Transport phenomena in Weyl semimetals

Justin H. Le
Department of Electrical & Computer Engineering
University of Nevada, Las Vegas
lejustin.lv@gmail.com

December 16, 2016

1 Motivation

Although most studies of the quantum Hall effect have taken place under temperatures and external magnetic fields that would be impractical for applications in high-mobility electronics, quantum Hall-like transport phenomena, such as the quantization of transverse resistance, have been demonstrated in the absence of an external field, now referred to as the quantum anomalous Hall effect [Qia+14]. This discovery motivates the continuation of studies in the unique magnetotransport properties of novel materials that exhibit gapless edge modes, namely topological insulators, graphene, and Dirac and Weyl semimetals. These properties in Weyl semimetals, for instance, depart significantly from observations made in other well-understood electronic phases of matter.

In this article, we review some of the transport phenomena of Weyl semimetals that distinguish them from other candidates of high-mobility materials, as well as the physical properties that lead to these phenomena. Particularly, Weyl semimetals exhibit Weyl nodes, which can be interpreted as a three-dimensional analogue of the two-dimensional Dirac cones (linear dispersion relations) that occur at band intersections in graphene. We will review the theoretical notions underlying these Weyl nodes and how interesting transport properties may arise from them.

Weyl semimetals have potential applications in high-speed communications, high-mobility electronics, and high-power laser design due to a number of attractive and anomalous properties that they exhibit, namely the masslessness of the carriers that they host, known as Weyl fermions, and the structural capacity for precise frequency selectivity in the transmission of light. As these properties require the preservation of only one type of symmetry, they are more robust than they are in other candidate materials considered for these applications.

The motivation for current applied research lies in adapting the experimental methods developed in very recently for scaling up the fabrication and characterization process of Weyl semimetals. Particularly, recent experiments have succeeded in observing the presence of Weyl nodes, the bulk states of these semimetals, in the absence of a high external magnetic field, which introduces opportunities for adapting the materials for commercial application. In this new setting, it remains to be seen whether the attractive transport properties can be engineered in accordance with the previous literature on the transport theory of Weyl nodes. As the majority of literature on this topic has focused on transport phenomena described strictly in relation to the magnetic field, such as negative magnetoresistance and anomalous Hall effects, and in spite of their widespread interest to the scientific community, it remains unclear how these behaviors can be studied in the context of engineering.

2 Theory

In contrast with topological insulators, in which the transport properties arise from surface states, the transport properties of Weyl semimetals occur as a consequence of bulk states that rely on the topological stability of Weyl nodes. Here, Weyl nodes can be interpreted as points of contact in the first Brillouin zone between nondegenerate bands, but from the gauge-theoretic perspective, they are in fact points at which Berry connection exhibits no curvature, making them monopoles.

Recall that in the quantum Hall effect, the Berry connection $A(k)$ is analogous to the vector gauge potential found in electromagnetism, i.e., observables remain invariant under gauge transformations of this potential but physical consequences of electromagnetic fields can be computed from it. Although the deepest topological results concerning Weyl semimetals come from the study of this potential in the context of manifold theory, we neglect the formal results here and present only the concepts relevant to the characterization of Weyl semimetals by their transport properties.

By defining the potential and Berry curvature, respectively,

$$\begin{aligned} A(k) &= i\langle u(k)|\nabla_k u(k)\rangle \\ F(k) &= \nabla_k \times A(k), \end{aligned} \tag{1}$$

where $u(k)$ is a Bloch wave, and letting dS be the differential element on any Fermi surface enclosing a Weyl node, the curvature satisfies

$$\chi = \frac{1}{2\pi} \oint_{FS} F(k) \cdot dS,$$

where χ is the chirality of the node. By this characterization, the chirality corresponding to a particular Berry curvature is analogous to the magnetic charge corresponding to a magnetic field, respectively, making the Weyl node analogous to a magnetic monopole.

In low temperature, the system is said to be in the quantum limit, in which only the zeroth Landau level contributes to the transport phenomena between Weyl nodes. Recall that the Landau levels are the spectrum of the Hamiltonian in the presence of a magnetic field, as in the quantum Hall effect theory. In this regime, a charge pumping effect takes place between Weyl nodes—in the presence of an applied electric field (which itself is parallel to the external magnetic field), quasiparticles essentially vanish from a Weyl node and reappear in the corresponding Weyl node of opposite chirality. This chiral anomaly, as it is called, leads to a number of unusual transport properties, the most immediate of which is negative magnetoresistance.

