Emergent technology based on Fermi-arcs?

Transport evidence for Fermi-arc-mediated chirality transfer in the Dirac semimetal Cd_3As_2
P. J. W. Moll, N. L. Nair, T. Helm, A. C. Potter, I. Kimchi, A. Vishwanath, J. G. Analytis. *Nature* **535**, 266 (2016): DOI: 10.1038/nature18276

Current at a Distance and Resonant Transparency in Weyl Semimetals
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Recommendation and commentary by Luis Balicas, NHFML.

Introduction: A lot of work was reported recently on Weyl semi-metallic systems which are three dimensional materials characterized by strong spin-orbit coupling, lack of either time-reversal or inversion symmetry, and whose band gaps close at an even number of discrete points in the Brillouin zone, the so-called Weyl points. In the neighborhood of the Weyl points, the electronic bands are predicted [1], and found [2] to disperse linearly, i.e. $\varepsilon_F = \pm\hbar v_F|k|$. Therefore, in these compounds the charge carriers behave as bulk Dirac-like quasiparticles. The Berry phase curvature pseudospin is predicted to display singularities at the Weyl points which act as either sinks or sources of Berry phase. The flux of Berry phase flowing through an imaginary surface enclosing one of these points is predicted to acquire values of 2π, thus leading to Weyl points with either positive or negative chirality. This implies that any arbitrary two-dimensional plane intersecting the Brillouin zone would observe a change in Chern number by ± 1 when crossing a Weyl point. Hence, the surface of these crystals are predicted to display electronic surface states consisting of open line segments, or Fermi arcs, connecting pairs of bulk Weyl points of opposite chirality [3]. In angle resolved photoemission experiments, the Fermi arcs have been used as a surface fingerprint of the topological character of the bulk band structure [2, 4].

These Fermi arcs were predicted to lead to novel and unusual phenomena. For example, through a combination of semiclassical analysis and numerical methods, Potter *et al.* [3] predicted that up to certain critical magnetic-field strength, which is inversely proportional to sample thickness, these Fermi arcs on the surface of Weyl semi-metals would contribute to a novel type of quantum oscillatory phenomena. For samples having thicknesses comparable to their carrier mean free path, these open Fermi arcs would participate in unusual closed magnetic orbits which would traverse the bulk of the sample

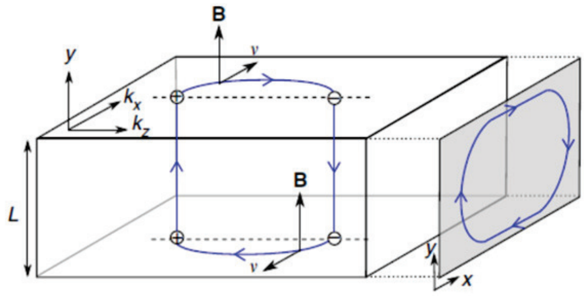

Figure 1: Quantum oscillations from Weyl Fermi Arcs. Semiclassical orbit in a magnetic field along y, involving surface states that gives rise to quantum oscillations in a finite thickness slab (shown in mixed real space in y and momentum space in x, z directions; inset shows corresponding real space trajectory). From Ref. [3].

and subsequently connect the opposite surfaces of the crystal. Similarly to the cyclotronic orbits of conventional carriers on a bulk Fermi surface, these so-called "Weyl orbits would lead to oscillations in the density of states periodic in inverse magnetic field and contribute to the de Haas van Alphen or the Shubnikov de Haas effects. Rather than resulting from momentum transfer via the Lorentz force, this orbit would be driven by the transfer of chiral fermions from one Weyl node to another, or the effect leading to the so-called Adler-Abel-Jackiw or chiral anomaly claimed to lead to anomalous negative magnetoresistivity in Weyl semi metallic systems [5, 6].

