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Lattice quantum Monte Carlo study of chiral magnetic effect in Dirac semimetals

D.L. Boyda [a], V.V. Braguta [a,b], M.I. Katsnelson [c,d], A.Yu. Kotov [b,e,f,*]

[a] Far Eastern Federal University, School of Biomedicine,, 690950 Vladivostok, Russia
[b] Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, 141980, Russia
[c] Radboud University, Institute for Molecules and Materials, Heyendaalseweg 135, NL-6525AJ Nijmegen, The Netherlands
[d] Ural Federal University, Theoretical Physics and Applied Mathematics Department, Mira Str. 19, 620002 Ekaterinburg, Russia
[e] Moscow Institute of Physics and Technology, Institutskii per. 9, Dolgoprudny, Moscow Region, 141700, Russia
[f] Institute for Theoretical and Experimental Physics, 117259 Moscow, Russia

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ABSTRACT

In this paper Chiral Magnetic Effect (CME) in Dirac semimetals is studied by means of lattice Monte Carlo simulation. We measure conductivity of Dirac semimetals as a function of external magnetic field in parallel $\sigma_{\parallel}$ and perpendicular $\sigma_{\perp}$ to the external field directions. The simulations are carried out in three regimes: semimetal phase, onset of the insulator phase and deep in the insulator phase. In the semimetal phase $\sigma_{\parallel}$ grows whereas $\sigma_{\perp}$ drops with magnetic field. Similar behaviour was observed in the onset of the insulator phase but conductivity is smaller and its dependence on magnetic field is weaker. Finally in the insulator phase conductivities $\sigma_{\parallel,\perp}$ are close to zero and do not depend on magnetic field. In other words, we observe manifestation of the CME current in the semimetal phase, weaker manifestation of the CME in the onset of the insulator phase. We do not observe signatures of CME in the insulator phase. We believe that the suppression of the CME current in the insulator phase is connected to chiral symmetry breaking and

* Correspondence to: Institute for Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117259 Moscow, Russia.
E-mail addresses: boyda_d@mail.ru (D.L. Boyda), braguta@itep.ru (V.V. Braguta), m.katsnelson@science.ru.nl (M.I. Katsnelson), kotov@itep.ru (A.Yu. Kotov).

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generation of dynamical fermion mass which take place in this phase.

1. Introduction

Anomalies are fundamental objects in relativistic quantum field theory. There are a lot of manifestations of the quantum anomalies in high energy physics [1]. One example of the anomaly based phenomena is the Chiral Magnetic Effect(CME) [2–4]. The essence of this phenomenon is generation of nondissipative electric current along external magnetic field in systems with the imbalance between the number of right-handed and left-handed fermions. One believes that the CME was observed in heavy ion collision experiments RHIC and LHC through the measurements of fluctuations in hadron charge asymmetry [5,6].

Recent discovery of Dirac [7–9] and Weyl Semimetals [10,11] opens the possibility to study relativistic quantum field theory phenomena in condensed matter physics. Characteristic feature of these materials is that the low energy fermionic spectrum is similar to massless 3D Dirac fermions, what allows to observe different manifestations of the quantum anomalies and, in particular, the CME.

To observe the CME, it is necessary to create system with imbalance between the number of right-handed and left-handed fermions. This can be done if one applies parallel electric $\mathbf{E}$ and magnetic $\mathbf{B}$ fields to the system, what leads to generation of the density of chiral charge with the rate [12]

$$\frac{d\rho_5}{dt} = \frac{e^2}{4\pi^2\hbar^2 c}\mathbf{E}\cdot\mathbf{B} - \frac{\rho_5}{\tau}. \tag{1}$$

The first term in last equation describes the production of chiral charge due to the chiral anomaly, while the second one describes the decrease of chirality due to the chirality-changing processes. Note that we use Lorentz–Heaviside units throughout the paper. The τ is the relaxation time of chiral charge which was studied in [13,14]. At large times as the result of the balance between production due to the anomaly and decrease due to the chirality-changing processes, the system stabilizes at the chiral charge density given by the formula

$$\rho_5 = \frac{e^2}{4\pi^2\hbar^2 c}\mathbf{E}\cdot\mathbf{B}\tau \tag{2}$$

The chiral charge density can be parameterized by the chiral chemical potential μ_5 through the equation of state (EoS) $\rho_5 = \rho_5(\mu_5)$. Below we are going to use the linear response theory for which the electric field $\mathbf{E}$ is considered as a perturbation. In this limit one can state that the chiral chemical potential created in the system is small. For the small chiral chemical potential the EoS can be written as

$$\rho_5 = \mu_5\chi(T,B) + O(\mu_5^3), \tag{3}$$

where the $\chi(T,B)$ is a function of magnetic field and temperature. It is clear that in the limit of small magnetic field $eB/T^2 \to 0$ the behaviour of the function χ is determined by temperature and the $\chi(T,B) \sim T^2$. In the limit of large magnetic field $eB/T^2 \to \infty$ the function χ is determined by degeneracy on the lowest Landau level and one can expect that $\chi(T,B) \sim eB$. As was noted above the influence of the external magnetic field on the system with chiral imbalance leads to generation of electric current which is given by the formula

$$\mathbf{j}_{\mathbf{CME}} = \frac{e^2}{2\pi^2}\mu_5\mathbf{B}. \tag{4}$$

Combining formulae (2)–(4) one acquires conductivity due to the CME

$$j^i_{CME} = \sigma^{ij}_{CME}E^j,\ \sigma^{ij}_{CME} = \frac{e^4}{8\pi^4\hbar^2 c}\frac{\tau}{\chi(T,B)}B^iB^k \tag{5}$$