Quantum transport in Dirac and Weyl semimetals: a review

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ABSTRACT

Topological semimetals are well known for the linear energy band dispersion in the bulk state and topologically protected surface state with arc-like Fermi surface. The angle resolved photoemission spectroscopy experiments help confirm the existence of linear Dirac (Weyl) cone and Fermi arc. Meantime, the transport experiments are very important for its intimate relationship with possible applications. In this concise review, recent developments of quantum transport in two typical topological semimetals, namely Dirac and Weyl semimetals, are described. The 3D Dirac semimetal phase is revealed by the Shubnikov–de Haas oscillations. The Weyl Fermions-related chiral anomaly effect is evident by negative magnetoresistance, thermal power suppression, and nonlocal measurements. The Fermi arc mechanism is discussed and several corresponding transport evidences have been described. The point contact-induced superconductivity in Dirac and Weyl semimetal is also introduced. Perspectives about the development of topological semimetals and topological superconductors are provided.

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1. Introduction

Materials are traditionally classified as insulators, semiconductors, and metals based on their electronic properties. In solid-state physics, the energy band theory successfully explains the phenomena in semiconductors, which seemed mysterious to physicists in 1930s. Since 1970s, a new kind of phase theory has emerged, like Kosterlitz–Thouless (KT) phase transition [1,2], Haldane phase [3,4], quantum Hall states [5–9] et al. They behave very differently from the well-known Landau Fermi liquid theory and Landau Ginzburg Wilson theory of phase transitions and spontaneous symmetry breaking [1–27]. Because such phase transition shows non Fermi liquid behavior and doesn’t require symmetry breaking. Such exotic phase theory ushered the recent development of topological materials, such as topological insulators [10,11] and topological semimetals [12–27]. The symmetry protected phase comes from the special energy band of the materials. The energy band in a specific momentum space region would obey Dirac or Weyl equation. Such linear energy band dispersion shows distinctly different behavior with the traditional parabolic energy band dispersion, as can be seen in Figure 1. Different energy bands classify various materials. What’s more, this linear energy band dispersion can be topologically protected, which means that the linear energy band dispersion would preserve as long as the system symmetry is not broken. Notice that here the topology [28], which concerns about the geometric sphere and torus, Chern number, etc., is different from the quantum topology, which derives from long-range quantum entanglement microscopically. Quantum topology is common in chiral spin states [29,30], fractional quantum Hall states [8,9], superconducting order [31], Majorana zero modes [32], etc. The concept of ‘order’ means the organizations of the particles. Quantum topology is related to the topological order, which describes a new kind of order beyond symmetry description and can be defined by robust ground state degeneracy and non-abelian geometric phases of the degenerate ground states, macroscopically. Therefore, the topological insulators or topological semimetals don’t have the topological order.

Figure 1. Schematic illustration of different types of representative materials. (a) Direct bandgap semiconductor. (b) Indirect bandgap semiconductor. (c) Topological insulators. (d) Semimetal with valence band and conduction band touching. (e) Semimetal with valence band and conduction band overlapping in different momentum point. (f) Topological semimetal owns linear energy dispersion in the bulk. (g) Topological semimetal has additional hole pockets near the Weyl point.
Instead, they have symmetry protected topological (SPT) states, or a short ranged quantum entangled SPT state [28]. There are other topological phases that don’t have topological order, like Haldane phase [3,4]. Though topological semimetals don’t have a topological order, they still have topologically protected states which help develop many exotic properties, like Fermi arc. In this way, the corresponding transport behavior of topological materials is topologically protected and robust against the environment perturbations, promising an ideally low-consumption device application in the future. Combined with superconductors, the superconducting proximity effect on topological materials would be promising for a novel topological superconductor behavior [11] and the corresponding Majorana fermion or Majorana zero mode. The non-Abelian statistic properties of Majorana zero mode provide a possible approach for quantum computing [33].

The topological semimetals have markedly different electronic properties from metals, conductors, and insulators [34,35]. If the electrons in low energy region obey Weyl equation, the semimetal can be termed as Weyl semimetal [19]. In Weyl semimetal, the conductance and valence bands intersect at certain points in momentum space known as Weyl nodes. Around the Weyl nodes, the low energy physics is given as 3D two component Weyl fermions $H = v\sigma \cdot k$, where $\sigma$ is the Pauli matrix and $k$ is the crystal momentum. The sign of $v$ corresponds to different chirality of the Weyl nodes: +1 or −1. It has been demonstrated that the total number of Weyl nodes must be even, because the magnetic charge denoted by Berry curvature must be zero in a band structure. Therefore, a minimal case to realize Weyl semimetal has only a pair of Weyl nodes, which can only be realized in a time-reversal-symmetry (TRS) breaking system [19,25,27]. Usually this can be realized by magnetic order. The band crossing found by Wan et al. [19] is an example of accidental degeneracy in quantum mechanics [34,35]. Without additional symmetry constraints, such accidental degeneracies are vanishingly improbable in one and two dimensions, but can occur at isolated points in momentum space in three dimensions [36]. They have also predicted the existence of Fermi arc on the Weyl semimetal surface, which is a non-closed loop and connects the projection points of the Weyl nodes onto the surface Brillouin zone. The TRS breaking system attracted much attention in the early days, however, a number of obstacles [16,37] stand in front of realizing these magnetic Weyl semimetals such as strong correlations, destruction of sample quality, magnetic domains in photoemission experiments. On the other hand, the TI-based Weyl semimetals also have to face the fabrication difficulty, because it is usually difficult to control the fine-tuning of spin–orbit strength [20,26,38]. Alternately, one may consider systems with broken inversion symmetry [18] in which a minimum of four Weyl nodes are present. This route to realize Weyl semimetal can be realized in a single crystal without compositional modulations. In 2015, two groups independently predicted that TaAs class [16,17] could be a proper candidate for Weyl semimetal. Soon after that, the first inversion symmetry breaking Weyl semimetal was realized [39,40]. Angle-resolved photoemission spectroscopy (ARPES) has offered
a powerful tool to directly demonstrate the energy band structure and help to confirm the existence of Weyl semimetal. A series of spectroscopic experiments have been conducted to demonstrate the energy band structure of Weyl semimetals, such as TaAs [39–47], TaP [48–50], NbAs [51], NbP [44,45,49,52–54], MoTe2 [55–58], WTe2 [59,60], Mo_{x}W_{1-x}Te_{2} [61–64].

