Mixed-valence insulators with neutral Fermi surfaces

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DC, I. Sodemann & T. Senthil, arXiv:1706.00418
I. Sodemann, DC & T. Senthil, *to appear*

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Talk online at http://debanjanchowdhury.wix.com/homepage

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Topological mixed-valence insulators

- Topological insulators: Spin-orbit coupled band-insulators of electrons without exotic (fractionalized) quasiparticles.

- Many experimental realizations: $Bi_{1-x}Sb_x$, Bi_2Se_3, Bi_2Te_3,…. Well described within band-theory.

Hasan, Kane, 2010; Qi, Zhang, 2011

- Role of strong correlations? Candidate materials?

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Hasan, Kane, 2010; Qi, Zhang, 2011

- Role of strong correlations? Candidate materials?

- Mixed-valence systems are ideal candidates!

- SmB_6 is currently the most popular candidate correlated topological insulator.

Dzero, Sun, Galitski, Coleman, 2010

The conundrum

- Is SmB_6 a correlated topological insulator that is adiabatically related to the usual topological band insulator?

OR

- Does SmB_6 host a truly exotic insulating bulk with gapless fermionic excitations?

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Rest of this talk: 1) Overview of the experimental puzzles.
2) Theory of emergent neutral Fermi surfaces in a three dimensional mixed-valence insulator (in the bulk).

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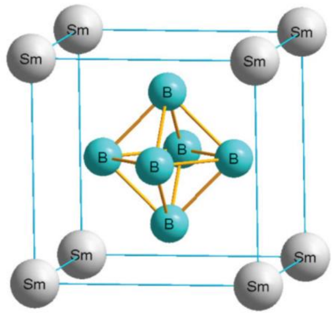
SmB_6 : A classic mixed valence insulator

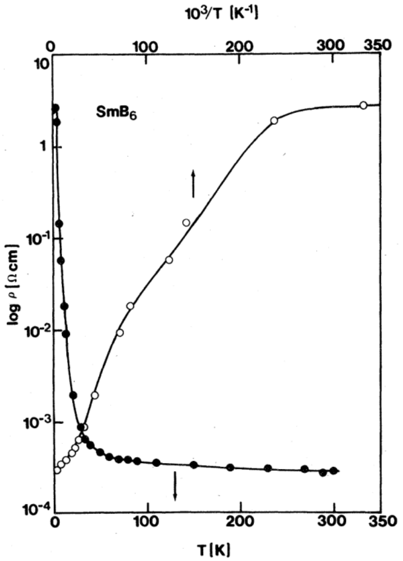


- Simple cubic structure. Mobile d-electrons and strongly correlated f-electrons with strong spin-orbit coupling. Menth, Buehler, Geballe, 1969

- The valence of Sm fluctuates between Sm^{2+} and Sm^{3+}.
  Sm^{2+} : $4f^6$ (completely filled crystal field split J=5/2 shell)
  Sm^{3+} : $4f^5\ 5d^1$ (one mobile d-electron and one f-hole)
  Chazalviel et al., 1976

- A bulk electrical insulator. Resistivity saturates at low temperatures due to metallic surface. (Maybe topological?)
  Wolgast et al., 2013; Zhang et al., 2013

- Many unusual features in the bulk! (In-gap states?)



Allen, Batlogg, Wachter, 1979

Mott, 1974; Varma 1976

SmB_6 : A classic mixed valence insulator

- Many low-temperature anomalies:

  Linear in T specific heat from bulk states.

  Flachbart et al., 2006; Phelan et al., 2014; Wakeham et al., 2016

  Sub-gap optical absorption.

