

# Quantum Oscillations Due To Fermi Arcs In Weyl Semimetal

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**Abstract** - The surface states of Weyl semi-metals (SM's) consist of disjointed Fermi-arcs. This unusual surface-Fermiology provides a fingerprint of the topological features of the bulk Weyl-phase. Using a combination of semiclassical and numerical methods , in contrast to naive expectation, there are closed magnetic orbits involving the open- surface Fermi-arcs. Below a critical field strength that depends on sample thickness, these orbits produce periodic quantum oscillations of the density of states in a magnetic field, enabling a variety of experimental probes of the unconventional Fermi-arc surface states. The orbits are also essential for reproducing the bulk chiral anomaly in a finite slab espite the fact that the protecting crystal symmetry is broken by a surface, we show that Dirac materials can still host unconventional surface-states, which can be detected in quantum oscillations experiments.

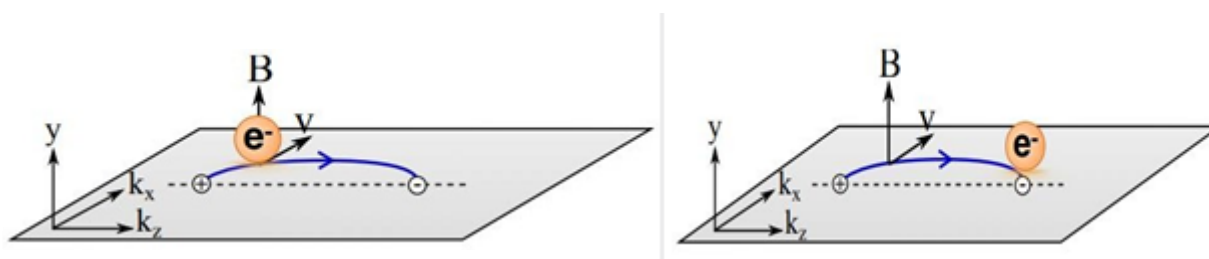
**Key Words** : *Weyl-phase , Crystal symmetry , Quantum oscillations , Fermi-arcs , Surface-Fermiology*

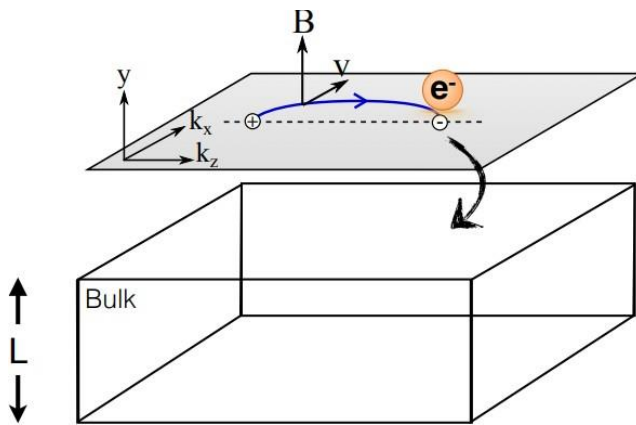
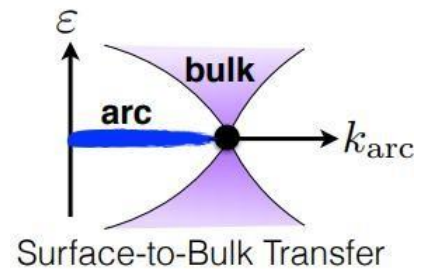
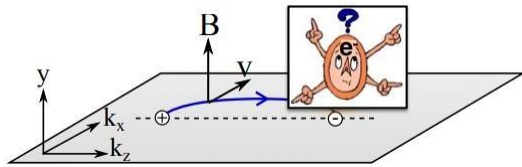
## INTRODUCTION

The rich cross-pollination between high energy and condensed matter physics has led to deeper such as spontaneous symmetry breaking, phase transitions and renormalization . Such knowledge has, in turn, greatly helped physicists and materials scientists to better understand magnets, superconductors and other novel materials, leading to practical device applications . In the past decade, there has been significant interest in realizing high energy particles in solid state systems. The theoretical attempts to explain graphene's properties using solid-state physics led to an equation similar to one otherwise seen in cosmology and colliders: the Dirac equation.

Following graphene's discovery, many materials with nodal band crossings, known as topological insulators and semimetals , were discovered, generating significant research excitement. The topological Dirac and Weyl semimetals are crystalline solids whose low- energy electronic excitations resemble the Dirac and Weyl fermions in high-energy particle physics, respectively. In particular, although the Weyl fermion played a crucial rule in the standard Model , it has never been observed as a fundamental particle. The realization of the topological Weyl semimetal state enables the observation of this elusive particle in physics. Topological semimetals further allow for band crossings beyond high-energy classifications. Primary examples include the type-II Weyl and Dirac semimetals, the nodal-line semimetals , and the unconventional fermion semimetals . Due to the rich variety of crystalline and magnetic symmetry properties of condensed matter systems, it is likely that this is only the tip of an iceberg and there are ample new topological semimetals awaiting discovery. These topological

semimetals provide platforms for studying a number of important concepts in high energy physics (e.g. the chiral anomaly) in table-top experiments. Moreover, they extend the classification of topological phases from gapped matter (e.g. insulators) to gapless systems (e.g.metals)..