It should be noticed that either TRS breaking or inversion symmetry breaking is needed in Weyl semimetal. Otherwise, there will be double degeneracy for all k, which leads to the emergence of Dirac fermions obeying [12–15]

\[
H = \begin{pmatrix}
\nu \sigma \cdot k & 0 \\
0 & -\nu \sigma \cdot k
\end{pmatrix}.
\]

This is the reason why Dirac point can be considered as the superposition of two Weyl points. Not only the bulk states own such property, the surface states near the projection of a Dirac point can also be considered as a superposition of a helicoid and anti-helicoid, according to the different chirality of the surface state [65]. But notice that there would be crossing in both bulk states and surface states. If there is no additional symmetry protecting such band crossing [13,66], the hybridization from two Weyl nodes with opposite chirality would open up a gap and thus the linear energy band dispersion would disappear, so does the Fermi arc. Therefore, additional symmetries like nonsymmorphic symmetry [65], C4 rotation symmetry [15], etc. are required in 3D Dirac semimetals. After the theoretical predictions [12,15] of Na_{3}Bi and Cd_{3}As_{2} in 2012, 2013, respectively, a series of ARPES experiments have also been conducted to prove the existence of these Dirac semimetals [67–72].

Despite a large amount of ARPES experiments have been conducted in the past years, the transport experiments play an important role to help us understand the applicable properties of topological semimetals. In this review, we follow the recent experimental research progress in the transport behavior of Dirac and Weyl semimetals. We will first introduce the bulk transport behavior of topological semimetals. After that, we will focus on the Fermi arc transport of topological semimetals. And then the possible topological superconductivity is described. At last, a concise perspective and conclusion are provided.

2. Quantum transport of bulk states in topological semimetals

2.1. SdH oscillations and giant positive magnetoresistance

Shubnikov-de Haas (SdH) oscillation measurement is one of the most common transport experiments to confirm the unusual phase in materials whose energy band satisfies linear energy dispersion [73], like graphene [74] or topological insulators [10,11]. SdH oscillation comes from the Landau quantization of electronic states under high magnetic field. The magnetoresistance would oscillate with a period depending on the inverse of magnetic field (1/B) as the Fermi level crosses
one and another Landau level. Furthermore, the motion of electrons in a solid may result in a nonzero Berry’s phase. Especially, when the energy band satisfies linear dispersion, an extra Berry phase \( \pi \) could be induced. Thus the oscillation in 3D system can be described by \( \cos 2\pi \left( \frac{B}{B_{\text{F}}} - \delta + \gamma \right) \) [75], where \( 1/B_{\text{F}} \) is the SdH frequency, \( \gamma \) equals zero for linear energy band dispersion and \( \delta \) is a phase shift determined by the dimensionality, taking the value 0 for 2D case or \( \pm 1/8 \) for 3D case. When it comes to topological semimetal [76–86], a nontrivial topological state should satisfy \( \gamma = 0 \) and \( \delta = \pm 1/8 \). Thus the Landau fan intercept should be \( \gamma - \delta = \pm 1/8 \). But it should be noticed that whether resistance peaks or valleys are used to identify the Landau indices in Landau fan plotting, because the two different treatments can introduce a system error of \( \pi \) while linear dispersion also introduces a Berry phase \( \pi \). This could sometimes be confusing because a trivial state with a special resistance peaks selection could have the same intercept value with a nontrivial state with a particular resistance valleys selection. Recently, Wang et al. [87] pointed out that though both resistivity peaks [75,78,82,84,85] and valleys [76,79,86] have been used to identify Landau indices in Landau fan plotting, the resistivity peaks should be assigned integers in the Landau index plot. They also point out that the phase shift delta would be \( \pm 1/8 \) or \( 5/8 \) for a Dirac semimetal or paramagnetic Weyl semimetal, while for a Weyl semimetal with broken time-reversal symmetry, the phase shift no longer promises discrete known values. In a word, though SdH oscillation measurement is one of the most common transport experiments, it still should be cautious to treat the phase shift calculation [76,86]. Apart from phase shift, through the anisotropic behavior of the SdH oscillation, the anisotropic geometry of the Fermi surface of Cd\(_3\)As\(_2\) can be calculated [82].