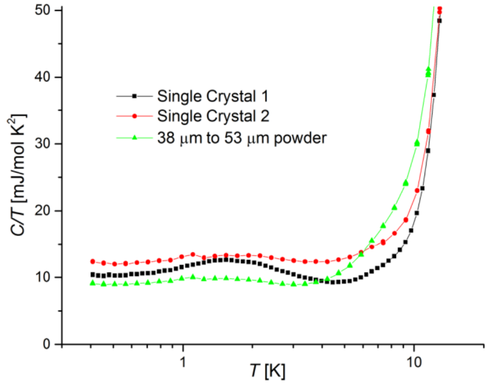
  N.J. Laurita et al., 2016

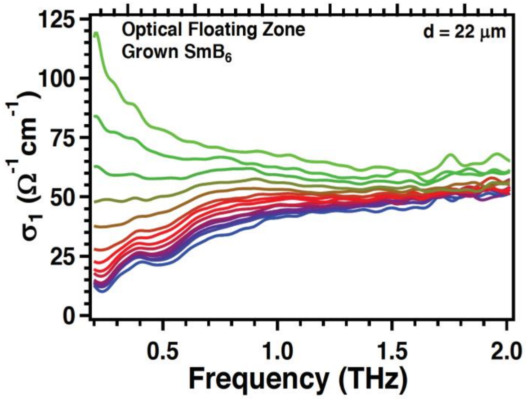
- NMR relaxation

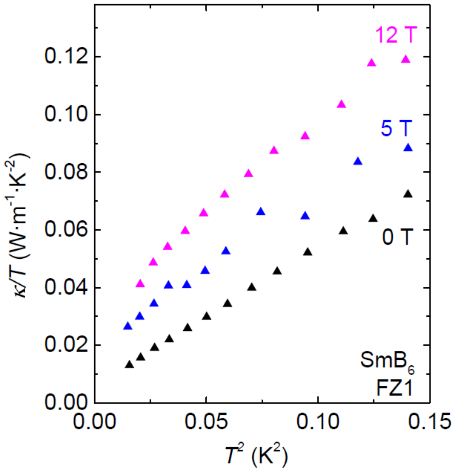
  V. Mitrovic et al., *unpublished*; T. Caldwell et al., 2007

  (Field induced) thermal conductivity*

  M. Hartstein, S. Sebastian et al., *unpublished*





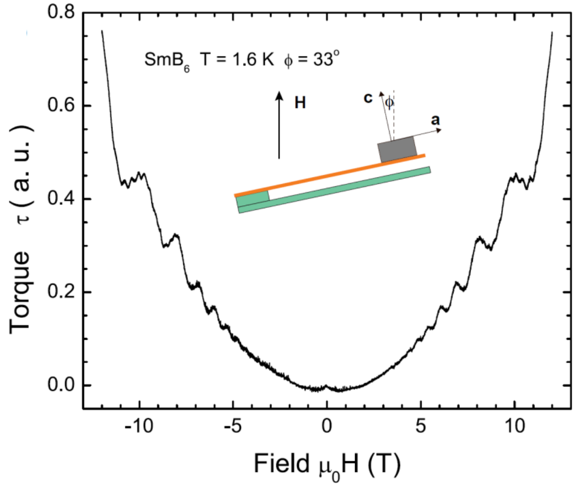


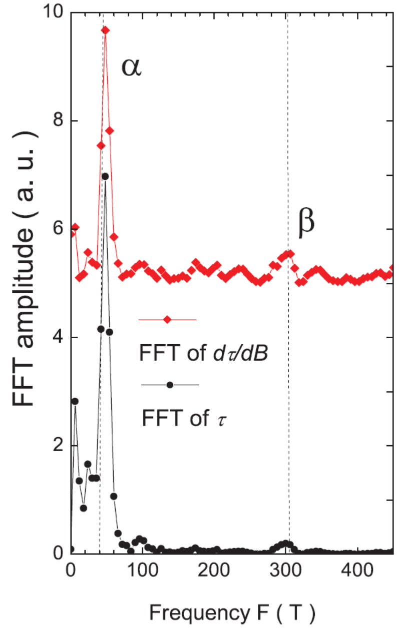
* Not present universally

Y. Xu et al., 2016

Quantum oscillations in SmB_6

- Oscillations from two-dimensional metallic surface states?
- Seen in magnetization but not in resistivity.
- Sharp (small) frequencies.

