Strongly Interacting Electron Systems

Transition metal oxides form crystals that have phases with exotic properties such as high temperature superconductivity, ferromagnetism, ferroelectricity, and charge and orbital ordering. Often these phases are in competition with each other leading to complicated phase diagrams, for example $YBa_2Cu_3O_7$, which is a high temperature superconductor, and $LaMnO_3$, which exhibits a “colossal magneto resistance” at a magnetic field induced metal-to-insulator transition. The important operative effect in all these materials is the strong interaction energies between the d-state electrons on the transition metal ions. As electrons hop on or off the transition metal ion the Coulomb energy of the ion changes by an amount large compared with the electron kinetic energy. This can inhibit the hopping leading to an insulator as observed by S. N. Mott in 1949. Conversely the electrons can cleverly use various other degrees of freedom to get around this large energy barrier and, in the process, produce metals, superconductors and the other exotic phases. These degrees of freedom include spin, orbital state, and ion positions (including vibrational motions).

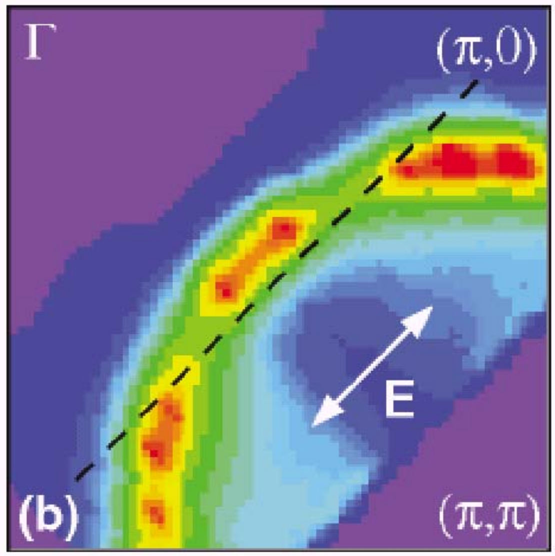
Even in conventional metals like copper or aluminum the electron interaction energies are not particularly small. In fact they are comparable with their kinetic energy, as measured by their Fermi energy. However, in 1941 Lev Landau observed that the Pauli principle so restricts the scattering processes that the electrons behave very nearly like non-interacting Fermions, i.e., they become a Landau Fermi liquid. But in the transition metal compounds the interactions are so strong in some cases that this Landau picture breaks down. The resulting exotic phases are interesting both because of the strong interaction physics and because many of the resulting complex behaviors have potential for important applications. One of these potentials is related to the new subject of spintronics and has lead to the term “orbitronics.” The intriguing and yet defiant question in this field is how the transformation from a Fermi liquid to a Mott insulator occurs in these systems.

The motion (or transport) of the charges in response to electric and magnetic fields provides important clues to the central mystery of these materials and bears directly the curious metal-insulator transition as well as on important applications of the materials. Prof. Drew’s group has developed novel techniques to observe charge transport in these materials in high magnetic fields. These techniques involve measurements at infrared wavelengths where the optical frequency is greater than the scattering rates of the charge carriers so that their intrinsic response becomes apparent. They also probe the characteristic frequencies of the system such as the carrier scattering rates, the plasma frequency $\omega_p^2 = 4\pi ne^2/m^*$ (which, together with the carrier scattering rate, determines the electrical conductivity) and the cyclotron frequency $\omega_C = eB/m^*c$, where n is the carrier density, m^* their effective mass, B the applied magnetic field.

The high temperature superconductors, such as $YBa_2Cu_3O_7$ and $Bi_2Sr_2CaCu_2O_8$, superconduct at the relatively balmy temperatures of 100 K. The pure insulating versions of these materials have exactly one valence electron per copper ion. These electrons are constrained from hopping to other Cu ions by the strong Coulomb barrier. That is, they are Mott insulators. Superconductivity in these materials results from doping or alloying these pure insulating starting compounds. When electrons are added or removed by chemical doping the extra charge carriers perturb the localized carriers so that they all become mobile and the material becomes a metal and a superconductor below a critical temperature T_C. The mechanism responsible for the superconductivity in these materials 18 years after their discovery still remains a mystery.

Equally puzzling is their normal or non superconducting state above Tc. The properties of this state are particularly strange as doping is reduced and the materials approach the Mott insulator state. Many researchers have advanced complex and creative ideas to understand these properties. As the electrical conductivity may be considered to be proportional to the number of carriers and inversely proportional to effective mass of the carriers, the approach to the insulating state may be understood in terms of either increasing the effective carrier mass or reducing the carrier density. In the first scenario interactions impede the motion of the carriers so that they acquire a large effective mass causing both the plasma frequency and cyclotron frequency to reduce continuously to zero. In the other scenario, as the doping density is reduced the carriers organize themselves in momentum space so that some are localized and some others are mobile. That is the carrier density decreases continuously to zero. This momentum space dependent localization implies a spatial modulation of the charge density, which is driven by the efforts of the carriers to reduce the strong Coulomb repulsion energy. In this case the effective carrier density is reduced but the effective mass is not strongly affected so that the plasma frequency is reduced but the cyclotron frequency is not.

Recently Dr. Drew's group has made infrared magneto-transport measurements on several differently doped samples of $YBa_2Cu_3O_7$ that have shown that, as the insulating state is approached, the plasma frequency decreases but the cyclotron frequency does not. Therefore the experiments indicate that the second scenario applies; the carrier density reduces but their effective mass remains nearly constant. Together with photoemission experiments, shown in the figure, these results indicate that the Fermi surface in the cuprates breaks up into smaller pieces when the hole doping is below a critical level. Although this result does not directly solve the question of the mechanism for the high temperature superconductivity, it does answer an



The figure, from Z. -X. Shen's group at Stanford University [N. P. Armitage et al., Phys. Rev. Letters 87, 147003 (2001)], shows evidence from photoemission for a break up of the Fermi surface in the underdoped cuprate superconductors. Γ is the center of the Brillouin zone and (π,0) is the corner [k_x= π/a, k_y= π/a]. The red areas correspond to Fermi surface "arcs". The dashed line is the Brillouin zone boundary associated with a charge density wave. The magneto-transport experiments in from Drew's group provide evidence that these "arcs" correspond to one half of a Fermi pocket – the original Fermi surface has broken up into smaller Fermi surface pockets.

important question about the non-superconducting state near the metal-insulator transition. Since the superconductivity in these materials is found to occur only near the metal-insulator transition the insights provided by this experiment are important for progress on this bigger question.

Dr. Dennis Drew is a professor of physics specializing in experimental condensed matter physics at the University of Maryland. His research interests include statistical and thermal physics; infrared properties of superconductors; optical properties of strongly interacting electron materials; semiconductor heterostructures; quantum dots, quantum computation and near-field optical scanning microscopy.

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