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Review

Chiral magnetic and vortical effects in high-energy nuclear collisions—A status report

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ABSTRACT

The interplay of quantum anomalies with magnetic field and vorticity results in a variety of novel non-dissipative transport phenomena in systems with chiral fermions, including the quark–gluon plasma. Among them is the Chiral Magnetic Effect (CME)—the generation of electric current along an external magnetic field induced by chirality imbalance. Because the chirality imbalance is related to the global topology of gauge fields, the CME current is topologically protected and hence non-dissipative even in the presence of strong interactions. As a result, the CME and related quantum phenomena affect the hydrodynamical and transport behavior of strongly coupled quark–gluon plasma, and can be studied in relativistic heavy ion collisions where strong magnetic fields are created by the colliding ions. Evidence for the CME and related phenomena has been reported by the STAR Collaboration at Relativistic Heavy Ion Collider at BNL, and by the ALICE Collaboration at the Large Hadron Collider at CERN. The goal of the present review is to provide an elementary introduction into the physics of anomalous chiral effects, to describe the current status of experimental studies in heavy ion physics, and to outline the future work, both in experiment and theory, needed to eliminate the existing uncertainties in the interpretation of the data.

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1. Introduction

Quantum Chromodynamics (QCD) presents a remarkable example of a theory with known symmetries and well established elementary constituents, but with emergent behavior that remains mysterious to this day. In spite of forty years of intense effort, it is still not clear how the asymptotic states of QCD perturbation theory – colored quarks and gluons – transform into the asymptotic states actually observed in experiment, the color-singlet hadrons. Because the confinement of color is not present in perturbation theory, its mechanism has to arise from a non-perturbative dynamics.

It is widely perceived that such non-perturbative dynamics originates in the topological sector of QCD. The main topic of this review, namely the Chiral Magnetic Effect (CME), is motivated by attempts to find observable manifestations of the topological structure of the theory. In this review we will provide a simple intuitive introduction into CME and other similar anomalous transport effects, discuss the phenomenology of these effects for heavy ion collisions, and review the current status of experimental search. For the rest of the Introduction, however, let us first discuss the theoretical foundations and the distinctive features of the CME phenomenon.

A salient feature of QCD ignored in the perturbative approach is the compactness of the non-Abelian gauge group. This may well be at the origin of the difficulties of perturbative QCD in describing the ground state of the theory. Indeed, the compact gauge group SU(3) allows for topologically nontrivial configurations of the gluon field. The existence of these configurations in the ground state of the theory essentially modifies the vacuum structure—a superposition of an infinite set of topologically distinct states connected by tunneling instanton transitions [1] becomes the "θ-vacuum" of the theory [2,3]. It is likely that topological effects in QCD are responsible for the chiral symmetry breaking (see [4] for a review) and possibly for confinement (see [5] for a recent proposal).

The crucial importance of the compactness of the gauge group for the structure of the ground state can be illustrated by using electrodynamics of superconductors as an example. The U(1) gauge group of electrodynamics with elements $e^{i\varphi}$ can be treated both as a compact (i.e. defined on a circle, with identification $\varphi \to \varphi + 2\pi n$) or a non-compact (i.e. defined on an infinite line) group. The Abrikosov vortex in a type II superconductor [6] corresponds to the continuous circle onto circle $S_1 \to S_1$ mapping from the azimuthal angle of space onto the phase angle of the electromagnetic order field, and its existence is thus linked to the compactness of U(1). One would not be able to understand the existence of the ground state of a superconductor using any finite order computation in U(1) perturbation theory.

The example of the Abrikosov vortex is suggestive since it emerges as a crucial ingredient of confinement mechanism proposed for QCD by 't Hooft [7], Mandelstam [8], and Nambu [9]. Indeed, if magnetic monopoles existed, a pair of magnetic monopole and anti-monopole inside a superconductor would be connected by the Abrikosov vortex, since magnetic field is expelled from the bulk of the material due to Meissner effect. As the vortex possesses a fixed amount of energy per unit of length, the monopole and anti-monopole would be bound by a linear confining potential. In the dual picture with magnetic and electric charges exchanged, the opposite electric charges become connected by an confining electric flux tube expelled from the bulk due to the condensation of magnetic charges (dual to the condensate of electrically charged Cooper pairs).

Superconductors also demonstrate the deep link between topology and non-dissipative currents. Since this link is of crucial importance for our discussion, let us elaborate on it by using superconductor as an example. Around the Abrikosov vortex, there exists a supercurrent that screens the magnetic field of the vortex in the bulk. The corresponding physics is captured by the London relation between the electric current and gauge potential ($\nabla \cdot \vec{\mathbf{A}} = 0$):

$$\vec{\mathbf{J}} = -\lambda^{-2}\vec{\mathbf{A}}. \tag{1}$$