Bismuth in strong magnetic fields

"Signatures of Electron Fractionalization in Ultraquantum Bismuth",
K. Behnia, L. Balicas and Y. Kopelevich,
arXiv:0802.1993, Science **317**, 1729 (2007).

"Phase Transitions of Dirac Electrons in Bismuth",
L. Li, J.G. Checkelsky, Y.S. Uher, A.F. Hebard, R.J. Cava and N.P. Ong,
Science **321**, 547 (2008).

Recommended with a commentary by Catherine Kallin, McMaster University

Experiments on bismuth continue to yielded surprising results, even after decades of extensive study. Much of bismuth's exceptional behavior is due to its extremely long mean free paths (up to several millimeters) and unusual band structure. The Fermi surface of consists of a hole pocket and three Dirac electron pockets which occupy only 10^{-5} of the Brillouin zone. Because of the extremely small carrier density, magnetic fields of order 10T should be sufficient to achieve the quantum limit, i.e. to confine the carriers to the lowest Landau level. Therefore, one would expect the electronic properties to be featureless as a function of magnetic field above 10T or so. However, recent transport and torque magnetometry measurements at high fields revealed some surprises.

Behnia, Balicas and Kopelevich studied the Hall resistivity and the Nernst effect in bismuth in large magnetic fields. Previously, for fields less than 12T, they had observed peaks in the Nernst coefficient, which coincided with Landau levels crossing the Fermi level and emptying.[1] They referred to this as the "quantum Nernst effect".

More recently, Behnia and coworkers found unexpected peaks in the Nernst signal coincident with quasi-plateaus in the Hall resistivity at fields as high as high as 31T. Specifically, by using the quantum Nernst effect peaks as a reference, they found peaks at 2/3, 2/5 and 2/7 of the first integer peak (where one just reaches the quantum limit) and these peaks coincided with quasi-plateaus in the Hall resistivity. This is reminiscent of the fractional quantum Hall effect. However, bismuth is three dimensional, so the peak at 1 corresponds to having all the elections in the lowest Landau level, but is not a filled Landau level. Nevertheless, from these results, Behnia and coworkers speculated that bismuth might support a correlated, fractionalized state below the quantum limit.

In other recent work, Ong and coworkers (Li et al.) investigated the magnetization of bismuth, using torque magnetometry. Again, they found structure well beyond the expected quantum limit. For fields up to 31T and oriented so as to probe the electron pockets (i.e., trigonal fields), they observed jumps in the magnetization. Furthermore, they observed hysteresis, suggesting a first order phase field-induced phase transition.

Motivated by the torque magnetometry results, Alicea and Balents studied a tight-binding model appropriate for bismuth and found two novel features, which are likely to be relevant to these experiments.[2] First, they found that strong spin-orbit generates an unconventional Zeeman effect and noticeably suppresses the quantum limit for trigonal fields, which qualitatively explains the structure at fields greater than 10T. Comparing Fig. 3 of Li et al. to Fig. 1a of Alicea and Balents, shows that the general features of the high field data can be understood in a non-interacting picture which properly treats the spin-orbit coupling. Furthermore, Alicea and Balents found electron interactions are likely to lead to Wigner crystal phases near the emptying of a low Landau level, which could explain the observed hysteresis.

On the other hand, the high field structure arising in the hole band as seen in transport measurements remains a puzzle.[3] This structure is not explained by the calculations of Alicea and Balents, although their work does suggest there could be charge density instabilities in the hole band. Huber et al.[4] have proposed that the structure observed, in the transport and in the torque magnetometry measurements, might be due to surface states. They argue that the surface plays a key role because the mean free path is longer than the sample size and they investigate this role in the transport of bismuth nanowires.

In summary, independent measurements have revealed striking structure in the electronic properties of bismuth at magnetic fields as high as 30T. There are indications that at least some of this structure may be understood without invoking electronic correlations. Also, the role of surfaces warrants further investigation. However, the observation of hysteresis suggests that a distinct phase may be stabilized at large fields. Furthermore, due to the small hole velocity, one would expect correlation effects to be strong and possibly lead to Wigner crystal or charge density wave formation.[2] In addition, Burnell, Bernevig and Arovas found a fractional quantum Hall state can be stabilized in a bulk, isotropic material at very low carrier density, if it is accompanied by a staging transition where the electrons reorganize themselves in layers perpendicular to the magnetic field.[5] All of this suggests that further work at high magnetic fields is needed to clarify what features, if any, are due to surface effects and whether electronic correlations do, in fact, stabilize a new phase in bismuth.

[1] K. Behnia, M.A. Measson, and Y. Kopelevich, Phys. Rev. Lett. 98, 166602 (2007).
[2] J. Alicea and L. Balents, arXiv:0810.3261.
[3] In the transport measurements, the three electron pockets did not appear to contribute to the quantum oscillations in the ultraquantum limit.
[4] T.E. Huber, A. Nikolaeva, L. Konopko and M.J. Graf, arXiv:0810.3872.
[5] F.J. Burnell, B.A. Bernevig and D.P. Arovas, arXiv:0810.1757.