Besides the SdH oscillation, a giant linear magnetoresistance can be observed when the magnetic field is perpendicular to the driven current [77], which can be ascribed to a remarkable protection mechanism that strongly suppresses backscattering in zero magnetic field, resulting in a high mobility and a transport lifetime 10\(^4\) times longer than the quantum lifetime. The lifting of this protection by the applied magnetic field leads to a very large magnetoresistance. This may relate to changes to the Fermi surface induced by the applied magnetic field. A similar result has also been reported [88]. Still, the reason why this protection mechanism exists and why the shift of Fermi surfaces in momentum could lift the protection remains questionable. In fact, there exist two mechanisms before to explain the linear MR behavior. One is the Parish Littlewood theory [89] which explains the LMR in highly disordered Ag\(_{2\pm\delta}\)Se and Ag\(_{2\pm\delta}\)Te. The linear MR arises from the existence of large mobility fluctuation, which may not exist in single crystals with high quality. The other one is the Abriskosov theory [90]. A linear MR arises in a gapless semiconductor with a linear dispersion relation when all electrons are filled into the lowest Landau level, namely fulfilling the quantum limit. When a linear MR could be observed in very low magnetic field, the Abriskosov theory seems not applicable [77,88]. In the same material Cd\(_3\)As\(_2\) but being n-doped, a
nonsaturating linear MR in ultrahigh magnetic field ~65 T was reported to be caused by disorder effects [79], rather than the protection mechanism mentioned above. The 65 T magnetic field renders Cd$_3$As$_2$ approaching quantum limit and no discernible Fermi surface changes in the quantum limit. In another Dirac semimetal TlBiSSe [83], the large linear MR is believed to be governed by the Hall field. A large and nonsaturating MR has also been observed in NbP [80]. But it should be noticed that NbP has a band structure different from traditional Weyl semimetal. The band structure of NbP exhibits both hole pockets from normal quadratic bands and electron pockets from linear Weyl bands. Therefore it is believed that the large MR in NbP comes from electron–hole resonances, similar to a previous report on WTe$_2$ [91]. Up to now, the mechanism of large MR in topological semimetals still remains an open question.

Note that once a magnetic field exceeding a critical value is applied, the time reversal symmetry is broken, thus rendering the Dirac semimetal transformed to the Weyl semimetal. Besides chiral anomaly effect as shown below, such transformation can also be detected in other traditional transport phenomena, such as universal conductance fluctuation [92]. Because of the broken time reversal symmetry, the Gaussian symplectic ensemble would change to the Gaussian unitary ensemble and orbital-related degeneracy (degenerate Weyl nodes) would also change from 2 to 1. Thus the amplitude of the UCF would decrease by a factor of $2\sqrt{2}$ with a relatively large magnetic field applied.

2.2. Chiral anomaly effect-related transport phenomena

Still, the most intriguing property of bulk states in topological semimetals is chiral anomaly effect. When a magnetic field is applied, Landau levels would form. The dispersion relation can be expressed as:

$$\epsilon_n = v_F \text{sign}(n) \sqrt{2\hbar|n|eB + (\hbar k \cdot B)^2}, \quad n = \pm 1, \pm 2, \ldots$$

Crucially, the zeroth Landau level disperses linearly and the slope corresponds to the chirality of Weyl node. By combing the semiclassical formula $\hbar \dot{k} = -eE$, one can deduce that the charge in each of the g chiral Landau bands is non conserved, satisfying [93]

$$\frac{\partial Q_n^{(g)}}{\partial t} = g \frac{\partial Q_n^{(g)}}{\partial t} = -V \frac{e}{4\pi^2 \hbar^2} E \cdot B.$$  

The $E \cdot B$ term tells us the magnetic field must be parallel to the electric current to induce the charge imbalance of Weyl nodes, inducing the chiral anomaly effect. The quantum limit condition ($n = 0$ Landau level) demonstrates that the carrier density should not be too large, or the $n = 0$ landau level contribution would be smeared out. This is the reason why the chiral anomaly-induced negative magnetoresistance (NMR) is pronouncedly observed in Na$_3$Bi with low carrier density ($\sim 10^{17}$ cm$^{-3}$) [94] while in the same material but with high carrier density ($\sim 10^{18}$ cm$^{-3}$) [77], a large linear MR was observed.

2.2.1. Negative magnetoresistance

It was pointed out over 30 years ago [95] that the charge imbalance induced by $E \cdot B$ term between different Weyl nodes requires large momentum scattering process
to relax. When the scattering from one Weyl point to another can be neglected or the internode scattering time $\tau_i$ is large enough, a longitudinal current associated with chiral anomaly effect could be generated, rendering a NMR.

The chiral anomaly-induced NMR is firstly observed in $\text{Bi}_{0.97}\text{Sb}_{0.03}$ crystal, which is identified as Dirac semimetal [96]. Around zero magnetic field, a cusp-like maximum in conductivity is observed, ascribed to weak anti-localization (WAL) effect. The coexistence of WAL effect under both parallel and perpendicular magnetic fields supports the nature of three-dimensional Dirac fermions. WAL effect, which is quantum correction to conductivity in nature, can be understood by the language of berry phase $\pi$ in topological materials, since the phase difference between two time reversed routes is the same with berry phase circulated along the loop [97]. The accumulation of berry phase $\pi$ can suppress backscattering [98] between two time reversed routes, and contribute to conductivity. In addition, in topological semimetals, a robust connection between WAL (WL) effect and the value of magnetic charge is illustrated [97]. The $-\sqrt{B}$ dependence of 3D WAL effect has also been reported [96,99–103]. Besides WAL effect ($B < 0.4$ T), an upturn in magnetoconductivity above 0.4 T is observed in $\text{Bi}_{0.97}\text{Sb}_{0.03}$ crystal when the direction of magnetic field is parallel to electric field. It is explained as chiral anomaly effect-induced NMR. As rotating the magnetic field from parallel to perpendicular direction with respect to electric field, NMR is suppressed firstly and translates into positive magnetoresistance, consistent with chiral anomaly effect-induced transport behavior. Nevertheless, the fine control of chemical composition of $\text{Bi}_{0.97}\text{Sb}_{0.03}$ crystal is not so easy to achieve. The theory predicted Dirac semimetals $\text{Na}_3\text{Bi}$ [12] and $\text{Cd}_3\text{As}_2$ [15], which are protected by crystal symmetry, seem offer a good platform.

