"Neutral" Metals

1. **Particle-hole symmetry reveals failed superconductivity in the metallic phase of two-dimensional superconducting films**
   Authors: N. P. Breznay and A. Kapitulnik
   Science Advances 3 no.9, (2017)

2. **A Bose metal has no cyclotron resonance**
   Authors: Y. Wang, I. Tamir, D. Shahar, and N. P. Armitage
   arXiv:1708:01908

Recommended with a Commentary by Michael Mulligan, UC Riverside

Experiments

A common belief among condensed matter physicists is that, in the absence of superconductivity or the quantum Hall effect, disordered electrons localize in two spatial dimensions at zero temperature ($T = 0$). Consequently, any evidence to the contrary could indicate a new state of matter.

A particularly striking example occurs in homogeneously disordered superconducting films. First reported to occur in a MoGe sample almost 23 years ago [1], the anticipated quantum phase transition from a superconductor to an insulator upon the application of a transverse magnetic field was unexpectedly disrupted by an intervening metallic regime. Subsequent investigations [2] revealed a putative $T = 0$ metallic phase: the low-temperature dc electrical resistance extrapolates to a non-zero value at $T = 0$, roughly two orders of magnitude smaller (on average) than the normal state dc resistance, $\rho_{\text{normal}} \sim 1\ k\Omega/\Box$, for a range of applied magnetic fields. To the extent that such finite-temperature measurements reveal the nature of the quantum state, I will take the point of view implied by the most naive extrapolation: there is a *metallic* ground state. Similar behavior has been found in a variety of other thin films and quasi-two-dimensional systems, even when time-reversal symmetry is preserved and some other parameter, such as the electron density or film thickness, is varied. A nice review of this phenomena can be found in [3].

Recently, two independent groups have probed the Hall response of what is believed, for all intents and purposes, to be the same metallic state. Their remarkable findings can be roughly summarized as follows: the charge carriers, responsible for the $T = 0$ conduction, *do not feel* the external magnetic field. More precisely, for a range of magnetic field $H_{M1} < H < H_{M2}$, Breznay and Kapitulnik [4] found the dc electrical Hall resistance of InO (and TaN) films to be vanishingly small, $\rho_{xy}(H) = 0 \pm 5 \times 10^{-4}\ \Omega$, while the longitudinal resistance $\rho_{xx}(H) \sim 10^{-2}\rho_{\rm normal}$ at the lowest measured temperature $T = .12\ K \ll T_c \sim 2\ K$ (see the red curves in panels A and B in Fig. 1). Wang, Tamir, Shahar, and Armitage [5] studied the ac conductance of morphologically similar films in the metallic regime accessed by magnetic fields $2\ T < H < 7.5\ T$ (see the temperature-dependent dc resistance curves in Fig. 2 (a)). (Higher values of the external field are believed to drive the system into an insulating state.) In apparent violation of Kohn's theorem, which says conventional metals exhibit a cyclotron resonance at a frequency $\omega = eH/m$, where e is the electric charge and m is the band mass (m is the band mass, rather than the bare mass in these materials due to the broken translational invariance), the ac conductance measurements in Fig. 2 (b) show only a broad peak centered at $\omega = 0$. As the authors point out, the measurements set a lower bound on the effective mass equal to $16,000\ m_e$, where m_e is the bare electron mass, or, alternatively, an upper bound on the effective charge equal to $e/16,000$ of the charge carriers!

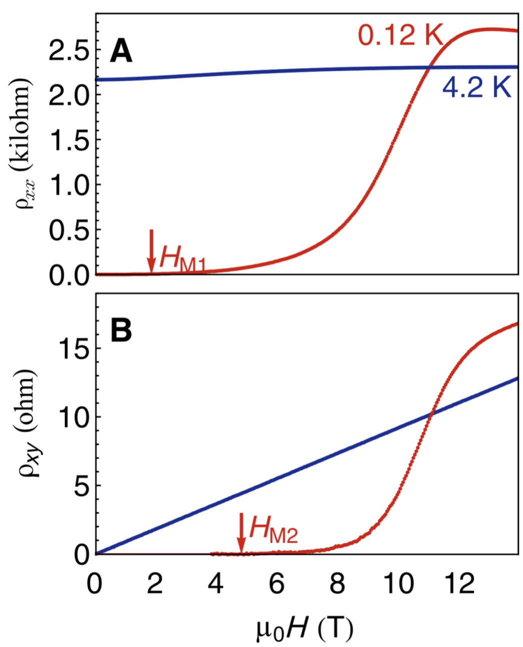

Figure 1: dc $\rho_{xx}(H)$ and $\rho_{xy}(H)$ [4].

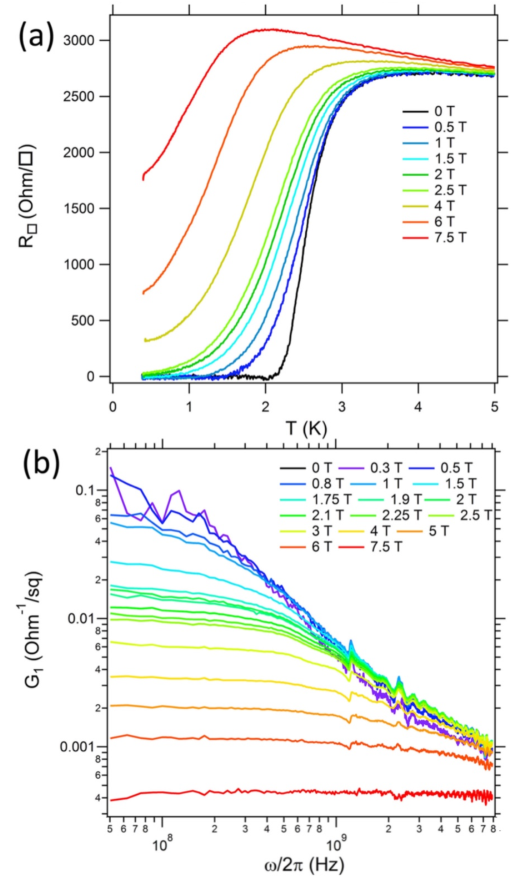

Figure 2: (a) dc $\rho_{xx}(T)$ and (b) ac conductance $\sigma_{xx}(\omega)$ for varying external magnetic field [5].

Speculation

Why should the Hall response be so small in the putative $T = 0$ metallic phase? Most naively, broken time-reversal invariance suggests a non-zero Hall effect. While it is conceivable that the $T \to 0$ dc Hall resistance $\rho_{xy}(H) = \frac{\sigma_{yx}}{\sigma_{xx}^2+\sigma_{xy}^2}$ in [4] is immeasurably small because the metal is so conducting, $\sigma_{xx}(T \to 0) \gg e^2/h \gg |\sigma_{xy}(T \to 0)|$, the ac conductance measurements in [5] appear to contradict this hypothesis.

Emergent symmetries (i.e., symmetries of a system appearing at long distances that are broken microscopically) are ubiquitous in condensed matter physics. As the authors [4, 5] remark, vanishing Hall response implies a sort of emergent particle-hole symmetry (at least for the low-energy degrees of freedom that comprise the metal). What is even more remarkable is that this particle-hole symmetry appears to persist for a range of magnetic field!

It could be helpful to consider InO samples belonging to a different region of parameter space. In more disordered samples, there appears to be a direct transition from a superconductor to an insulator at which two emergent symmetries obtain as ω and T are reduced to zero: (i) a particle-hole symmetry that sets $\sigma_{xy}(\omega/T) = 0$ and (ii) a self-duality that fixes $\sigma_{xx}^2(\omega/T) + \sigma_{xy}^2(\omega/T) = (4e^2/h)^2$. The metallic quantum critical point exhibits a larger symmetry than the $T = 0$ metallic phase; self-duality is not preserved within the metal. Is the critical point in any way related to the metallic phase? If so, how is the broken self-duality related to the robust particle-hole symmetry found in the metallic phase?

References

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[5] Y. Wang, I. Tamir, D. Shahar, and N. P. Armitage, arXiv:1708.01908.