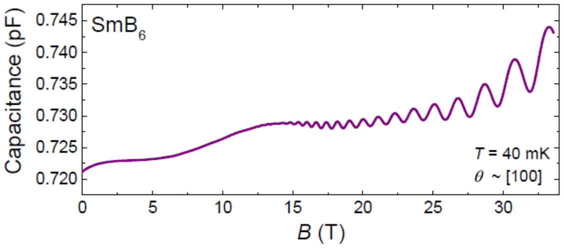


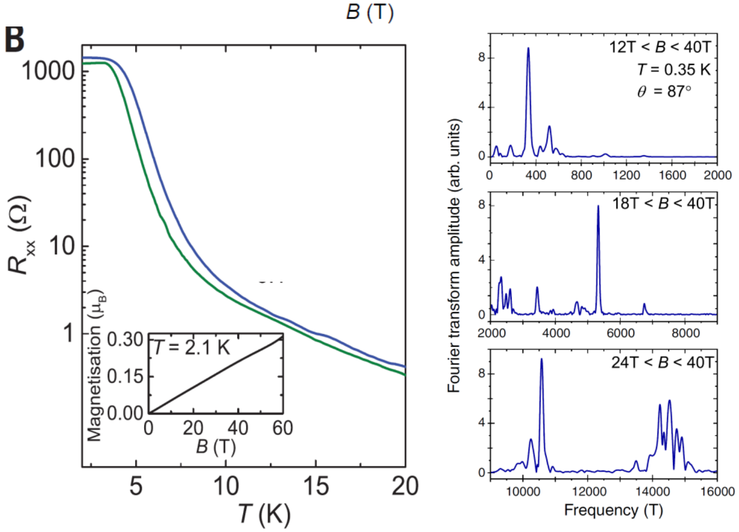


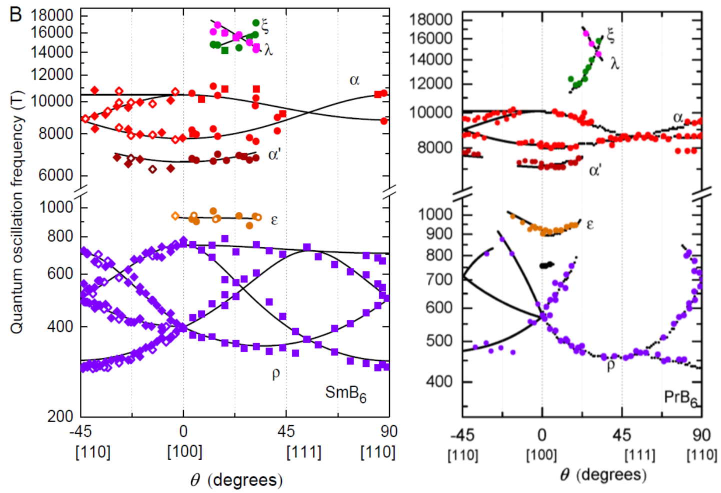
G. Li et al., Science 2014; Denlinger et al., 2016

Quantum oscillations in SmB_6

- Quantum oscillations in magnetization (but not in resistivity).
- Sharp frequencies.
- New high frequency oscillations (similar to observations in other metallic hexaborides).
- Angular dependence?
- Low temperature enhancement and deviation from Lifshitz-Kosevich behavior.
- Radical proposal: Oscillations arising from the bulk in-gap states!







B. Tan et al., Science 2014; Hartstein, Sebastian et al., *unpublished*

Exotic bulk in SmB_6 ?

- Is there a Fermi-surface of neutral Fermions in three dimensions that is consistent with all of these experimental observations (and related theoretical considerations)?
- A standard example: spinon Fermi-surface coupled to U(1) gauge field. Relevant for organics.

  Motrunich, 2005; Lee, Lee 2005
  Yamashita et al., 2008; Yamashita et al., 2010
- What is the microscopic origin of the neutral fermion? How can one stabilize a phase with Fermi-surface of neutral fermions in a mixed-valence insulator?