To observe the chiral anomaly effect, a relatively low carrier density is needed. As mentioned above, only the one with low carrier density ($\sim10^{17}\text{ cm}^{-3}$) [94] is able to generate the chiral anomaly effect-induced NMR. Like $\text{Bi}_{0.97}\text{Sb}_{0.03}$ crystal [96], a similar NMR behavior was also observed in $\text{Na}_3\text{Bi}$ [94] and $\text{Cd}_3\text{As}_2$ [104]. When an external magnetic field is applied, the degenerate Dirac point splits into two separate Weyl nodes along the magnetic field direction and thus a Dirac semimetal is transformed into a Weyl semimetal, as shown in Figure 2(a). Thus the chiral anomaly effect emerges when the magnetic field is parallel to the electric field. In Figure 2(b), a chiral charge current will be driven from one Weyl node to another, thus leading to an additional electric conductivity, rendering the NMR. Furthermore, NMR should gradually disappear with magnetic field direction deviates from the electric field direction, which is also confirmed by the angle-dependent experiment, shown in Figure 2(c). It has been demonstrated that a relatively low carrier density is very important to observe the chiral anomaly effect. Apart from fine control of bulk sample growth, topological nanostructures can be adopted to get a relatively low carrier density, such as $\text{Cd}_3\text{As}_2$ nanowires or nanoplates [104]. The carrier density is $\sim10^{17}\text{ cm}^{-3}$, and fermi level can easily
be tuned to the Dirac point by back gate voltage. In fact, the basic transport characterization of the sample, like resistance–temperature ($R$–$T$) curve can give us information about low carrier density. In Figure 2(d), a semiconductor-like $R$–$T$ curve is observed in Cd$_3$As$_2$ nanowire. The resistance experiences a firstly increase with the temperature decreasing from 300 K. Then the resistance decreases at a critical temperature $\sim$30 K. Such behavior is due to the low carrier density of the sample. When the temperature is relatively high, the transport is dominated by thermally activated carriers. Thus a semiconductor-like behavior is observed because the carrier density is very low and the Fermi level is located near Dirac point. In contrast, the thermal activation model fails in the low temperature region. The transport is dominated by the intrinsic carrier density near the Dirac point and a metallic behavior is observed. Similar to other Dirac semimetals, NMR is observed with the direction of magnetic field along the current direction, or even with twenty degrees’ deviation. The relatively large angular deviation may be related to the moderate positive magnetoresistance under perpendicular magnetic field. Besides, the NMR can be tuned by temperature (Figure 2(e)) and back gate voltage through changing the density of chiral states. It can reach −63% at 60 K,

Figure 2. The negative magnetoresistance in Dirac semimetals. (a) The Dirac cone shift under an external magnetic field in Dirac semimetal Na$_3$Bi [94]. When an external magnetic field is applied, the degenerate Dirac point will split into two Weyl nodes along the magnetic field direction in the momentum space. Thus a Dirac semimetal is transformed into a Weyl semimetal. (b) The chiral anomaly effect [94]. When the magnetic field is parallel to the electric field, the chiral anomaly effect occurs, rendering the charge imbalance between the two Weyl nodes. Thus a chiral current happens, leading to an additional electric conductivity and the observed negative magnetoresistance. (c) The angle dependent experiment of magnetotransport [94]. Apparently the negative magnetoresistance decreases with the magnetic field direction deviating from the electric field direction and finally disappears when the magnetic field is perpendicular to the electric field. (d) Dirac semimetal Cd$_3$As$_2$ [104]. The resistance–temperature ($R$–$T$) curve shows a typical low-carrier density behavior. (e) The negative magnetoresistance at different temperature [104]. (f) The chiral anomaly-induced thermal power suppression effect [132].
and remain negative under room temperature. We have also observed the translation from NMR to positive magnetoresistance through altering the Fermi level far away from Dirac point under 10 T, which confirms that a chemical potential near Weyl point is needed to observe the NMR [94]. It’s worth noting that the direction of magnetic field is along the Cd$_3$As$_2$ nanowire (<112> growth direction), deviating from the C4 rotation symmetry direction. The broken of fourfold rotational symmetry will result in massive Dirac fermions with a gap opening near the neutral point [15], which may hinder the detection of NMR. However, our data indicate that chirality remains a good quantum number with the gap opening under $m<<\mu$ [105], although the magnitude of the NMR is reduced owing to the contribution of non-chiral states. Similar NMR phenomenon observed in ZrTe$_5$ crystal is also explained as evidence of chiral anomaly effect in Dirac semimetal [106]. Nevertheless, the spectroscopic phenomena are controversy [106–109]. In an experiment [108], ZrTe$_5$ crystal hosts a large full gap of $\sim 100$ meV on the surface, which demonstrates that ZrTe$_5$ is a semiconductor rather than a Dirac semimetal.

