} normalized to give the number of holes per Cu atom. Also shown is the 2D color map projection of the data onto temperature and doping plane. While the high temperature data shows a monotonic evolution of n_{Hall}(p) with increasing doping, upon cooling to ~50 K, the anomalous cusp at p=0.15 becomes apparent. This must be associated with an abrupt change in the Fermi surface suggesting a quantum phase transition (QPT) between two different metallic phases in the normal state. This observation also highlights the necessity of the high magnetic fields to reveal the intrinsic normal state behavior at low temperatures.

hole per unit cell near optimal doping (p=0.16) corresponding to roughly 7 carriers per each hole introduced with doping. At about the same hole doping level where superconductivity is most robust, n_{Hall} variation with doping exhibits a sharp change suggesting that two competing ground states underlie the high temperature superconducting phase.

A typical field dependence of the Hall signal in a superconducting BSLCO sample with a zero field T_c=33 K is shown in Figure 1. As the magnetic field suppresses superconductivity, the low temperature ($T < T_c$) Hall signal rapidly increases and then recovers its conventional linear-in-magnetic-field behavior. The value of R_H is then determined from a linear fit to the Hall resistivity data in this high field regime, $\rho_{xy}(H)=R_H H$ (dashed lines in Figure 1). In marked contrast to behavior seen in high temperature superconductors at high temperatures, upon cooling R_H becomes relatively temperature independent, signaling the recovery of Hall behavior typical of common metals, thus allowing us to investigate the evolution of the density of states in the low temperature limit. Figure 2 shows the surprising temperature and doping dependencies of n_{Hall}. We note that the rapid increase of n_{Hall} with doping in the low temperature limit shows a remarkably linear correlation with doping dependence of T_c in the underdoped regime ($p \leq$ 0.15) indicating that the superfluid density in the superconducting state corresponds to the carrier density in the underlying normal state throughout the underdoped regime. The observed maximum value of n_{Hall} implies a big Fermi surface that fills close to half a Brillouin zone.

The pronounced cusp in the zero-temperature-limiting value of the Hall number at optimal doping must be associated with an abrupt change in the Fermi surface, and thus suggests a quantum phase transition between two different metallic phases in the normal state of the high temperature superconductors. From this behavior one can argue that the occurrence of high temperature superconductivity is fundamentally related to quantum fluctuations associated with a zero-temperature phase transition. Recently, a number of models that involve quantum phase transition (QPT) between two different metallic phases in the normal state of the high temperature superconductors have been the subject of active debate among physicists. It takes an extremely high magnetic field to suppress the superconductivity and reveal a clear signature of a QPT in the normal state in the zero temperature limit.