Weyl nodes are stable in the sense that they appear in pairs almost invariably due to the non-degeneracy of bands. Degeneracy of bands leads to a widely gapped spectrum, and here the importance of symmetry-breaking can be seen—preservation of both time and inversion symmetry would lead to each state being doubly degenerate, and thus, Weyl nodes are created experimentally through the breaking of at least one of these symmetries. Furthermore, Weyl nodes are robust against perturbations that respect translational invariance, which would typically make them sensitive to impurities, but with smooth disorder, it is expected that many transport properties of the semimetal may prevail even in the presence of impurities [HPV12].

The significance of the three-dimensionality of Weyl semimetals can be seen by noting that points of degeneracy between bands can only occur when crystal momentum reaches zero in all three dimensions. In the Hamiltonian, this requirement is embodied by the three-dimensional Atiyah-Bott-Shapiro [Ho 05] form,

$$H = \pm v_F \sigma \cdot k,$$

where σ denotes the Pauli matrices and the sign denotes the chirality of the Weyl nodes. Since the dispersion relation is linear at these points, they can be interpreted as the three-dimensional analogue to the Dirac cones that appear in two-dimensional systems such as graphene. Experimentally, pairs of Weyl nodes have arisen as the "splitting" of a Dirac cone. On the other hand, moving the pair toward each other, annihilation of Weyl nodes can occur if the pair have opposing chiralities, as mentioned.

It should be noted that Weyl degeneracy nodes arise in a number of three-dimensional magnetic materials, but only in the Weyl semimetals of interest in this article do no other states correspond directly with the Fermi level besides the Weyl nodes.

The electromagnetic response of Weyl semimetals have been generalized to account for scattering due to impurities, and it was in this work that certain universal characteristics of Weyl semimetals were first given theoretical grounding. These characteristics include the intrinsic anomalous Hall conductivity, which is intrinsic in the sense that no contributions are made from impurity scattering or from bands that are only partially filled [**burkov15**]. Additionally, the negative magnetoresistance that has long been regarded as a signature transport property of Weyl semimetals has likewise been given treatment as a universal characteristic in this work.

In metals, relaxation of the conducting state and of collective electron momentum occurs via impurity or phonon scattering, each of which gives rise to a different temperature dependence of DC conductivity. However, electron-electron interactions conserve momentum and lead to no such effect. In contrast, even in the absence of disorder, Weyl semimetals exhibit an unusual property in that their DC conductivity relies entirely on electron-electron interactions, which is reminiscent of behaviors in graphene and Dirac semimetals. In previous candidates for the realization of Weyl semimetals, this behavior can be attributed to the conducting state consisting of electrons and holes having net zero momentum, making relaxation of the states sensitive to the Coulomb interactions [HPV12]. Interestingly, at low frequencies, the optical conductivity of Weyl semimetals decays more quickly with decreasing temperature than in metals, but at high frequencies, it has direct linear proportionality with temperature.

3 Experiments

Previous works have emphasized scientifically interesting phenomena such as negative magnetoresistance, which predicts that the longitudinal resistivity of the semimetal decreases with increasing magnetic field [Kim+13]. Yet, it is unclear how this property can be connected with the setting that lacks a magnetic field. In contrast, recent experiments have focused on searching for material candidates that have an underlying structure which inherently breaks inversion symmtery and thereby satisfies the condition for the creation of Weyl nodes without the use of an external field. Band structures have been obtained for such candidates, including tantalum arsenide (TaAs), through DFT calculations employing generalized gradient approximation.

TaAs represents anexperimentally siginificant step forward in the study of Weyl semimetals—restrictive conditions on the fabrication and measurement process were avoided by searching through a large number of candidates which lack symmetry and by employing only a stoichiometric, or integer-ratio, chemical composition, paving the way for the scalability and reproducibility of studies in Weyl semimetals with a focus on engineering. Here, measurements of the bulk states were carried out through angle-resolved photoemission spectroscopy.

4 Applications & Outlook

A major experimental interest in recent years is the development of angularly selective materials that are transparent to light at only one incident angle but reflective at all other angles. This filtering technique has been demonstrated in a setup of relative simplicity, precision of selection, and scalability (with respect to incident wave frequency) [She+14]. Weyl semimetals have been considered as a candidate for angular selectivity in three dimensions [Lu+15].