Experimental Observations: In order to test the predictions by Potter *et al.* [3], Philip Moll and collaborators built, through Focused Ion Beam (FIB) techniques microstructures out of Cd_3As_2 single crystals. Cd_3As_2 is a well-known Dirac semi-metal candidate characterized by a simple, small and nearly spherical Fermi surface [7]. The application of electromagnetic fields to either Weyl or Dirac semimetals is predicted to induce a pumping of electric charges between Weyl nodes with opposite chirality, due to the chiral anomaly. Through the residual resistivity, and the known carrier effective mass of Cd_3As_2, Moll *et al.*, estimated a transport mean free path l of 1 μm. By making a series of micro-bridges having thicknesses t ranging from 3 to 0.15 μm, respectively both above and below l, the authors were able to determine a critical thickness of the order of ~ 2 μm below which a novel quantum oscillatory frequency can be observed. This new frequency $F_W \sim 60$ T is distinct from its bulk counter-part, i.e. $F_b \sim 40$ T, while displaying a pronounced angular dependence as the magnetic-field is rotated. While F_b is nearly independent on angle, F_W is observed to vary as $1/\cos\theta$ indicating that the associated orbit depends only on the component of the field perpendicular to the surface, or that the orbit necessarily involves a surface state. In addition, the amplitude of the oscillations associated with F_W decay exponentially as the thickness of the sample increases, or as the probability of tunneling between both surfaces decrease. In order to further confirm that F_W does not result from a trivial surface state, Moll *et al.* produced samples with triangular cross-sections. The idea is to subject the charge carriers to a distribution of distinct Weyl orbits as they tunnel through the bulk and between both surfaces of the crystal. This would prevent the coherent superposition of Weyl orbits and smear out the oscillatory frequency F_W if it resulted from the Fermi arcs on the surface of the crystal. If instead it resulted from a trivial surface state, this micro-structured geometry would have no effect on F_W. It turns out that triangularly shaped crystals do not display oscillations at the frequency F_W confirming that it must result from orbits involving Fermi arcs on opposite surfaces of the crystal. Finally, Moll *et al.* subjected the surface of their crystals to a FIB treatment to increase its roughness, observing basically no effect on the amplitude of F_W, which confirms that carriers circulating on these Fermi arcs are topologically protected from scattering, and this could have technological implications.

It appears therefore that Moll *et al.* have confirmed that the Fermi arcs, previously observed by ARPES, do affect the transport, and thermodynamic quantities in Dirac/Weyl semi-metals (through the density of states). Below I briefly discuss a couple of additional predictions by Baum *et al.* associated with these arcs.

Additional Predictions by Baum *et al.*: According to Baum *et al.*, these arcs could lead to the observation of additional effects. For example, under a magnetic field the application of a voltage differential between two leads placed lets say on the top surface of the crystal, should generate a negative voltage on its bottom surface due to the sense of circulation of carriers subjected to a Weyl orbit. In a way this would create a topologically protected voltage inverter. The fundamental current question is if the unique transport properties of such topological states could be harvested for room temperature applications. For example, compounds such as WTe_2 and particularly the orthorhombic phase of $MoTe_2$ were predicted [8] and subsequently found by ARPES [9] to correspond to a novel type of Weyl semi-metallic system. These co-called Weyl type II systems are characterized not by a linear touching between bands but by a linear touching between electron- and hole-like Fermi pockets. In practical terms, these linear touching points, or Weyl nodes and associated Fermi arcs are analogous to the ones seen in the TaAs class of materials. But the dichalcogenides are exfoliable and can be grown in large area through chemical vapor deposition or molecular beam epitaxy techniques. In addition $MoTe_2$ can crystallize also in the semiconducting α phase with a band gap of 1 eV which is comparable to the gap of Si. This opens the possibility of producing devices combining the semiconducting character of α-$MoTe_2$ with interconnects fabricated from semi-metallic $MoTe_2$ whose Fermi arcs would prevent dissipation.

In addition, Baum *et al.* also predicted that an AC current cycle due to a pulse of electromagnetic field on the top surface of a Weyl semi-metallic system would lead to emission from the lower surface every time the frequency is an integer multiple of $\omega_0 = 2\pi/T_0$ where T_0 is the size of the Weyl orbit from one Fermi arc to the next through the bulk of the sample divided by the Fermi velocity v_a. Thus, by shaping the crystal of a Weyl semi-metallic system with the desired geometry one could create a special type of optical filter that would "transmit only the harmonics of a chosen fundamental frequency, acting as frequency multiplier.

In other words, we are witnessing the emergence of topology in physics not only as a field of fundamental scientific interest, but also as a field of untapped technological potential.

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