Chiral anomaly-induced NMR has also been observed in intrinsic Weyl semimetals, such as TaAs [101,110], TaP [84], NbAs [103,111], NbP [85,103], and type-II Weyl semimetals represented by WTe$_2$ [112,113]. In type-II Weyl semimetal, Weyl fermions are predicted to emerge at the boundary of electron and hole pockets. Its unique feature of Fermi surface can induce planar orientation dependent NMR, and has been observed in WTe$_2$ thin film [112,113]. Besides, NMR has been observed in many other systems, such as Half-Heusler-GdPtBi [114], black phosphorus [115], PdCoO$_2$ [116] and transition metal dipnictides [117–120]. The NMR in Half-Heusler-GdPtBi [114] is explained as the band crossing and Weyl nodes appearing under the effect of Zeeman effect. The pressure dependent NMR in black phosphorus occurs only when the direction of magnetic field and electric field is parallel. It is associated with transition from semiconductor to Dirac semimetal phase under hydrostatic pressure [115]. NMR has also been reported in PdCoO$_2$, when direction of magnetic field is along the interlayer direction. It is possibly due to axial anomaly between Fermi points in a field induced quasi one-dimensional dispersion [116]. In transition metal dipnictides, only positive magnetoresistance is observed in some experiments [121–123]. In other experiments, the observed NMR is not ascribed to the existence of Weyl fermions [118,120], but for an unknown scattering mechanism [118] or an exotic origin of topological surface states [120].

Also, there are many other reasons need to be ruled out to confirm chiral anomaly effect-induced NMR. For example, current jetting effect [124,125], which is characterized by a highly non-uniform current distribution in the sample, can induce the NMR, as reported in TaAs family [126,127]. In addition, in the ultra-quantum limit [95,128,129], certain impurity can also induce NMR in three-dimensional metal according to theoretical proposals [130,131].
2.2.2. Thermoelectric transport

Electrical conductivity directly demonstrates the conductivity of the materials. It is associated with carrier mobility, carrier density, and so on. However, it is usually difficult to study the energy dependence of the transport, because gating is generally non-uniform for 3D materials because of screening [132]. Complementary to the electrical conductivity, thermoelectric effect provides unique information on the electronic transport and has been used to study two-dimensional massless Dirac fermions in graphene [133–136] and three-dimensional massive Dirac fermions [137]. Thermo-power, which is equivalent to Seeback coefficient when the temperature gradient is constant according to Boltzmann formulation [134], is extremely sensitive to the carrier type of the system, and can also be understood quantitatively according to semiclassical Mott relation. With Mott relation, thermo-conductivity is associated with the derivative of the electric conductivity with respect to energy. Therefore, it reflects the energy dependence of the transport.

Thermoelectric effect has been predicted to exist in Weyl and Dirac semimetals [138,139]. When the magnetic field is parallel to the temperature gradient, there would introduce a large contribution to the thermal conductivity [138]. The thermal conductivity would be quadratic in magnetic field length, similar to the magnetic field dependence of the longitudinal electric conductivity. In fact, the thermal response of Weyl fermions has been observed experimentally. In a recent experiment on Cd₃As₂ nanoplate [132], it turns out that when the magnetic field is parallel to the direction of temperature gradient, thermal-power indeed shows a quadratic suppressed dependence on the magnetic field length and even changed its sign under high magnetic field, shown in Figure 2(f). This is related to the inverse proportionality of conductivity to energy in chiral anomaly-induced magneto-conductivity and its competition with Drude term. Besides, the $B^2$ coefficient of thermos conductivity is twice than electric conductivity induced by chiral anomaly. Of course, there would be other reasons that can induce a negative Seeback coefficient such as the two competing carrier type (namely holes and electrons). In fact, we have also done detailed research on the Dirac semimetal Cd₃As₂ nanoplate [140]. It has been demonstrated that there would exist Hall anomaly due to two carriers competing in the transport behavior. Two different kinds of carriers, namely electrons and holes, would contribute inversely to the Hall voltage. The Hall voltage experiences a sign change, demonstrating such competing behavior. In the thermoelectric experiment, it is shown that when the magnetic field is not large, namely in the weak magnetic field, the carriers are dominated by holes. Therefore, in such magnetic field range, the single-band can be approximately adopted. In fact, the control experiment with a perpendicular magnetic field applied excludes two-carrier model. When a perpendicular magnetic field is applied, the Seeback coefficient behavior can be fully explained by a dominant single band theory. To fully explain the chiral anomaly-induced unusual thermal coefficient, the Mott relation is used. Despite the wide application of Mott relation, its applicability to Weyl fermions in the condition of chiral
anomaly is not a priori knowledge. The thermoelectric experiments indicate that Mott relation works in this case.

The thermoelectric response of Weyl nodes in Cd$_3$As$_2$ is related to the splitting of Dirac node. However, in half-Heusler GdPtBi, the formation of Weyl nodes is associated with Zeeman effect-induced band crossing [114]. Weyl nodes’ formation is guaranteed by field-steering property of NMR and changing from moderately heavy mass in zero B to small mass of Dirac states in high B. The suppression of Seeback coefficient and thermal response function is observed when the direction of magnetic field is parallel with temperature gradient. And the suppression is weakened when magnetic field deviates from the direction of temperature gradient, or when the temperature increases, demonstrating the relation with chiral anomaly effect. Besides, the thermal-electric response is anisotropic when magnetic field and temperature gradient is along different crystal orientation index, indicating the anisotropy of Weyl node formation. The thermal response of Weyl fermion offers a unique way of identifying chiral anomaly-related phenomena. Besides, it implies zero gap semiconductors with strong spin-orbital coupling can be helpful in exploring Weyl fermion-related exotic physical phenomena.

2.2.3. Nonlocal transport

In contrast to other anomaly-related transport experiments, Parameswaran et al. [141] proposed an experimental configuration based on the diffusion of valley imbalance. Pair of local electrodes were deposited on the top and bottom surface of the microplate, from which an electric current and local magnetic field can be applied. At a distance away from the local electrodes, another pair of nonlocal electrodes were deposited the same way, from which nonlocal voltage can be detected with a local magnetic field applied. The valley concept analogous to semiconductor concept refers to the Weyl node index which can be accounted as another quantum number.