### Quantum Oscillations from Fermi Arcs

For develop an effective surface theory for the surface states of a Weyl semimetal. The Theory includes the peculiar Fermi arc states on the surface as well as leakage of the states from the surface to the bulk. Subjecting the model to a magnetic field perpendicular to the surface results in quantum oscillations. The oscillations are different from the usual ones since they do not involve a closed Fermi surface cross section, the Quantum oscillations can be understood semiclassically as resulting from motion of electrons on the surface Fermi arcs as well as tunneling through chiral Landau levels associated with the bulk. In this work we develop an effective surface theory and use it to analyze the quantum oscillation in the semiclassical regime and beyond. Specifically, we show that when a pair of Weyl points are close to each other the surface quantum oscillations acquire a phase offset which originates from the bulk. While the surface states are responsible for a large part of the electron motion, tunneling through the bulk is necessary for completing the orbit. This tunneling makes use of the bulk, zero energy, chiral Landau level in each Weyl node. When the nodes are close in momentum space their chiral levels overlap and a gap at zero energy is formed. This gap causes the phase offset in the surface quantum oscillations. Topological semimetals enable a kaleidoscope of novel electronic properties. They support exotic, topologically protected boundary modes such as the topological Fermi arcs and drumhead surface states. These surface states have been directly observed in spectroscopic measurements . The Fermi arcs also lead to unusual quantum cyclotron orbits (the Weyl orbits) as observed in quantum 4 oscillation measurements . Because of the linear dispersion and the spin (pseudo-spin) momentum locking, low-energy electrons in topological semimetals are highly robust against crystalline disorder and imperfections, leading to very high electron mobilities . The compensating electron and hole carriers further cause non-saturating magnetoresistance and magneto-thermopower . The application of parallel electric and magnetic fields can break the apparent conservation of the chiral charge. Such chiral anomaly leads to enhanced conductivity with an increasing magnetic field. The diverging Berry curvatures near the nodal points support distinct anomalous transport phenomena including intrinsic anomalous Hall effects , and anomalous Nernst effects . They also support significantly enhanced optical and optoelectronic phenomena including large (even quantized) photocurrents , second-harmonic generation , optical activity and gyrotropy and Kerr rotation . Furthermore, thinning down a three-dimensional (3D) topological semimetal into

two-dimensions (2D) may give rise to new 2D topology including the quantum spin Hall insulator and the quantum anomalous Hall insulator. These unconventional transport and optical properties of topological semimetals can pave the way for the realization of dissipationless electronic and spintronic devices as well as efficient photodetectors and energy harvesters. The area of 3D topological semimetals is fast growing; many papers have been published on theoretical predictions and experimental studies. There have been many review articles, which introduce progresses in theoretical and experimental studies on topological semimetals. We are focused on electronic transport and quantum oscillation studies on topological semimetals; these two topics have not been reviewed comprehensively in previous review articles. Before we start detailed discussions on these topics, we will first briefly introduce each prototype topological semimetal phase and discuss their band

structure characteristics, topological invariant and symmetry protections. Disjointed Fermi arcs in Weyl semimetals can intertwine with chiral bulk modes and participate in unusual closed magnetic orbits in the presence of a vertical magnetic field. Here, we carry out a quantum oscillation study of such unusual Weyl magnetic orbits in the Dirac semimetal Cd<sub>3</sub>As<sub>2</sub>, a close cousin of Weyl semimetals. We find that extra two-dimensional (2D) quantum oscillations emerge at high fields, which superimpose on a three-dimensional bulk background and can be attributed to the Weyl magnetic orbits, when the thickness of the nanoplates is smaller than the mean free path of the electrons. Further evidence of 2D quantum oscillations from the Weyl magnetic orbits is provided by nonlocal detection, which demonstrates an alternative way to study the quantum transport properties of Fermi arcs under magnetic field

Parameters obtained from transport and quantum oscillation experiments at based temperatures (1.5-5 K), including MR at 9T, residual resistivity  $\rho_{res}$ , transport mobility  $\mu_T$ , quantum relaxation time  $\tau_q$ , quantum mobility  $\mu_q$ , and effective mass ratio  $m^*/m$

