Fermi surface of a high temperature superconductor revealed by angular magneto-resistance oscillations.

M. Abdel Jawad, N. E. Hussey, A. Carrington, A. P. Mackenzie & L. Balicas

Introduction

All cuprates can be viewed as doped Mott insulators. Upon doping, a phase diagram (Fig. 1) of the experimental data reveals the existence of an open Fermi surface along either one or two reciprocal axes. The oscillations come from the cancellations at specific angles of the c-axis drift velocity around a cylindrical orbit centered at any k|(Fig. 2). These angles were first predicted by Yamada for s=2 multidimensional systems and are given by:

\[ k_x = c \sin \theta, \quad k_z = c \sin \phi, \]

where \( k_x \) and \( k_z \) are the Fermi wavevectors along the c-axis and x-axis, respectively. This principle, one of the first angles, is the shape of any cylindrical Fermi surface simply by analyzing the angles at which extra features appear, under sufficient electron cyclotron motion (\( \omega \)).

AMRO are oscillations in the interchain or interlayer resistance upon rotating angle at fixed temperature and fixed field that vary with the existence of an open Fermi surface along either one or two reciprocal axes. The oscillations come from the cancellations at specific angles of the c-axis drift velocity averaged over a cylindrical orbit centered at any k|(Fig. 2). These angles were first predicted by Yamada for s=2 multidimensional systems and are given by:

\[ k_x = c \sin \theta, \quad k_z = c \sin \phi, \]

where \( k_x \) and \( k_z \) are the Fermi wavevectors along the c-axis and x-axis, respectively. This principle, one of the first angles, is the shape of any cylindrical Fermi surface simply by analyzing the angles at which extra features appear, under sufficient electron cyclotron motion (\( \omega \)).

The oscillations come from the cancellations at specific angles of the c-axis drift velocity averaged over a cylindrical orbit centered at any k|(Fig. 2). These angles were first predicted by Yamada for s=2 multidimensional systems and are given by:

\[ k_x = c \sin \theta, \quad k_z = c \sin \phi, \]

where \( k_x \) and \( k_z \) are the Fermi wavevectors along the c-axis and x-axis, respectively. This principle, one of the first angles, is the shape of any cylindrical Fermi surface simply by analyzing the angles at which extra features appear, under sufficient electron cyclotron motion (\( \omega \)).

AMRO studies since it has only one simple barrel-shaped Fermi surface revealed by ARPES in studying the evolution of the ground state in high-Tc superconductors. Although Tl2201 at this level of overdoping clearly comes from the side of the diagram in which more conventional behavior is observed, it is still a high-temperature superconductor (Tc~22K). Moreover, its resistivity anisotropy is actually larger than that seen in optimal doped cuprates from other families, so the condensates of this work may well have wider implications across the cuprate phase diagram. Of course, we do not expect this Fermi surface to remain intact as we approach half-filling. Nonetheless, in providing crucial information on the dimensionality of the electronic ground state, it is a benchmark for the next generation of ARPES studies in high-Tc superconductors, capable of a mass doping transition.

Conclusion

We have demonstrated the existence of a 3D coherent Fermi surface in overdoped Tl2201. Although Tl2201 at this level of doping clearly comes from the side of the diagram in which more conventional behavior is observed, it is still a high-temperature superconductor (Tc~22K). Moreover, its resistivity anisotropy is actually larger than that seen in optimal doped cuprates from other families, so the condensates of this work may well have wider implications across the cuprate phase diagram. Of course, we do not expect this Fermi surface to remain intact as we approach half-filling. Nonetheless, in providing crucial information on the dimensionality of the electronic ground state, it is a benchmark for the next generation of ARPES studies in high-Tc superconductors, capable of a mass doping transition.

Reference:

More details about this work can be found on the following paper:


Fig. 1 Generic phase diagram of the hole doped cuprates. The arrow indicates the doping level (p = 0.24) of the Tl2201 crystals used in this study.

