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# Chiral magnetic effect in condensed matter systems

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**Abstract**

The chiral magnetic effect (CME) is the generation of electrical current induced by chirality imbalance in the presence of magnetic field. It is a macroscopic manifestation of the quantum chiral anomaly[1, 2] in systems possessing charged chiral fermions. In quark-gluon plasma containing nearly massless quarks, the chirality imbalance is sourced by the topological transitions. In condensed matter systems, the chiral quasiparticles emerge in gapless semiconductors with two energy bands having pointlike degeneracies opening the path to the study of chiral anomaly[3]. Recently, these novel materials – so-called Dirac and Weyl semimetals have been discovered experimentally, are suitable for the investigation of the CME in condensed matter experiments. Here we report on the first experimental observation of the CME in a 3D Dirac semimetal $ZrTe_5$ [4].

*Keywords:* Chiral magnetic effect, Dirac semimetals, Weyl fermions, quark-gluon plasma

Relativistic theory of charged chiral fermions in three spatial dimensions possesses so-called chiral anomaly [1, 2]. Of particular interest is the chiral magnetic effect (CME) [5] - the generation of electric current in an external magnetic field induced by the chirality imbalance [6]. This phenomenon is currently under intense study in relativistic heavy ion collisions at Relativistic Heavy Ion Collider (RHIC) at BNL and at the Large Hadron Collider (LHC) at CERN, where it was predicted [7] to induce the fluctuations in hadron charge asymmetry with respect to the reaction plane. The experimental data from the STAR [8] Collaboration at RHIC and ALICE [9] Collaboration at LHC indicate the fluctuations consistent with the theory expectations. Closely related phenomena are expected to play an important role in the Early Universe, possibly causing the generation of primordial magnetic fields [10, 11, 12, 13, 14]. However, the interpretation in all these cases is under debate due to lack of control over the produced chirality imbalance.

In condensed matter physics, the chirality imbalance can be introduced in a controlled way by putting the system with chiral quasiparticles into parallel electric and magnetic fields. In 1983, Nielsen and Ninomiya demonstrated a similarity between the fermion system of lattice gauge theories and the electron system of crystals, and pointed out that in gapless semiconductors where two energy bands have pointlike degenera-

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cies, there should exist quasi-particles that behave like the Weyl fermions subject to the chiral anomaly [3]. In particular, these charged Weyl fermions would have to exhibit the chiral magnetic effect [5]. The recent discovery of three dimensional (3D) Dirac semimetals, $ZrTe_5$ [4], $Cd_3As_2$ and $Na_3Bi$ [15, 16, 17, 18] enables experimental studies of the quantum dynamics of relativistic field theory in condensed matter systems.

A prominent signature of the chiral magnetic effect in Dirac systems in parallel electric and magnetic fields is the positive contribution to the conductivity that has a quadratic dependence on magnetic field [5, 19, 20]. This is because the CME current is proportional to the product of chirality imbalance and the magnetic field, and the chirality imbalance in Dirac systems is generated dynamically through the anomaly with a rate that is proportional to the product of electric and magnetic fields. As a result, the longitudinal magnetoresistance becomes negative [19, 20].

A detailed discussion of the mechanism of the chiral magnetic effect in Dirac semimetals can be found in Ref. [4]. An illustration of the chiral magnetic effect in Dirac semimetals is shown in Fig. 1.

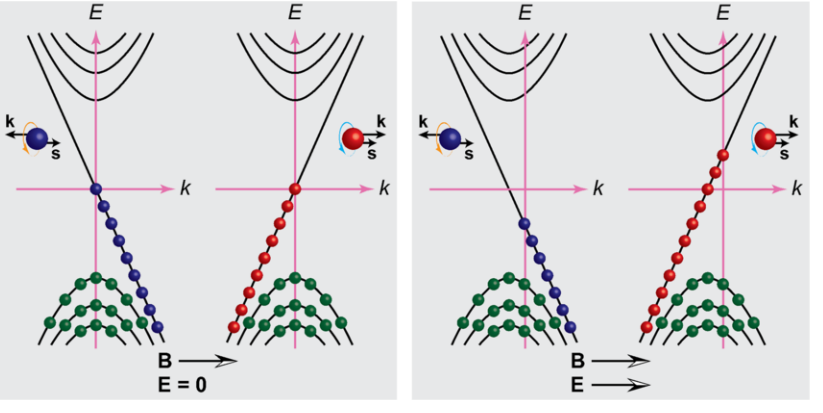


Fig. 1. Illustration of the chiral magnetic effect in Dirac semimetals. *Left panel*: the left- and right-handed fermions occupying various Landau levels in the presence of magnetic field $\vec{B}$. On the lowest Landau level, the spins of positive (negative) chiral fermions are parallel (anti-parallel) to the external magnetic field. Therefore, for a positive fermion to be right-handed (i.e., have a positive projection of spin on momentum) means moving along the magnetic field, and for a negative fermion – moving against the magnetic field. The left- and right-handed fermions are equally numbered under zero electric field $\vec{E}$. *Right panel*: Under external electric field parallel to magnetic field, the positive (negative) fermions accelerate (decelerate) along the electric field that is also parallel to magnetic field direction. This creates a non-zero chemical potential, leading to a net CME current.

In the absence of external fields, each Dirac point in Dirac semimetals initially contains left- and right-handed fermions with equal chemical potentials. If the energy degeneracy between the left- and right-handed fermions gets broken, a chiral chemical potential $\mu_5$ is generated with the corresponding density of chiral charge given by [5]

$$\rho_5 = \frac{\mu_5^3}{3\pi^2 v^3} + \frac{\mu_5}{3v^3}\left(T^2 + \frac{\mu^2}{\pi^2}\right), \tag{1}$$

where $\mu = (\mu_R + \mu_L)/2$ and $T$ are the chemical potential and the temperature, and $v$ is the Fermi velocity. Under the external electric and magnetic fields, the generation rate of chiral charge is given by

$$\frac{d\rho_5}{dt} = \frac{e^2}{4\pi^2\hbar^2 c}\vec{E}\cdot\vec{B}. \tag{2}$$

The chirality-changing scattering can mix the left- and right-handed fermions in Dirac semimetals. By