The Fermi Surface of underdoped high-T_c superconductors

"Quantum oscillations and the Fermi surface in an underdoped high-T_c superconductor," Nicolas Doiron-Leyraud, Cyril Proust, David LeBoeuf, Julien Levallois, Jean-Baptiste Bonnemaison, Ruixing Liang, D.A. Bonn, W.N. Hardy and Louis Taillefer, Nature **447**, 565 (31 May 2007).

"Electron pockets in the Fermi surface of hole-doped high-T_c superconductors", David LeBoeuf, Nicolas Doiron-Leyraud, Julien Levallois, R. Daou, J.-B. Bonnemaison, N.E. Hussey, L. Balicas, B.J. Ramshaw, Ruixing Liang, D.A. Bonn, W.N Hardy, S. Adachi, Cyril Proust and Louis Taillefer, Nature **450**, 533 (22 November 2007).

Recommended with a commentary by Catherine Kallin, McMaster University

A central issue in high temperature superconductivity is the nature of the pseudogap phase which exists in the underdoped regime of the cuprates and how this phase gives rise to superconductivity as the temperature is lowered. Although overdoped cuprates appear to behave as conventional metals with a large Fermi surface above the superconducting transition temperature, the underdoped regime is quite different. Here ARPES finds disconnected "Fermi arcs" which, in one measurement, are extrapolated to shrink to a point at zero temperature.[1] Furthermore, in the underdoped regime, the superfluid density scales with hole doping which suggests that this regime is more closely connected to the Mott insulating antiferromagnetic phase at zero doping than it is to the metallic phase of the overdoped regime. These and other results have led many groups to focus on non-Fermi-liquid descriptions of the pseudogap phase of the cuprates.

Therefore, it came as a surprise that Proust, Taillefer and coworkers observed quantum oscillations in the electrical resistance of underdoped YBCO, establishing the existence of a well-defined Fermi surface when the superconductivity is suppressed by a magnetic field. The low temperature Hall resistance ($0.4<T<7$ K) in fields up to 62 T exhibits low-frequency Shubnikov-de Haas (SdH) oscillations as expected for a Fermi surface made up of small pockets. This is in striking contrast to the large Fermi surface observed in the overdoped regime. For example, the frequency of the quantum oscillations in YBCO at a doping of 0.1 hole per planar Cu atom corresponds to a Fermi surface which encloses only 3% of the area enclosed by the large Fermi surface in Tl-2201 at doping $p=0.25$.

More recently, LeBoeuf *et al.* found that the sign of the Hall resistance of YBCO in the underdoped regime changes from positive (hole-like) to negative (electron-like) as the temperature is lowered. This work shows that the small Fermi pockets giving rise to the observed quantum oscillations are *electron* pockets. Luttinger's theorem then requires that hole pockets also be present. However, the Fermi surface calculated for YBCO in the local density approximation does not display electron pockets. Scenarios which could lead to a Fermi surface reconstruction and small electron pockets include various spin, charge or other orderings, such as antiferromagnetism [2], d-density wave [3], or stripe [4] order. For example, a (π, π) ordering wavevector is expected to give rise to small electron pockets near $(\pi,0)$ and hole pockets in the vicinity of the nodal points at ($\pi/2$, π/2). If the mobility of the electron pockets dominates at low temperature, this picture is compatible with the measurements of Doiron-Leyraud *et al.* and of LeBoeuf *et al.* On the other hand, there is no clear evidence for the existence of antiferromagnetic or density-wave order in YBCO at these dopings, so further investigation into possible mechanisms for Fermi surface reconstruction is needed.[5] One open question is whether density or antiferromagnetic fluctuations would be sufficient to explain the data.

The question also remains as to how to reconcile the SdH oscillations with the Fermi arcs (or proposed Fermi Dirac points at zero temperature) observed by ARPES. First, one might point out that even systems with Dirac points, such as graphene, will typically display oscillations in the magnetoresistance, although not with period 1/H. Since only a few (3-4) oscillations are observed one might question whether the SdH data really shows 1/H oscillations. However, a larger number (7-8) of dHvA oscillations have recently been observed in YBCO[6], lending strong support to the interpretation of the SdH data. Another possibility is that the Hall resistance measurements detect only the electron pocket due to the high mobility in the elastic scattering regime, while ARPES detects only the hole pockets (and only one side, due to quasiparticle interference effects) with strong inelastic scattering obscuring the electron pockets. A third possibility is that these two measurements are not observing the same state, since the SdH measurements are done in a large magnetic field. It has been proposed, for example, that the magnetic field might induce antiferromagnetism, leading to the low oscillation frequency observed [7].

These results suggest a number of avenues for future investigation. If the Fermi surface is reconstructed as suggested above, this implies that the sign change of the Hall coefficient in the underdoped regime signals a phase transition to an ordered state and both the order and the transition should be observable in other measurements. In the absence of such corroborating evidence for order, one needs to investigate other mechanisms for Fermi surface reconstruction, including fluctuation effects. Measurements on other cuprates, with different inelastic scattering near (π,0), could shed light on the differences between the ARPES and SdH measurements. Another interesting question is how the Fermi surface might evolve from small electron and hole pockets at low doping to the large Fermi surface seen at large doping.

At face value, these new results seem to suggest that exotic, non-Fermi liquid theories are not required even in the underdoped regime of the cuprates. However, more work is needed to fully understand the implications of these measurements and to reconcile them with the ARPES results.

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