Fig. 2 Variation of the c-axis drift velocity v(0) (arrows) around a cylindrical orbit (red) on a simple quasi-2D Fermi surface (blue) and centered at k, for \( \theta = 0 \) and \( \phi = 0 \).

Fig. 3 Ternary elemental crystal representation of the Tl2Ba2CuO5+delta superconductor (Tl2Ba2CuO5+delta). The large arcs are the cubic members of the cuprate family. Its doping range goes from optimally doped (Tc~38K) to heavily overdoped (Tc ~ 10K) regions. Even in the highly overdoped region however, the resistivity anisotropy remains large (> 1000) (Fig. 4). Tl2201 is also a good candidate for AMRO studies since it has only one simple barrel-shaped Fermi surface, centered at the X point of the Brillouin zone.

Fig. 4 Polar AMRO sweeps in an overdoped Tl2201 single crystal (T ~ 38K). The data were taken at 4 K and 100T. The different azimuthal orientations of each polar sweep are related to the Cu-O-Cu bond direction.

Fig. 5 AMRO in an overdoped Tl2201 single crystal (T ~ 38K). Similar AMRO patterns were also observed on 5 other crystals with a similar doping level. One striking feature of this data is the strong 0 dependence of the AMRO implying a rather complicated but nevertheless coherent c-axis dispersion. The second striking feature is the peak at 0K.

Fig. 6 Reciprocal space of a body-centered tetragonal crystal. The atoms are in red and the Brillouin Zone is in black.

As Tl2201 is a body centered tetragonal crystal (Fig. 3), it has a characteristic stacking of the Brillouin Zone lattice[5] (shown in Fig. 6) that simplifies tetradimensional resistance oscillations on the Fermi surface. The appropriate Fermi surface can be most elegantly defined by an expansion in cylindrical coordinates:

\[ r_r = r_x \sin \phi, \quad r_z = r_z \sin \phi, \quad \phi = \phi, \]

where \( r_r \) and \( r_z \) are the Fermi radii along the c-axis and x-axis, respectively. This principle, one of the first angles, is the shape of any cylindrical Fermi surface simply by analyzing the angles at which extra features appear, under sufficient electron cyclotron motion (\( \omega \)).

The plotting procedure is presented in Fig. 7. Fig. 7a shows a simulation of the data incorporating the lowest order parameters, i.e. k_1, k_2, and k_3. Adding the 2nd order term in the c-axis dispersion k_4 improves the fitting whilst going one step further to include k_5 results in an excellent simulation of the experimental data (Fig. 7d). The parameters for all the fittings are k_1 ~ 45, k_2 ~ 40 cm, k_2 ~ 10, k_2 ~ 3, k_2 ~ 0.021cm, and k_4 ~ 0.005cm. Note that this value of k_4 agrees with that estimated from low-temperature Hall effect and in-plane resistivity measurements.

These parameters give us a 3D Fermi surface as shown in Fig. 8 and a 2D projection as represented in Fig. 9. A striking aspect of Fig. 9 is the 8 points where the c-axis dispersion vanishes. Recognition of the role of oxygen bonding orbitals in CuAs orbitals in c-axis conductance is the cuprate to a well-known prediction of the existence of such dispersive nodes at certain symmetry points in the Brillouin zone. These nodes are found to coincide with the nodes in the a-axis parameter and the hot spots and cold spots around the Fermi surface. Hence, their influence on the superconducting states are expected to be profound.

Fig. 8 and a 2D projection as represented in Fig. 9. A striking aspect of Fig. 9 is the 8 points where the c-axis dispersion vanishes. Recognition of the role of oxygen bonding orbitals in CuAs orbitals in c-axis conductance is the cuprate to a well-known prediction of the existence of such dispersive nodes at certain symmetry points in the Brillouin zone. These nodes are found to coincide with the nodes in the a-axis parameter and the hot spots and cold spots around the Fermi surface. Hence, their influence on the superconducting states are expected to be profound.

Fig. 9 Projection of the deduced Fermi surface onto the ab-plane. The magnitude of the c-axis hopping has been increased twofold to emphasize the geometry.