# FULL FERMI SURFACE OF A HIGH TEMPERATURE SUPERCONDUCTOR REVEALED BY ANGULAR MAGNETORESISTANCE OSCILLATIONS

*Full Fermi surface of a high-$T_c$ superconductor*

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We report the first observation of polar angular magnetoresistance oscillations in the high-$T_c$ cuprate $Tl_2Ba_2CuO_6$. These measurements establish the existence of a coherent three-dimensional Fermi surface on the overdoped, superconducting side of the cuprate phase diagram, even in materials with extreme electrical anisotropy. Detailed analysis of the oscillations reveals that $c$-axis dispersion vanishes at specific symmetry points. This observation has implications for our understanding of a wide range of unusual metallic and superconducting properties of cuprates.

Key words: High-$T_c$ cuprate, Fermi surface,

## 1. INTRODUCTION

To many, the high-$T_c$ superconductors represent perhaps the most striking example to date of the breakdown of Landau's Fermi-liquid description of metals. One of the fundamental signatures of a Fermi-liquid is a Fermi surface, the locus in reciprocal space of long-lived quasi-particle excitations that govern the electronic properties at low temperatures. In conventional metals, these excitations have well-defined momenta with components in all three dimensions. The failure to unambiguously observe such an entity in the



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cuprates, coupled with their unusual, highly 2D electronic properties above $T_c$, have led to an intensive theoretical search for novel (strongly correlated) electronic ground states in two dimensions.

Polar angular magnetoresistance oscillations or AMRO [1] have been used extensively to probe the topology of the Fermi surface in other layered metals, particularly the organics. The applicability of AMRO to the cuprates however has been hampered principally by their large scattering rates and the correspondingly small probability of cyclotron motion. With this in mind, we set out to observe AMRO in crystals of the cleanest cuprate (overdoped $Tl_2Ba_2CuO_{6+\delta}$ (Tl2201)) using the world's highest persistent magnetic field (45 Tesla) [2]. The simple band structure of Tl2201 [3], coupled with an absence of additional conducting elements, e.g. CuO chains, makes interpretation of any AMRO data in principle straightforward.

Tl2201 crystals (typical dimensions 0.2 x 0.1 x 0.02 mm$^3$) were mounted in a quasi-Montgomery configuration and the resultant zero-field *c*-axis resistivity curves $\rho_c$ were found to exhibit good metallicity despite a large resistive anisotropy $\rho_c/\rho_{ab}$ > 1000. The high-field magnetoresistance measurements were carried out inside a $^3$He cryostat inserted into the 45T Hybrid magnet at the NHMFL in Florida, USA.

## 2. RESULTS AND DISCUSSION

Fig. 1A shows AMRO data $\Delta\rho_c(\phi, \theta)$ for one crystal ($T_c$ ~ 20K) taken at 4.2K and 45T. Similar features were observed in 6 other crystals. The different traces represent polar AMRO sweeps at given azimuthal angles $\phi$ relative to the Cu-O-Cu bond direction ($\{k_x, k_y\} = (\pi, 0)$). Each sweep contains significant $\theta$-dependent structure that is summarised as follows. (i) a sharp dip in $\rho_c$ at $\theta = 90^o$ for low $\phi$, which we attribute to the onset of superconductivity at angles where $H_{c2}(\phi, \theta)$ is maximal, (ii) a broad peak around ***H***//*ab* ($\theta = 90^o$) that is maximal for $\phi \sim 45^o$, consistent with previous *azimuthal* AMRO studies in overdoped Tl2201 [4], (iii) a small peak at ***H***//*c* ($\theta = 0^o$) and (iv) a second peak in the range $25^o < \theta < 45^o$ whose position and intensity vary strongly with $\phi$.

Such strong $\theta$- and $\phi$-dependence can only arise from a coherent open Fermi surface with significant in-plane anisotropy. The Fermi surface of such a quasi-two dimensional metal is most elegantly expressed in the form of an expansion in cylindrical coordinates [5]: