Unexpected richness in the high-field physics of graphite

Two phase transitions induced by a magnetic field in graphite
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Recommended with a commentary by Jason Alicea, Caltech

Large magnetic fields often efficiently enhance electron-electron correlations in solids as beautifully exemplified by the 2D electron gas confined to the lowest Landau level. There the complete quenching of electron kinetic energy in a sense renders interactions infinitely strong, yielding spectacular phenomena ranging from the fractional quantum Hall effect to composite Fermi liquids and beyond. Interestingly, the 3D electron gas has also long been known to harbor rich interaction-driven high-field physics even though the kinetic energy remains partially unquenched [1]. Much is undoubtedly left to be discovered in this higher-dimensional setting, however, given the paucity of explorations relative to the 2D case. Recent experiments by Fauqué *et al.* on a classic system—graphite—indeed reveal unanticipated behavior that will likely shed new light on the fate of electrons in bulk crystals at ultra-high magnetic fields.

Some background discussion is in order to put their findings in perspective. In three dimensions, magnetic fields rearrange the electronic states into Landau level *bands* that remain dispersive along the field direction. One can profitably (though somewhat crudely) view the system as an array of 1D 'wires' that encode helical electron trajectories at different locations in the sample [2]. Enhanced correlation effects can be expected on general grounds due to the effectively reduced dimensionality—which both promotes Luttinger liquid-like physics [2] and creates perfect nesting at the Fermi level for each 'wire'. In the so-called ultra-quantum limit where the electrons populate only a single Landau level band, the following elegant picture emerges at weak coupling [3]. Due to the nesting condition repulsive interactions drive a $2k_F$ charge-density-wave (CDW) instability below a finite critical temperature. The resulting phase is no ordinary CDW, however—in modern parlance it represents a 'weak 3D topological phase' that smoothly connects to stacks of integer quantum Hall layers. Accordingly, the field-induced CDW supports a sheath of gapless chiral surface states along the sample boundaries parallel to the field. These surface states enjoy protection due to their chirality and can dominate electrical transport at sufficiently low temperatures [4]. (As an aside, weak attractive interactions do not yield a BCS instability but rather generate a marginal Fermi liquid state [3].)

Approaching the ultra-quantum limit requires field strengths where the cyclotron energy becomes comparable to the Fermi energy—an absurd proposition in typical conductors. This is where dilute semimetals such as graphite enter prominently. Graphite's minuscule carrier density (of order 10^{18}cm^{-3}) places the ultra-quantum-limit scale at an eminently accessible value near 10T for fields oriented perpendicular to the layers. Consistent with expectations based on the above theoretical picture, signatures of a field-induced phase transition in this material were first identified more than three decades ago through sharp increases in the magnetoresistance [5]. Many experiments followed including a work that, curiously, found transport evidence for the *removal* of the field-induced instability at around 50T [6].

Fauqué *et al.* pushed these studies into a previously unexplored regime, employing