The promise of "Weyltronics" that exploit the masslessness of their carriers for high mobility also leads naturally to the discussion on optical computing that arise in the development of two-dimensional photonic crystals. Although one-dimensional photonic crystals have already found application in a number of commercial products, two-dimensional photonic crystals have been proposed as a means of transmitting light with high speed and improved control over frequency selectivity, as in the context of optical fibers and other technologies. With photonic crystals, frequency selection can be achieved merely by the structural properties of the material, in contrast with the use of refractive indices in conventional optical fibers. However, the difficulty of fabricating photonic-crystal-based fibers on a large scale have prevented it from replacing traditional technologies. With surfacing experimental studies of Weyl points in photonic crystals, a new area of topological photonic crystals has been introduced, in which the understanding of photonic crystals can be connected to the vast literature on topological crystals, especially those concerning transport properties. Most notably, the advent of experimental techniques that avoid the use of external fields has also connected the transport theory of these materials to a more practical setting for high-speed computing and communications. Weyl points have even been observed in three-dimensional photonic crystals using these novel methods [LJS14].

References

[1] Petr Ho řava. “Stability of Fermi Surfaces and K Theory”. In: *Phys. Rev. Lett.* 95 (1 June 2005), p. 016405. DOI: 10.1103/PhysRevLett.95.016405. URL: http://link.aps.org/doi/10.1103/PhysRevLett.95.016405.

[2] Pavan Hosur, S.A. Parameswaran, and Ashvin Vishwanath. “Charge Transport in Weyl Semimetals”. In: *Physical Review Letters* (2012).

[3] Pavan Hosur and Xiaoliang Qi. “Recent developments in transport phenomena in Weyl semimetals”. In: *Comptes Rendus Physique* 14.9–10 (2013). Topological insulators / Isolants topologiquesTopological insulators / Isolants topologiques, pp. 857–870. ISSN: 1631-0705. DOI: http://dx.doi.org/10.1016/j.crhy.2013.10.010. URL: http://www.sciencedirect.com/science/article/pii/S1631070513001710.

[4] Shin-Ming Huang et al. “A Weyl fermion semimetal with surface Fermi arcs in the transition metal monopnictide TaAs class”. In: *Nature Communications* (June 2015). DOI: 10.1038/ncomms8373. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4490374/.

[5] Heon-Jung Kim et al. “Dirac versus Weyl Fermions in Topological Insulators: Adler-Bell-Jackiw Anomaly in Transport Phenomena”. In: *Phys. Rev. Lett.* 111 (24 Dec. 2013), p. 246603. DOI: 10.1103/PhysRevLett.111.246603. URL: http://link.aps.org/doi/10.1103/PhysRevLett.111.246603.

[6] A Yu Kitaev. “Unpaired Majorana fermions in quantum wires”. In: *Physics-Uspekhi* 44.10S (2001), p. 131. URL: http://stacks.iop.org/1063-7869/44/i=10S/a=S29.

[7] Ling Lu, John Joannopoulos, and Marin Soljacic. “Topological photonics”. In: *Nature Photonics* (2014), pp. 821–829. DOI: 10.1038/nphoton.2014.248.

[8] Ling Lu et al. “Experimental observation of Weyl points”. In: *Science* 349.6248 (2015), pp. 622–624. ISSN: 0036-8075. DOI: 10.1126/science.aaa9273. eprint: http://science.sciencemag.org/content/349/6248/622.full.pdf. URL: http://science.sciencemag.org/content/349/6248/622.

[9] B. Q. Lv et al. “Experimental Discovery of Weyl Semimetal TaAs”. In: *Phys. Rev. X* 5 (3 July 2015), p. 031013. DOI: 10.1103/PhysRevX.5.031013. URL: http://link.aps.org/doi/10.1103/PhysRevX.5.031013.

[10] Palash Pal. “Dirac, Majorana and Weyl fermions”. In: *American Journal of Physics* (2011). DOI: 10.1119/1.3549729.

[11] Zhenhua Qiao et al. “Quantum Anomalous Hall Effect in Graphene Proximity Coupled to an Antiferromagnetic Insulator”. In: *Phys. Rev. Lett.* 112 (11 Mar. 2014), p. 116404. DOI: 10.1103/PhysRevLett.112.116404. URL: http://link.aps.org/doi/10.1103/PhysRevLett.112.116404.

[12] Yichen Shen et al. “Optical Broadband Angular Selectivity”. In: *Science* 343.6178 (2014), pp. 1499–1501. ISSN: 0036-8075. DOI: 10.1126/science.1249799. eprint: http://science.sciencemag.org/content/343/6178/1499.full.pdf. URL: http://science.sciencemag.org/content/343/6178/1499.

[13] Xiangang Wan et al. “Topological semimetal and Fermi-arc surface states in the electronic structure of pyrochlore iridates”. In: *Physical Review B* (2011).

[14] Su-Yang Xu et al. “Discovery of a Weyl fermion semimetal and topological Fermi arcs”. In: *Science* (2015).