  Chowdhury, Sodemann, Senthil, 2017

Periodic Anderson model

- The valence of Sm fluctuates between Sm^{2+} and Sm^{3+}.
  Sm^{2+} : Fully filled crystal field multiplet
  Sm^{3+} : One mobile d-electron (charge -e) and one f-hole (charge e)

$$f_\alpha \rightarrow \varepsilon_{\alpha\beta} f_\beta^\dagger = \tilde{f}_\alpha$$

- Simplest possible model:

$$\begin{aligned} H &= \sum_{k\alpha} \epsilon_d(k) d_{k\alpha}^\dagger d_{k\alpha} + \epsilon_f(k) \tilde{f}_{k\alpha}^\dagger \tilde{f}_{k\alpha} \\ &+ \sum_r (\epsilon_{\beta\gamma} V_{\alpha\beta} d_{r\alpha}^\dagger \tilde{f}_{r\gamma}^\dagger + H.c.) - U_{df} \sum_r n_r^{\tilde{f}} n_r^d \\ &+ U_{ff} \sum_r n^{\tilde{f}_r} (n^{\tilde{f}_r} - 1), \end{aligned}$$

- Average d-electron density = f-hole density

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On-site Coulomb interaction largest scale

- Average d-electron density = f-hole density

Fermionic Composite Excitons

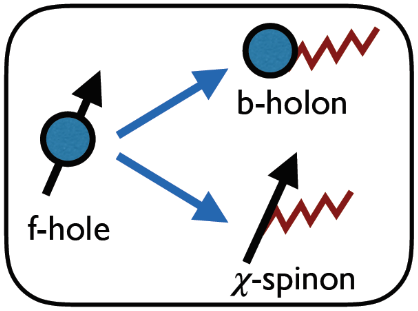
- Fractionalize the f-hole into:
  Holon (b) – spinless Boson that carries physical charge e
  Spinon (χ) – spin ½ Fermion that is electrically neutral

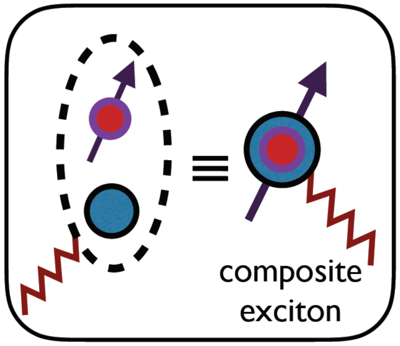
- Spinon and holon coupled to emergent U(1) gauge-field, a.

- Electrical insulator when holon is gapped ($\langle b \rangle = 0$).
  Density of doped holes, away from 4f^6 configuration, is x ($\langle b_{\boldsymbol{r}}^\dagger b_{\boldsymbol{r}} \rangle = x$).

- At large U$_{df}$, Coulomb attraction between holons and conduction electrons may lead to formation* of excitons: charge neutral fermions carrying spin ½ .

$$\tilde{f}_{\boldsymbol{r}\alpha} = b_{\boldsymbol{r}}\chi_{\boldsymbol{r}\alpha}$$





$$\psi_\alpha = b d_\alpha$$

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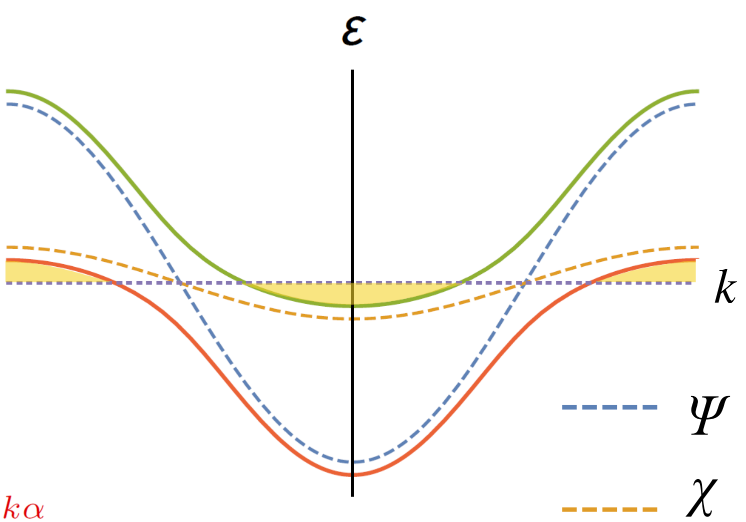
* 1) Similar to "molecular fermion" in Bose-Fermi mixtures (without gauge-field).
2) Fermionic excitons in multicomponent QH systems (Barkeshli et al., 2016).

