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The axial anomaly in chiral tilted Weyl semimetals

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ABSTRACT

The axial anomaly is investigated based on Fujikawa's method for chiral tilted Weyl semimetals, in which the Weyl cones with different chiralities tilt to opposite directions. When the electric field (EF) is parallel to the magnetic field (MF), the axial anomaly contributed by electromagnetic fields along tilt direction is reduced less than that along other directions. This results in that the associated effects, such as anomalous Hall effect, chiral magnetic effect and negative magnetoresistivity, are suppressed anisotropically. More interestingly, when the EF is perpendicular to MF, the axial anomaly has a new contribution from the mixed product of tilt vector, EF and MF, which is asymmetry under reversing tilt direction (electron–hole asymmetry) and leads to a current between Dirac cones with different tilt directions and novel magnetoresistivity (MR). Specifically, this contribution can change the properties of MR in some experimental establishments and makes trivial components of MR in un-tilted Weyl semimetal develop non-trivial properties. These changes are consistent with the MR phenomena observed in experiments, such as gate-tunable negative longitudinal MR, Hall MR, extremely large and non-saturating MR.

1. Introduction

Dirac semimetals and Weyl semimetals have drawn enormous interest recently [1–6]. For these materials, the low-energy quasi-particles are massless Dirac fermions or Weyl fermions, which are

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described by Dirac equation or Weyl equation respectively. The massless feature protected by crystal symmetries can lead to many novel physical properties [7]. An important one is axial anomaly, which has been widely investigated both in theory and experiment [8–15].

In quantum field theory, the appearance of axial anomaly indicates that the axial gauge symmetries $U_A(1)$ of classical Dirac fields can no longer be valid at the quantum level, which implies that the axial current $j_5^\mu = \langle e\gamma^\mu\gamma_5\rangle$ cannot be conserved but rather satisfies [8–10,16]

$$\partial_\mu j_5^\mu = \frac{e^2}{2\pi^2}\boldsymbol{E}\cdot\boldsymbol{B}. \tag{1}$$

Here, e is the charge of an electron and γ^μ are matrices satisfying $\gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2\eta^{\mu\nu}$, where the indices of Greek letters $\mu, \nu = 0, 1, 2, 3$ are Minkowski space–time indices and $\eta^{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$ is Minkowskian matric. $\boldsymbol{E}$ and $\boldsymbol{B}$ are strengths of electric field (EF) and magnetic field (MF).

The anomalous equation (1), originally obtained in quantum field theory for standard Dirac fermions, has been associated with many important physical effects in condensed matter physics, such as chiral magnetic effect [10,17], anomalous Hall effect [8], Fermi arcs [3] and negative magnetoresistivity (MR) [18–21]. While these elementary Dirac fermions are invariant under Lorentz transformations [16], the emergent "relativistical" quasi-particle can however break Lorentz symmetry essentially in condensed matter physics. These emergent "relativistical particles" may beyond the scope of traditional quantum field theory and have novel exciting properties [22–24]. One typical example is the type-II Weyl fermion which provides an excellent platform to investigate the corresponding properties of such "relativistical particles".

Recently, many efforts associated with axial anomaly reveal some novel properties for type-II Weyl semimetal both in theory and experiment. For example, anisotropic axial anomaly [25,26], gate-tunable negative longitudinal MR [21], Hall MR [27], extremely large and non-saturating MR [28–30] are observed in WTe_2. The theoretical analysis based on quasi-classical Boltzmann framework shows that the axial anomaly is anisotropic and the chiral-anomaly-induced negative longitudinal MR should exist along arbitrary directions [31]. However, the explicit form of axial anomalous equation for type-II Weyl semimetal was not given in [31] . Besides, since only the longitudinal components of resistivity was considered in Ref. [31] , they cannot explain the off-diagonal MR observed in experiments [21,27]. Thus, a full description of axial anomaly based on quantum theory is still in desperate need.

A non-trivial phenomenon in strained WTe_2 is that the compressive uniaxial strain can drive one of the two Weyl points from type-II to type-I [32], which implies that there is a considerable difference between the tilt directions of two Weyl points. Besides this phenomenon exists extensively in Weyl semimetal [33,34], this kind of difference also exists in hybrid Weyl semimetal [35]. Since the Lorentz symmetry is violated essentially in these systems, one can expect that such violation must lead to unique effects that have no analogues in conventional field theory.

In this paper, the axial anomaly in tilted Weyl semimetal is investigated. We only consider the model of a tilted Weyl semimetal with a single pair of Weyl points whose chirality is opposite. The generalization to other number of Weyl points is straightforward. We show that the tilt of two Weyl cones can be classified into two basic cases in Weyl semimetals. The first one is that the two Weyl cones are tilted to the same direction and the second one is that they are tilted to the opposite directions. The other cases can be considered as the superposition of these two cases. The Lagrangians of these two cases are given in Section 2. Based on quantum field theory in curved space–time, if the two Weyl points tilt to the same direction, the tilt cannot change the axial anomaly [36]. Thus, we will concentrate on the Weyl semimetal, in which the tilt directions of Weyl fermions are opposite if their chirality is opposite. We call such Weyl semimetal as chiral tilted Weyl semimetal. For the chiral tilted Weyl semimetal, the axial currents and their anomaly are obtained by Fujikawa's method in Section 3. In Section 4, we obtain the currents contributed by the axial anomaly and discuss their physical implications. In the last Section 5, a conclusion is given.

2. Lagrangian density of tilted Weyl and Dirac fermions

The general Hamiltonian of tilted Weyl fermions can be written as [32]

$$H = {v_0}^i k_i + \sigma^j {v_j}^i k_i = \boldsymbol{v}_0\cdot\boldsymbol{k} + \sigma^j\boldsymbol{v}_j\cdot\boldsymbol{k} \tag{2}$$