This mechanism is very similar to spin diffusion in the nonlocal measurement in other materials like graphene or carbon nanotube. The only difference is that here it’s the valley imbalance diffusion according to a length scale $l$ determined by the internode scattering processes and hence, can be quite large. To observe the chiral anomaly effect, a large $\tau_f/\tau$ is required, where $\tau$ is the mean free time and $\tau_f$ is the intervalley scattering time. It means that a weak intervalley scattering rate is necessary. Therefore, the diffusion length could be very large – even larger than the sample thickness, which is the length scale for a nonlocal Ohmic voltage. In the nonlocal region, a magnetic field is needed to probe such nonlocal voltage. In fact, if the magnetic field is not parallel to the perpendicular direction of the microplate, a nonlocal voltage would not be observed. However, their experiment proposal requires the magnetic field to be delicately tuned to different region of the sample, which makes it hard to conduct in the transport experiment. Recently, a nonlocal signal has been observed [142], adopting a Hall bar geometry with a uniform magnetic field applied to the whole sample.
3. Fermi arc transport

3.1. Fermi arc mechanism

Despite the abundant novel transport experiments of topological semimetals, most of them reveal the bulk states properties. While topology demonstrates itself in topological semimetals not only from the bulk states but also from the exotic surface states, namely Fermi arcs. Fermi arcs play a crucial role to demonstrate the nontrivial topological properties of topological semimetals. As we know, on the surface of a topological semimetal, the Fermi surface consists of open arcs connecting the projection of bulk Weyl points onto the surface Brillouin zone, instead of closed loops.

From topological prospective, Fermi arcs can be interpreted as the edge state of Chern insulators. Because different Weyl nodes own different chirality so the Chern number would be nonzero when enclosing only odd Weyl nodes while being zero when enclosing pairs of Weyl nodes. The topological phase transition will happen at the boundary of two systems with different Chern number, where the Fermi arc emerges.

Recently, the mechanism of Fermi arcs has been updated by Chen Fang et.al [65] that the surface dispersions of topological semimetals map to helicoidal structures. The bulk nodal points project to the branch points of the helicoids and the surface states near different Weyl nodes with opposite chirality correspond to helicoid or anti-helicoid structure. Thus they can form an iso-energy contour between different Weyl nodes known as Fermi arcs. For a Dirac semimetal, a Dirac point can be considered as the superposition of two Weyl nodes with opposite chirality. Thus the surface states near the projection of each Dirac point is a superposition of a helicoid and anti-helicoid, which cross each other along certain lines and may have two Fermi arcs [15]. However, they pointed out that such Fermi arcs could be lost due to the hybridization along the crossing lines if without non-symmorphic symmetry existing. This is the case for all Dirac semimetals discovered so far. But this still remains an open question, as there emerges evidence for the existence of Fermi arcs in Cd$_3$As$_2$ microplate transport experiment [143,144].

3.2. Anomalous quantum oscillation

Due to the bulk conductivity of the topological semimetal, it is usually very hard to resolve the surface contribution from the whole conductivity. Potter et al. [143] pointed out that the open Fermi arcs can participate in unusual magnetic orbits by traversing the bulk of the sample to connect opposite surfaces. The ‘Weyl orbit’ weaves together the chiral states in the bulk with the topological Fermi arc states on opposite surfaces in a closed orbit. Thus an unusual quantum oscillation should be observed and this proposal artfully circumvents the problem that the bulk states and surface states are both conducting in the traditional electrical measurements. Soon a Cd$_3$As$_2$ microplate (~100 nm thick) was used to conduct
the quantum oscillation experiment [144]. Figure 2(a) shows the sample configuration that Cd₃As₂ microplates with different thickness were adopted. The Weyl orbit is sketched in Figure 2(b) and a magnetic field was applied perpendicular to the plate surface and thus an unusual quantum oscillation frequency was observed in Figure 2(c), combining with the traditional quantum oscillation frequency. This frequency amplitude is highly depending on the thickness of the sample and the direction of the magnetic field. If the sample thickness is over the bulk mean free path, such an oscillation would not be observed. When the magnetic field is parallel to the surface, such an oscillation would disappear too. The angle dependence suggests a surface character of the quantum path associated with the unusual frequency. What’s more, they also try to modify the sample geometry using the FIB technique. They found that if the sample has a triangle cross section, the unusual quantum oscillation frequency would also disappear, due to the different sample thickness contributing to a series of different phases, which result in a destructive interference.

3.3. Aharonov–Bohm effect

Up to now, there are still rare reports about Fermi arc transport, though a lot of spectroscopy experiments have been done in the past years. Apart from the above proposal, the Aharonov–Bohm (AB) effect [145–154] is possibly another way to prove the existence of the topological surface state transport. Because the ingredients to observe AB effect in a nanowire is based on the core–shell model [155], which means that only the surface states participate in the transport behavior. If the bulk states participate, the random phases caused by different cross section area due to bulk states would be destructive, thus rendering no AB effect observed.