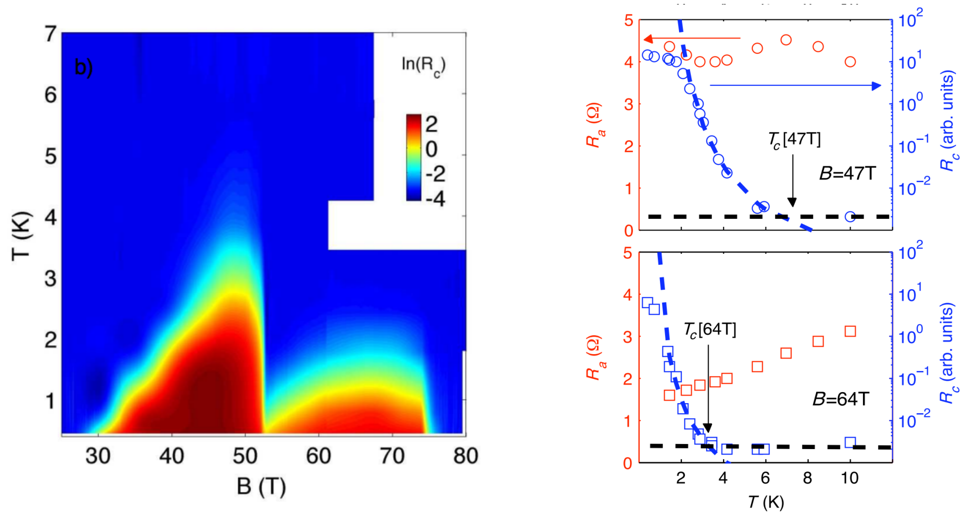

FIG. 1: Left panel: Graphite's c-axis resistance R_c (color scale) versus temperature and field. The two dome-like regions indicate successive field-induced phase transitions, the second of which was observed for the first time by Fauqué *et al.* Right panel: Temperature dependence of R_c and the in-plane resistance R_a at $B = 47$T (top) and 64T (bottom). These fields coincide with the domes in the left panel. All plots are adapted from arXiv:1303.4074.

pulsed fields to extend the magnetoresistance measurements up to an impressive 80T. Several surprises emerged. Perhaps most notably, the resistance R_c along the field direction reveals not one but *two* successive instabilities that eventually give way to reentrant metallic behavior above ~ 75T; see the left panel of Fig. 1. As temperature T is lowered across either phase transition R_c increases by orders of magnitude and then saturates. In dramatic contrast the in-plane resistance R_a exhibits exceptionally weak temperature dependence across the transitions as shown in the right side of the figure. These measurements suggest an unusual situation in which field-induced electronic instabilities produce insulating behavior along the field that coexists with metallic in-plane conduction.

It is natural to associate the observed phase transitions with interaction-induced density-wave formation. But precisely what kind? This question is subtle due to graphite's nontrivial band structure, spin and valley degrees of freedom, and the fact that the material is a compensated semimetal in the absence of doping. One might therefore reasonably expect multiple competing phases—e.g., charge, valley, and spin density waves among other more exotic possibilities—whose energetics depend sensitively on field. The situation is indeed reminiscent of the $\nu = 0$ state in single- and double-layer graphene where rich high-field phase diagrams have also been recently demonstrated [7]. Sorting out the competition among various candidate instabilities poses an interesting challenge for theory that is strongly constrained by the observed phenomenology. The origin of the wildly anisotropic resistance behavior raises another intriguing question. Fauqué *et al.* speculate that chiral surface transport might play a key role; such a scenario could be tested by performing experiments in Corbino-like geometries. More generally, the unexpected richness in graphite's phase diagram breathes new life into the high-field physics of bulk crystals, an area that appears ripe for further discovery.

[1] See, e.g., B. I. Halperin, Jpn. J. Appl. Phys. **26**, 1913 (1987)

[2] C. Biagini, D. L. Maslov, M. Yu. Reizer, and L. I. Glazman, Europhys. Lett. **55**, 383 (2001)

[3] An appealing renormalization group analysis is provided in V. M. Yakovenko, Phys. Rev. B **47**, 8851 (1993).

[4] L. Balents and M. P. A. Fisher, Phys. Rev. Lett. **76**, 2782 (1996)

[5] S. Tanuma, Y. Onuki, R. Inada, A. Furukawa, O. Takahashi, and Y. Iye, Physics in High Magnetic Fields, Vol. 24 of Springer Series in Solid State Sciences, edited by S. Chikazumi and N. Miura (Springer, Berlin, 1981); Y. Iye, P. M. Tedrow, G. Timp, M. Shayegan, M. S. Dresselhaus, G. Dresselhaus, A. Furukawa, and S. Tanuma, Phys. Rev. B **25**, 5478 (1982)

[6] H. Yaguchi and J. Singleton, Phys. Rev. Lett. **81**, 5193 (1998)

[7] A. F. Young, J. D. Sanchez-Yamagishi, B. Hunt, S. H. Choi, K. Watanabe, T. Taniguchi, R. C. Ashoori, and P. Jarillo-Herrero, Nature **505**, 528 (2014); P. Maher, C. R. Dean, A. F. Young, T. Taniguchi, K. Watanabe, K. L. Shepard, J. Hone, and P. Kim, arXiv:1212.3846