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Superconductivity in the Insulating Phase above the Field-tuned Superconductor to InsulatorTransition

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Recommended with a commentary by Steve Kivelson, Stanford University.

A key insight underlying much of the past success of solid state physics is that, despite the strong microscopic interactions between electrons, the low energy physics can be understood in terms of the properties of long-lived quasiparticles with properties similar to those of non-interacting electrons. It has long been understood that the justification for this Fermi-liquid approach is perturbative in the interaction strength – weak repulsive interactions do not fundamentally alter the character of the state. Conversely, the many instances where apparent breakdowns of the Fermi-liquid description have surfaced in various experimental systems have been avidly examined for clues of what important new physics emerges when the interactions between electrons are strong.

One of the many profound consequences of the Fermi liquid picture is the prediction that at sufficiently low temperatures, no metallic state is possible in two dimensions (2D) – rather, all quasiparticle states are localized. There have been several indications in the last two decades that metallic states of an anomalous nature occur in a variety of 2D systems, including Si MOSFETs and p-GaAs heterojunctions. A particularly compelling example of a clearly developed, and completely unanticipated 2D metallic state has been observed by A.Kapitulnik and his collaborators in thin superconducting films as the superconductivity is destroyed by the application of a transverse magnetic field, B. What makes this observation doubly important is that these anomalies occur in materials, MoGe and more recently InO, which in zero field behave like unexceptional metals and BCS superconductors.

The experiments on the MoGe films are reported in a series of papers[1-3]. In zero field, these films have a normal state resistance, ρ, in the range $0.6-1.3k\Omega$, which is comfortably smaller than the quantum of resistance, $h/e^2 = 25k\Omega$. All the films exhibit a sharp superconducting transition with a $T_c \sim 0.5-1.1$K, which is BCS-like as far as anyone can tell. The films are $w = 30$ to $60\AA$ thick, and therefore have an areal superfluid stiffness, $E_\theta \equiv \hbar^2 nw/8m \sim 1$eV $\gg k_B T_c$, so characteristic 2D (Kosterlitz-Thouless) features of the zero-field transition are expected to be confined to a very narrow range of temperatures near T_c. In particular, what this means is that the normal-state resistance is well-defined, in the sense that there is a substantial range of temperatures above T_c in which the resistance is essentially T and B independent.

Two distinct characteristic fields have been identified from the behavior of the resistivity data. There is a reasonably high field B^* that roughly corresponds to the condition of one flux quantum per coherence area, $B^* \sim \phi_0/\pi\xi_0^2 \sim 10$T, which was initially[1] identified as the point at which a superconductor to insulator transition occurs. For $B > B^*$, the resistance increases with decreasing temperature, while for $B < B^*$ it decreases. However, in [2], it was shown that for B not too much above or below B^*, this temperature variation ceases at low temperatures, and the resistance appears to approach a finite (metallic) zero temperature limit. Only below a considerably smaller critical field, $B_c \sim B^*/25$, does[3] the resistance approach 0 as $T \to 0$.

There are many things about this observation that are remarkable, but the most remarkable is the existence of a novel metallic state for $B_c < B \lesssim B^*$, and possibly beyond. The low temperature resistance in this regime is smaller, typically by several orders of magnitude, than the normal state resistance, indicating that some form of local superconducting correlations are present. However, it is certainly not possible to think of these as any sort of conventional quantum critical fluctuations, given the large range, $|B - B_c|/B_c \sim 25$, over which they are observed. There are many ways in which the anomalous metallicity of these superconducting films is reminiscent of anomalies in more exotic "highly correlated electronic systems," including the high temperature superconductors, a comparison that is made explicitly in the reference quoted above. However, precisely because the behavior of these films for $B = 0$ seems so safe and familiar, the anomalies that appear at finite B are particularly difficult to ignore, or to blame on unknown material complexities.

The unexpectedly metallic character of highly correlated 2D electronic systems is a *fact* that is here to stay - it is a major challenge in the field to come to grips with it.

1) A.Yazdani and A.Kapitulnik, "Superconducting-Insulating Transition in Two-Dimensional a-MoGe Thin Films." Phys. Rev. Lett. 74, 3037 (1995).

2) N.Mason and A.Kapitulnik, "Dissipation effects on the supercondutor-insulator transition in 2D superconductors," Phys. Rev. Lett. 82, 5341 (1999)

3) N.Mason and A.Kapitulnik, "True Superconductivity in a 2D Superconductor-Insulating System," Phys. Rev. B64, R60504 (2000).