AB effect was first raised in 1950s, which can be perfectly explained by Berry phase. In topological material nanostructures, it still plays an important role in transport experiments. For nanoribbon or nanowire, AB effect would come into effect when a parallel magnetic field is applied along the nanowire/nanoribbon direction. The experimental configuration is shown in Figure 3(d). When electrons circle along the circumference, a phase \(2\pi \Phi/\Phi_0\) would be induced, where \(\Phi_0\) is the magnetic flux quantum \(\hbar/e\), \(\Phi\) is the magnetic flux. Thus an oscillation would occur due to the magnetic field modulation of the phase changing, as shown in Figure 3(e). A typical magnetic field period of \(\Phi_0\) is observed. As the temperature increases, the oscillation amplitude decreases. With the magnetic field increasing, there emerges a \(\pi\) phase-shift when the magnetic field is larger than a critical value. This phase shift stems from the magnetic field-induced lifting of degeneracy. Notice that AB effect would not be observed in a cylinder, because a cylinder can be considered as a series of hollow cylinder with different radiuses [155]. Thus different radiuses corresponds different cross section area and then the phase induced by magnetic field would be correspondingly different. These different phases would be de-coherent and the AB effect would disappear. Therefore, the
AB effect observed in topological materials nanostructures is based on a core–shell model, which means that the bulk would not participate in the AB effect. This is why AB effect can be used to demonstrate the surface states contribution in the transport experiments. But on the other hand, Altshuler Aronov Spivak (AAS) effect comes from the interference of time-reversal paths, thus it would not be involved with initial phase randomness-induced de-coherence. In a nanowire with a much larger diameter, the surface-to-volume ratio is very small and thus surface states dominated AB effect would not be easy to observe while the bulk states dominated AAS effect would come into effect. As shown in Figure 2(f), AAS effect can be observed in a Cd₃As₂ nanowire with diameter ~200 nm. Combining AB effect and AAS effect observed in the nanowire, we can say that AB effect is an effective way to demonstrate the surface states domination in the transport experiment. Still, the detailed properties of Fermi arcs, like spin momentum locking property or unclosed Fermi loops, need further evidences in the transport experiment.

4. Point contact-induced superconductivity

Topological superconductor is famous for possibly holding the Majorana zero mode which obeys the non-Abelian braiding statistics. Achieving control of the Majorana fermions is both fundamentally and for applications to quantum computation [33]. There are proposals based on proximity effect with conventional superconductors or pressure-induced tuning of lattice structure and related electronic
states. The former have been reported in many experiments such as proximity effect on TI [156–170] or on Ferro chain [171–174] or on semiconductors with strong Rashba SOC [175–184]. As to the latter, pressure can be generated by point contact technique or diamond anvil cell device. With the increasing interest in nontrivial band structure in topological semimetals, topological superconducting phase can be constructed based on this three dimensional gapless system in theory [185–193]. The proximity-induced topological superconductor in time reversal symmetry breaking Weyl semimetals is believed to be confined to a few layers of surface, similar to that in topological insulators, although the bulk state of the Weyl semimetal is conducting [192]. Besides, topological superconductor in time reversal breaking Weyl semimetal is analyzed to have even more exotic surface states, which means crossed flat bands rather than Fermi arcs [191].

Experimentally, pressure-induced superconducting phase has been observed in topological semimetals [194–209]. Recently, a new unconventional superconducting phase in quantum mechanically confined region is revealed when applying a point contact on Dirac semimetal Cd₃As₂ with normal metal tip [196,197]. As shown in Figure 4(a), a typical device consists of a normal metal tip and a Cd₃As₂ bulk sample. When an appropriate pressure is applied from the tip to the bulk sample, the resistance–temperature (R–T) curve would show a transition behavior. In the ballistic limit, a robust zero bias conductance peak could be observed. Figure 4(b) presents the temperature evolution of the zero bias conductance peak

Figure 4. Point contact-induced superconductivity in Dirac semimetals. (a) A typical device for point contact measurement [196]. The R–T transition is observed. (b) Normalized dI/dV spectra at different temperatures varying from 0.28 to 3.8 K without an external magnetic field [196]. A zero bias conductance peak and double conductance peaks are observed. (c) In the thermal regime, the dV/dI spectra show a resistance dip (or conductance peak) due to superconductivity and double resistance peaks due to critical field effect [197]. (d) In the ballistic regime, the double conductance peaks demonstrate an energy gap up to 13 K and the zero bias conductance peak is observed [197].
from 0.28 to 3.8 K without an external magnetic field. Besides zero bias conductance peak, a double conductance peaks and double conductance dips symmetric to zero bias can be observed, with the peak smearing into broad hump at high temperature. With the magnetic field increasing, the zero bias conductance peak also gradually disappears.

Notice that whether the sample is in the ballistic limit in the point contact measurement should be confirmed before claiming an unusual zero bias conductance peak, because the zero bias conductance peak can also be observed when the point contact is in the thermal region [210,211]. Usually when the point contact diameter is a lot smaller than the elastic and inelastic scattering length, the ballistic limit is correct. However, if the point contact diameter is much larger than the elastic and inelastic scattering length, the point contact transport falls into the thermal regime. The local thermal effect could be very large and thus rendering the energy information useless [210–212] and the corresponding zero bias conductance peak should not be ascribed to nontrivial topological property of Dirac semimetal, such as Majorana zero mode, etc. In fact, Figure 4(c) shows us that the zero bias conductance peak could be observed when the point contact is in the thermal regime, the observed zero bias conductance peak comes from the superconductivity because under low bias the contact resistance is dominated by Sharvin resistance and the Maxwell resistance is zero because of superconductivity, while under high bias, the contact resistance is dominated by Maxwell resistance because of non-existing superconductivity. Usually the Maxwell resistance is much larger than the Sharvin resistance, and thus there is a resistance dip under the low bias and the zero bias conductance peak emerges. In fact, the zero bias conductance can be enhanced several fold larger than the value at high bias in the thermal limit [213]. When the point contact is in the intermediate region, the thermal effect plays a relatively small role in the transport and thus the Andreev reflection could not be smeared out. When the sample is made further into the ballistic region, the zero bias conductance peak emerges and a temperature independent pseudo-gap is observed, as shown in Figure 4(d). The observed zero bias conductance peak originates from the existence of Andreev bound state (ABS) due to a possible $p$-wave component in the order parameter symmetry of the new superconducting phase [214].