	MR at 9T	$\rho_{res}$ ( $\mu\Omega$ cm)	$\mu_T$ ( $cm^2 V^{-1} s^{-1}$ )	$\tau_q$ (ps)	$\mu_q$ ( $cm^2 V^{-1} s^{-1}$ )	$m^*/m_0$	Ref.
Cd <sub>3</sub> As <sub>2</sub>	34.5 - 1336	0.032 - 46.5	$4 \times 10^3 - 8.7 \times 10^6$	0.03 - 0.21	4,700 - 6,000	0.023 - 0.26	(45; 172; 178; 236; 237; 272)
Na <sub>3</sub> Bi	5.69-97.1	1.72 - 87	5,500 - 78,900	0.0816		0.11	(105; 176)
TaAs family	3 - 30,000	0.63 - 1.9	18,000 - 10,000,000	0.038 - 1.1	32,000	0.021 - 0.68	(46; 179-183; 191-194; 225; 227; 243)
WTe <sub>2</sub>	4,000 - 25,000	0.39 - 1.9	24,000 - 176,000			0.41 - 0.46	(48; 184; 186; 231)
MoTe <sub>2</sub>	2,653	28	16,000 - 58,000			0.8 - 2.9	(337-340)
PtSn <sub>4</sub>	1,000 - 2,100				14,257 - 15,809	0.05 - 0.36	(341-343)
PtBi <sub>2</sub>	12,000						(171)
Pt(Te/Se) <sub>2</sub>	A few tens		3,600 - 5,500			0.11 - 3.6	(229; 344)
PdTe <sub>2</sub>	A few tens			0.18 - 0.65	1,293 - 6,209	0.04 - 1.16	(229; 248)

In a Weyl semimetal, a spatially inhomogeneous Weyl node separation caused by lattice deformations can mimic the action of axial electromagnetic fields. Such fields can locally drive a chiral magnetic effect, a local macroscopic current, in equilibrium. In the present work, we study the interplay of external and intrinsic magnetic fields and explore the fate of bulk boundary oscillations in systems subjected to strain gradients. We show that the emerging intrinsic fields leave distinct hallmarks on the period of the oscillations by modifying the particle trajectories.

This makes the oscillations depend on the geometry of the system in an analytically traceable manner. We, therefore, predict that quantum oscillations are a natural way to observe and quantify intrinsic magnetic fields, both of which have not been achieved yet in the solid state. Band structures of three-dimensional crystalline materials can exhibit non-degenerate band crossings, functioning as monopoles emitting a momentum space equivalent of magnetic flux. These momentum space defects must come in pairs of opposite charges due to periodicity of the Brillouin zone. Electrons in the vicinity of such so-called Weyl nodes can be assigned a quantum number, chirality, determined by the charge of the 'Berry monopole'. The chirality can couple to observable transport phenomena and affect response functions for the system. As the terminology implies, there is a one-to-one correspondence between the effective theory describing these low energy excitations, and the physics of the high energy Weyl fermions.

Hence, Weyl semimetals (WSMs), materials hosting such nodes, offer a pathway for realizing relativistic phenomena in 3 + 1 dimensions, representing a microcosm contained within a solid state sample. The consequences of the chiral charges in field theory are well known and celebrated. In particular, the chiral magnetic effect (CME) is a current response from a single specie of Weyl fermions generated along the direction an externally applied magnetic field. The same phenomenon is expected to occur in WSM, due to the structure of the bulk Landau levels developing around the Weyl point: the lowest Landau level disperses in the direction of the field, with a group velocity that is determined by the sign of the topological charge of the nodes.

However, the detection of the CME in a solid state system is made complicated by the Nielsen- Ninomiya theorem, dictating that the CME vanishes in equilibrium due to a cancellation of contributions from nodes of opposite chiralities. Pair of nodes of opposite chiralities host counter propagating modes that cancel one another, resulting in zero total CME in equilibrium. One can obtain a non cancellation of the CME only in non-equilibrium conditions, either through dynamics, or through an imbalance of chiral chemical potentials.

In stark contrast to the discussion above, a CME arising from pseudo-magnetic fields can be sustained locally even in equilibrium conditions. Since such fields act with an opposite sign on the two types of chiral fermions, their contributions to equilibrium currents are added to one another instead of canceling. The only constraint imposed on such currents, is that they must vanish when integrating over the entire sample. This phenomenon is linked to a known fact from classical electromagnetism bound currents as a result of inhomogeneous magnetization can flow within a medium so long as the total dissipation-less current vanishes when averaged over the volume of the sample. In a magnetic field, electrons in metals repeatedly traverse closed magnetic orbits around the Fermi surface. The resulting oscillations in the density of states enable powerful experimental techniques for measuring a metal's Fermi surface structure. On the other hand, the surface states of weyl semimetals consist of disjoint, open

