EVIDENCE THAT THE MIXED VALENCE COMPOUND SMB_6 IS A TOPOLOGICAL INSULATOR

Discovery of the First Topological Kondo Insulator: SmB_6.
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S. Wolgast, C. Kurdak, K. Sun, J. W. Allen, D-J. Kim and Z. Fisk. *Robust Surface Hall Effect and Non-local Transport in SmB_6: Indication for an ideal Topological Insulator"*
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J. Botimer, D-J. Kim, S. Thomas, T. Grant, Z. Fisk and X. Jia.
Topological Kondo Insulators
Maxim Dzero, Kai Sun, Victor Galitski, and Piers Coleman,
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Recommended and a Commentary by Chandra Varma,
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The topological manner of thinking in condensed matter physics, which may be credited to David Thouless and to Duncan Haldane, among others, in elucidation of the quantum Hall effect, has in the hands of Kane and Zhang and Balents and Moore and their collaborators led to the discovery of the topological insulators in solids with spin-orbit coupling. They are based on applying topological reasoning to concepts in one electron theory whose origins go back to Herring in the 1930's and Luttinger in the 1950's. Experiments have followed, on anciently fabricated compounds, with significant confirmation. Most prominent among these are the experiments by Molencamp et al. on the quantized spin-Hall effect on a two-dimensional compound ($Hg_{1-x}Cd_xTe$) with a one-dimensional topological surface state and the spin-resolved ARPES experiments by Hasan et al. in a three dimensional compound ($Bi_2Se_3, etc.$) with two dimensional topological surface states.

The experimental realizations have more real-life problems than the theory. In Molencamp's experiment their is indeed strong evidence for quantization, but it is not nearly as clean as the standards set by quantum Hall effects in a magnetic field. Hasan's experiments give spectacular confirmation of the predicted tying of the spin-direction to the momentum but in the three-dimensional materials confirmation through transport measurements has been lacking. First, there is no quantization in transport to be expected in this case and second the materials investigated appear not to be bulk insulators. Now interesting help has arrived from a new direction - the three dimensional strongly correlated or Kondo or Mixed Valence insulator SmB_6.

Simple symmetry conditions on the product of parity of conduction and valence band edge states in semi-conductors, described by Fu and Kane[1] specify the topological insulators (given the spin-orbit coupling). (No one appears to have worked out what fraction of all insulators with large spin-orbit coupling may be expected to be topological insulators.) Dzero et al. looked at the band-structure of the strongly correlated or Kondo insulators and suggested that several which have been investigated for decades, including SmB_6, should be three dimensional topological insulators. Actually, there is nothing about their strongly correlated nature, which is central to their topological properties. It is known from the early theoretical work[2] on periodic array of the strongy correlated f-orbitals hybridized hybridized with wide band electrons from s and d orbitals that the phenomena is governed by Kondo effect leading to a periodic phase shift in the limit of zero energy plus a term whose coefficient is linear in energy with a scale set by the Kondo temperature. Well below the Kondo temperature, most properties follow simply from the requirements of Bloch's theorem on wave-functions in a periodic lattice. So whether one has a metal with strongly renormalized fermi-liquid parameters or an insulator simply depends on whether the number of electrons per unit-cell is odd or even. Dzero et al., used the Fu-Kane conditions and drew the important conclusion that the conditions for topological insulators in such compounds are more likely fulfilled in the Mixed-Valence limit of the Kondo problem, i.e. near the extreme of the particle-hole asymmetry, where the local moments fluctuate between two charge states with relative probablity of $O(1)$. This limit also has the advantage that in it, the Kondo temperature is of order the one-electron hybridization width itself, rather than be exponentially smaller. This and the large spin-orbit coupling in f-orbitals makes them ideal to search for topological insulators.

A curious property of SmB_6 has been known for decades: the conductivity decreases exponentially with temperature below about 20 K with a gap of about 20 K, but saturates to a constant value below about 1 K. One could argue it away by invoking all sorts of only partially satisfactory excuses. Spurred probably by the rampant recent discussion of topological insulators and by Dzero et al's paper, the authors of the paper above decided to check, through an ingenious but simple technique, whether the saturation conductivity is due to surface states. The techique is to have 8 current/voltage leads, 4 on opposite surfaces of the sample and measure the resistance with different combination of leads. All measured resistances should be linear combinations of each other but if one of the contributions is a purely surface contribution, there are geometries in which it dominates and geometries in which the bulk contribution dominate. The coeffiecients in a cubic crystal, like SmB_6 can be calculated well through modeling the electric field and current distribution for any given set of current and voltage contacts. In my opinion the authors have succeded very well in showing that there is indeed a distinct surface contribution which is unmixed with the bulk contribution. The corroboration of the topological nature comes from studying different samples with varying bulk resistances and showing that the surface contribution remains almost the same. In a second paper, noted above, Hall resistance independent of surface abrasion has been measured. In yet another paper noted below[3], tunneling conductance has been used to suggest surface states at low energies.

How is one to further attest to the topological nature of the surface states. A definitive possibility is spin-resolved ARPES but the success of the experiment relies on surface quality and has not been successful. So far, no surface states are even identified. A consistency check is to study change in surface conductivity at very small fields and low temperatures. The two dimensional surface states are anti-localized due to spin-orbit interactions[4] and in weak magnetic field are expected to show a resistance peak limited by inelastic scattering. But this is not unique to topological surface states but only to two-dimensional states with sufficient spin-orbit coupling. An interesting possibility, suggested to me by P.A. Lee is to study thermal conductivity, which at low temperatures should as for insulators $\to 0$ as T^3 for the bulk but be $\propto T$ for the electronic contribution from the surface states.

Are there aspects of strong correlations in such materials which may lead to qualitatively new effects in topological insulators, for example fractional quantum Hall effects. This is doubtful for the pure mixed-valence of Kondo insulators; both the effective quasi-particle one-particle energies and the quasi-particle interaction energies are renormalized by the many body effects to similar magnitudes. So in terms quasi-particles, they are similar to weakly correlated materials. However, defects in Kondo insulators, for example, non-magnetic impurity substituting for a rare-earth ions are expected to produce magnetic states due to creation of the 'Kondo-hole". These may lead to new low energy resonances with consequences not found in weakly correlated materials.

1. L. Fu and C. L. Kane, Phys. Rev. B76, 193512 (2007).
2. C.M. Varma and Y. Yafet, Phys. Rev. B 13, 2950 (1976); Rev. Mod. Phys. 48, 219 (1976).
3. X. Zhang et al., ArXiv.org/1211.5532

4. P.A. Lee and T.V. Ramakrishnan, Rev. Mod. Phys. 57, 287 (1985).