Similar results have also been reported in other topological materials [198,199,208,209]. But it should be noticed that zero bias conductance peak could not be considered as a strong proof to prove the existence of Majorana Fermions, especially a quantized tunneling conductance $2e^2/h$ has not been observed in the above experiments. In fact, there are many things to rule out, such as disorder [215] or just other crossing zero energy states or Kondo effects [216]. Recently, such point contact-induced superconducting behavior has also been reported in TaAs [198,199]. The spin polarization rate can be calculated by fitting the suppression of Andreev reflection based on BTK formalism [217]. They claimed they have observed a spin polarization rate up to 60%, lower than the value of 80% by
ARPES [46]. Still, the Majorana zero mode-induced zero bias conductance peak still needs more evidence and the mechanism behind the point contact-induced superconductivity is deferred to future investigations.

Besides the mesoscopic point contact, pressure can be generated by diamond anvil cell device. With hydrostatic pressure applied, superconductivity is observed in Cd$_3$As$_2$ crystal [207], accompanied by structure phase transition [218]. In WTe$_2$ crystal, the balance of hole and electron is broken, accompanied with the suppression and turning off of positive large magnetoresistance and appearance of a superconducting phase under a critical pressure [201]. A dome-shaped Tc–P phase is also unveiled in pressured WTe$_2$ [202] and MoTe$_2$ [203,204]. Two stage superconducting behavior in ZrTe$_5$ crystal is also observed, as ascribing to structural phase transition and magnetic susceptibility [200]. Nevertheless, it should be noticed that pressure does not necessarily lead to superconductivity. In NbAs crystal, no superconducting phase transition with temperature down to 300mK is observed with pressure up to 20GPa [219].

5. Perspective and conclusions

Weyl semimetals have been realized experimentally in two ways: inversion-symmetry broken systems, such as the TaAs family, and the Dirac semimetal under magnetic field. However, the TRS broken (magnetic order) Weyl semimetal [220] is still a future task. Moreover, a new kind of Weyl semimetal has arose, called typeII Weyl semimetal. The so-called typeII Weyl semimetals are with nearly minimal Weyl nodes, represented by WTe$_2$, MoTe$_2$, and Mo$_x$W$_{1-x}$Te$_2$ [221–225]. Unlike typeI Weyl semimetal, quasiparticles in typeII Weyl semimetal violate Lorentz invariance, and there is no counterpart in high energy physics [221]. Besides, in typeII Weyl semimetal, Weyl fermion is emergent at the boundary of electron and hole pockets with a finite density of states near the Weyl point [55], thus unusual phenomena are expected, such as planar orientation dependent chiral anomaly [112].

Interestingly, topological materials with nontrivial band structure, has been proposed to engineer topological superconductor with Majorana fermion zero mode. In fact, topological superconductors have been achieved utilizing the superconducting proximity effect between conventional superconductor and topological insulators [156]. The proximity effect between an s-wave superconductor and the surface states of a strong topological insulator induces a two-dimensional state resembling a spinless $p_x + ip_y$ superconductor, without breaking TRS [158,162,167]. Spin polarized STM/STS theories [161,164,165] were raised to further confirm the existence of Majorana zero mode. He et.al [160] pointed out that Majorana zero mode can induce selective equal spin Andreev reflections, where incoming electrons with specific spin polarization would be reflected as counter propagating holes with the same spin. If Majorana zero mode doesn't exist, then the electrons with specific spin would just be reflected with direction inverted.
This phenomenon has been confirmed by experiment that a spin selective Andreev reflection has been applied to a Bi$_2$Te$_3$/NbSe$_2$ heterostructure [169]. The zero bias peak of the tunneling differential conductance is shown to be depending on the direction of the tip spin polarization compared to the magnetic field. When they are parallel to each other, the spin selective Andreev reflections would occur due to the Majorana zero mode polarization is identical to the incoming electron spin, then a higher tunneling conductance is observed; while when they are antiparallel to each other, the Majorana zero mode polarization is not equal to the incoming electron spin, thus the spin selective Andreev reflections could not happen, rendering a lower tunneling conductance [169].

Besides, the disappearance of even Shapiro steps is also believed due to the appearance of Majorana zero mode. A radio-frequency irradiation has been applied in a Josephson junction in a HgTe quantum well [168,170], and a series of missing odd Shapiro steps were observed due to the gapless Andreev bound states of the edges. As indicated by Fu and Kane [156], such gapless Andreev bound states in the topological superconductor have a $4\pi$ periodicity. Such a $4\pi$ periodicity can be considered as an evidence for the existence of Majorana fermion [226]. Two Majorana modes fuse to produce an ordinary fermion and modify the periodicity of Josephson relation from $2\pi$ to $4\pi$ [157]. The Shapiro steps with a quantized voltage step $\Delta V = hf_0/2e$ would change to $\Delta V = hf_0/e$, suggesting that the supercurrent is carried by charge-$e$ quasiparticle instead of charge-$2e$ Cooper pairs.

These methods used in the topological insulators/superconductor heterojunctions can in fact be generalized to topological semimetals. Topological materials provide a wide platform to realize Majorana zero mode, which is believed to obey non-Abelian statistics. The non-Abelian anyons properties of Majorana zero mode can help to realize the so-called qubits [33]. In a topological quantum computer, qubits are nonlocal and operations like quasiparticle braiding are also nonlocal [33]. Thus quantum computing can be conducted in a way immune to environment errors, which is the specific characteristic of topological quantum computation, in contrast to non-topological quantum computation.

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