Effective model in the strong-binding limit

- Low energy degrees of freedom : composite excitons and spinons minimally coupled to U(1) gauge-field. (d-electrons and holons are gapped; electrical insulator)



- Density of excitons = Density of spinons = Density of d-electrons

- Effective Hamiltonian:

$$H = \sum_{k\alpha} \epsilon_k^{\psi} \psi_{k\alpha}^{\dagger} \psi_{k\alpha} + V \epsilon_{\alpha\beta} \psi_{k\alpha} \chi_{-k,\beta} + h.c + \epsilon_k^{\chi} \chi_{k\alpha}^{\dagger} \chi_{k\alpha}$$

- In addition, there is a strong on-site repulsion for the fCE.

- A possible ground state : Compensated semi-”metal” of fCE.

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Phenomenology of Fermionic CE liquids

- Specific heat : $C = \gamma T \quad \gamma \sim \ln(1/T)$
- NMR relaxation rate: $\frac{1}{T_1 T} = \text{const.}$
- Optical conductivity: $\sigma(\omega) \sim \omega^{\alpha}$ ($\alpha = 5/3$ or 2 depending on impurity mean-free path)

  Ng, Lee, 2007
- Thermal conductivity: $\kappa_{xx} \sim T$

  Katsura, Nagaosa, Lee, 2010

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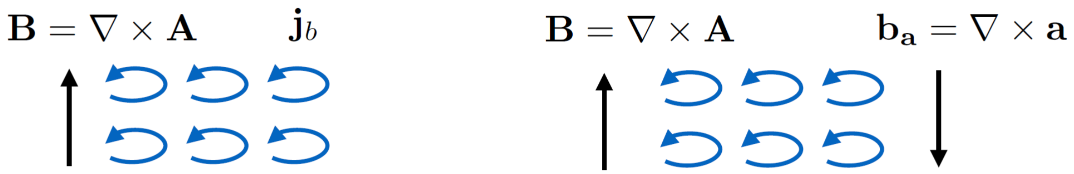
Effects of magnetic fields?

- External magnetic field induces an internal magnetic field.

Motrunich, 06

- Gapped holon (charged under external and internal gauge-fields) responds to external field and sets up currents that induce an internal magnetic field.



- Neutral fCE experience internal magnetic field and can exhibit Landau quantization.

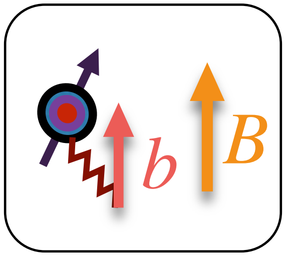
- Energy follows from gauge-invariance

$$u(b, B) = u_0 + \frac{(b-B)^2}{2\mu_b} + \frac{b^2}{2\mu_{\rm ce}} + \frac{B^2}{2\mu_v} + u_{\rm osc}(b) + .. \Rightarrow b = \alpha B, \text{ with } \alpha = \frac{\mu_{\rm ce}}{(\mu_{\rm ce} + \mu_b)}$$

Hard to compute α but expected to approach 1 close to metal-insulator transition.

- Frequency of oscillations

$$\Delta\left(\frac{1}{B}\right) = \frac{2\pi}{S_\perp^i}\left(1 + \frac{\mu_b}{\mu_{\rm ce}}\right)^{-1} = \frac{2\pi\alpha}{S_\perp^i}$$



Sodemann, Chowdhury, Senthil, *to appear*

Outlook

- Gapless fermionic excitations in a mixed-valence insulator?
- Theoretical description of a new phase in mixed-valence insulators.
  Low energy excitations: FERMIONIC COMPOSITE EXCITONS (Bound state of holon and conduction electron).
- Immediate consequence: Weak field thermal Hall effect.

$$\kappa^i_{xy} = (\omega_{c,i}\tau_i)\kappa^i_{xx} \qquad \omega_{c,i} = \alpha e|\mathbf{B}|/m_i$$

- Other correlated mixed-valence insulators (e.g. YbB_{12}) likely display similar phenomenology!