Phase Transitions of Dirac Electrons in Bismuth

Lu Li, J. G. Checkelsky, and N. P. Ong (Princeton Univ.)

Introduction

In the semi-metal element bismuth, the Fermi Surface (FS) is comprised of 3 electron ellipsoids and one hole ellipsoid. The 3 electron FS have a linear energy-momentum dispersion well described by the Dirac Hamiltonian. A long-standing impediment to the investigation of the Dirac electrons in high magnetic fields **H** is that when **H** is nearly aligned with the trigonal axis **Z**, the projected area of the hole FS is nearly equal to that of each electron ellipsoid. This has prevented the electron Landau Levels (LL) from being observed. Using high-resolution torque magnetometry, we have shown that with **H** at a small tilt angle θ to **Z**, the electron signals are greatly amplified. This has allowed us to resolve the electron LLs from the holes. Extending the torque measurements to higher fields, we observe jumps in the magnetization which imply a field induced transition to an interesting many-body state in which the 3-fold valley degeneracy of the Dirac electrons is lifted.

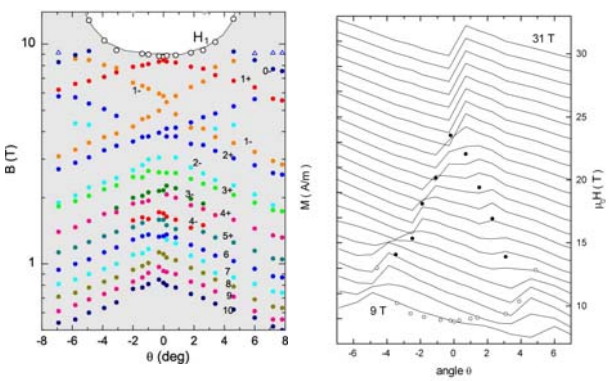

Figure 1 (a, left panel) The fields $B(n,\pm)$ at which Landau sub-level $(n,\pm)$ in bismuth cross the chemical potential ($\pm$ indexes the Kramers degeneracy). The crossings are inferred from torque magnetometry performed with **H** at a small tilt angle θ to the trigonal axis **Z**. The steep θ dependence of $B(n,\pm)$ reflects the strong LL dispersion in the Dirac electron pockets. The curve H_1 marks a transition to a many-body state above 10 T. The Panel b (right) plots the transverse magnetization M_{trans} vs. θ at selected field values from 9 to 31 T. The discontinuities at H_2 (solid circles) and at H_1 (open circles) define transitions to the many-body state. (For details see Li et al. [3]).

Results and Discussion

As shown in Fig. 1, the field $B(n, \pm)$ at which the LL with indices $(n, \pm)$, where $\pm$ labels the Kramers doublet, crosses the chemical potential disperses strongly with tilt angle θ (consistent with electron FS as opposed to the hole FS). At fields above 9 T, we observe the emptying of the last-but-one LL (0,-). Above 9 T, we observe a jump in magnetization at the field H_1, which signals a field-induced transition to the region shaded white. The right panel (b) shows traces of the transverse magnetization M_{trans} vs. tilt angle θ in fixed field ($9 < H < 31$ T). The jump in M_{trans} as θ crosses the boundaries of the cone-shaped region is evident. We interpret the jumps as field-induced transitions to a many-body state in which the 3-fold valley degeneracy is lifted. Within the cone shaped region, the electrons occupy a linear combination of valley states with much lower exchange energy. The report was published in Science [3].

Acknowledgements

This work is supported by a NSF grant (DMR 0213706). The authors wish to thank Dr. Scott Hannahs, Dr. Alexey Suslov and Dr. Eun Sang Choi for their generous assistance during the experiment.

The following papers acknowledge support from NHMFL.

1. J. G. Checkelsky, Lu Li, and N. P. Ong, Phys. Rev. Lett. **100**, 206801 (2008).
2. J. G. Checkelsky, Minhyea Lee, E. Morosan, R. J. Cava and N. P. Ong, Phys. Rev. B **77**, 014433 (2008).
3. Lu Li, J. G. Checkelsky, Y.S. Hor, C. Uher, A. F. Hebard, R. J. Cava and N. P. Ong, "Phase transitions of Dirac electrons in bismuth." Science **321**, 547 (2008).
4. Joseph G. Checkelsky, Lu Li, and N. P. Ong, "Divergent resistance at the Dirac point in graphene: evidence for a transition in high magnetic field." Cond-mat arXiv:0808.0906v1.
5. J. G. Checkelsky, Lu Li, G. F. Chen, J. L. Luo, N. L. Wang and N. P. Ong, "Large quasiparticle thermal Hall conductivity in the superconductor $Ba_{1-x}K_xFe_2As_2$." Cond-mat arXiv: 0811:4668v1.