Fermi arcs raising the question of whether they can be observed by standard quantum oscillatory techniques. Here, we find that the open Fermi arcs participate in unusual closed magnetic orbits by traversing the bulk of the sample to connect opposite surfaces. These orbits have anomalous features that are impossible for conventional surface states, and result in quantum oscillations that contain observable signatures of the topological character of the weyl semimetal. We

also apply our predictions to the compounds Cd<sub>3</sub>As<sub>2</sub> and Na<sub>3</sub>Bi that were recently proposed to be three-dimensional Dirac (doubled Weyl) semimetals, and propose experimental signatures of their possible Fermi arc states. Unlike metals, Weyl and Dirac semimetals possess open discontinuous Fermi surfaces Here, Potter et al. show how such materials may still exhibit characteristic Electronic oscillations under applied magnetic fields via bulk tunneling between Fermi arcs and predict their experimental signatures.

#### METHOD :

Numerical simulations

Numerical simulations were performed by modelling a Weyl SM slab by  $H=H_y+H_{\perp}$  where:

$$H_y \equiv -i v_{\perp} \partial_y \sigma^y$$

$$H_{\perp} \equiv -\frac{1}{8} v_z k_0 [1 - (2\hat{\pi}_z/k_0)^2] \sigma^z + v_{\perp} \hat{\pi}_x \sigma^x$$

and  $\mathbf{A}=Bz \hat{y}$  is the vector potential in the Landau gauge corresponding to a uniform magnetic field along  $\hat{y}$ . In this gauge,  $x$  momentum is a good quantum number, which just sets the location of the guiding centre for the Landau orbits, and can be taken as zero without loss of generality.

Then, we introduce LL raising and lowering operators via:

$$\pi_x = \frac{1}{\sqrt{2\ell_B}} (a^\dagger + a) \quad \pi_z = \frac{-i}{\sqrt{2\ell_B}} (a^\dagger - a)$$

which satisfy canonical commutation relations  $[a, a^\dagger]=1$ .

Eigenstates of  $H_y$  are  $e^{isk_y} |\sigma_y = s' = \pm 1\rangle$ , with corresponding to eigenvalue  $\varepsilon_y = ss' v_\perp k_y$ .

Eigenstates of  $H_\perp$  with eigenvalue  $\varepsilon_n$  were obtained numerically by truncating the oscillator basis  $a^\dagger |n\rangle = n |n\rangle$  to keep a finite number of  $|n\rangle$  with  $n < N_{\max}$ . This truncation breaks the canonical commutation relations of  $a$  and  $a^\dagger$  for states near the cutoff,  $N_{\max}$ , producing additional spurious low-energy solutions, which are removed by adding a regulator term that energetically penalizes  $|N_{\max}\rangle$ .

Eigenstates of full Hamiltonian are of the form:

$$\Psi_{E, k, m}^{(s, s')} = e^{isv_\perp k} \begin{pmatrix} (E + sv_\perp k) f_m(x, z) \\ s' \varepsilon_\perp, m g_m(x, z) \end{pmatrix}$$

where  $s, s' = \pm$ . Only certain superpositions of such eigenstates will satisfy the boundary conditions at the bottom ( $y=0$ ) and top ( $y=L$ ) surfaces of the slab. The proper boundary conditions can be identified by treating the vacuum ( $y < 0$  and  $y > L$ ) as an ordinary band-insulator with large gap. Equivalently, we can add a mass term to equation of the form  $M(y)\sigma^z$ , where  $M(y)=0$  inside the slab, and  $M(y)=M_0 > 0$  outside the slab. Continuity of the wave functions at the slab boundaries, on taking the limit  $M_0 \rightarrow \infty$ , require that  $\Psi(y=0, L)$  be eigenstates of  $\sigma^x$  with eigenvalues  $\pm 1$ , respectively.

## CONCLUSION

In summary, we have reviewed distinct electronic transport phenomena associated with the nontrivial band topology in different types of topological semimetals and discussed how to extract the fundamental properties of Dirac/Weyl fermions such as effective mass, quantum mobility and Berry phase from dHvA or SdH quantum oscillation measurements, topological semimetals exhibit a rich variety of exotic properties which are not seen in nonrelativistic electron systems. This includes chiral anomaly and planar Hall effect in WSMs, intrinsic anomalous Hall effect in time reversal symmetry-breaking WSMs, quantum oscillations due to Weyl orbits and AMR peak narrowing under high magnetic fields in DSMs, half-integer quantum Hall effect and quantum tunneling of the zeroth LLs in layered magnetic DSMs, vanishing magnetization and dynamic mass generation in the quantum limit of DSMs/WSMs. These properties are connected with the non-trivial band topology though the mechanisms for some of them have not been fully understood. Furthermore, As we got to know how DSMs/WSMs are linked with QSHI and QAHI and how these two quantum Hall states can be approached by reducing NLSMs/FM WSMs to 2D thin layers.

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