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Nuclear Physics A 956 (2016) 99–106

NUCLEAR PHYSICS A

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Chiral Magnetic Effect in Heavy Ion Collisions

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Abstract

The Chiral Magnetic Effect (CME) is a remarkable phenomenon that stems from highly nontrivial interplay of QCD chiral symmetry, axial anomaly, and gluonic topology. It is of fundamental importance to search for the CME in experiments. The heavy ion collisions provide a unique environment where a hot chiral-symmetric quark-gluon plasma is created, gluonic topological fluctuations generate chirality imbalance, and very strong magnetic fields $|\vec{\mathbf{B}}| \sim m_\pi^2$ are present during the early stage of such collisions. Significant efforts have been made to look for CME signals in heavy ion collision experiments. In this contribution we give a brief overview on the status of such efforts.

Keywords: Chiral Magnetic Effect, Heavy Ion Collision, Chiral Anomaly, QCD Topology

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1. Introduction

Our modern society and our daily lives heavily rely upon *electricity*, the knowledge about which originated from physicists' curiosity in exploring and understanding *electromagnetism of matter*. External electric and magnetic fields were used early on, and are still widely used today in many ways, as probes for the properties of materials under investigation. One of the most important discoveries, is the Ohm's Law, $\vec{\mathbf{J}} = \sigma\vec{\mathbf{E}}$, i.e. the generation of an electric current $\vec{\mathbf{J}}$ in the presence of external electric field $\vec{\mathbf{E}}$ with the conductivity coefficient σ characterizing the charge transport property of matter. Coming to the discussion of a new state of matter, the quark-gluon plasma (QGP), one might imagine the remote possibility of *quarkicity* and wonder what would be the electromagnetic transport properties of QGP when probed by external electromagnetic (EM) fields. The quarks are carriers of electric charges that respond to external EM fields. However the quarks are carriers of color charges as well and their transport dynamics would be dominated by strong interaction in QGP. The question of EM transport properties in QGP therefore concerns interplay between QED and QCD, and becomes more interesting particularly due to the *chiral symmetry* of QCD.

With the light quark current masses negligible compared to relevant energy scales, the QCD Lagrangian has an approximate chiral symmetry. However this symmetry is not realized in the ground state due to the formation of quark-anti-quark pair condensate in the vacuum of QCD which is dominated by strong quantum fluctuations with nonperturbative interactions. This is of course the well-known phenomenon of *spontaneously broken chiral symmetry* which is a fundamental property of QCD. On the other hand, first principle computations from lattice QCD have shown that with increasing temperature such vacuum condensate will be "melted" away with the chiral symmetry being restored at sufficiently high temperature

http://dx.doi.org/10.1016/j.nuclphysa.2016.02.027

$T > T_c \sim 165$MeV [1, 2]. Therefore, *a chiral-symmetric QGP at high temperature is also a fundamental prediction of QCD*. With such symmetry of light quark sector, the currents in QGP can be independently examined for right-handed (RH) and left-handed (LH) quarks. The chiral currents $\vec{\mathbf{J}}_{R/L}$ can then be combined into the familiar vector current $\vec{\mathbf{J}} = \vec{\mathbf{J}}_R + \vec{\mathbf{J}}_L$ and axial current $\vec{\mathbf{J}}_5 = \vec{\mathbf{J}}_R - \vec{\mathbf{J}}_L$. Recent studies on the transport properties of QGP in responses to external EM fields have found the generalized "Ohm's Table" for QGP:

$$\begin{pmatrix} \vec{\mathbf{J}} \\ \vec{\mathbf{J}}_5 \end{pmatrix} = \begin{pmatrix} \sigma & \sigma_5 \\ \sigma_{\chi e} & \sigma_s \end{pmatrix} \begin{pmatrix} \vec{\mathbf{E}} \\ \vec{\mathbf{B}} \end{pmatrix} . \tag{1}$$

In addition to the familiar Ohmic conducting effect, three interesting new effects are identified in the above table: the Chiral Magnetic Effect (CME) [3, 4, 5], the Chiral Separation Effect (CSE) [6, 7], and the Chiral Electric Separation Effect (CESE) [8, 9]. For detailed discussions on these anomalous transport effects and for more complete reference lists, we refer the readers to recent reviews in e.g. [10, 11, 12]. In this contribution, we focus on the Chiral Magnetic Effect and related phenomena in the quark-gluon plasma.

The CME predicts the generation of a vector current $\vec{\mathbf{J}}$ in response to external magnetic field $\vec{\mathbf{B}}$:

$$\vec{\mathbf{J}} = \sigma_5 \vec{\mathbf{B}} . \tag{2}$$

One may immediately realize that *normally* the above transport process is forbidden by symmetry considerations: $\vec{\mathbf{J}}$ is $\mathcal{P}$-odd and $\mathcal{CP}$-even, while $\vec{\mathbf{B}}$ is $\mathcal{P}$-even and $\mathcal{CP}$-odd. Indeed the CME could occur only in *a $\mathcal{P}$- and $\mathcal{CP}$-odd environment* where the CME conductivity σ_5 (being a pseudo-scalar quantity) is nonzero. More specifically $\sigma_5 = C_A \mu_5$ with C_A a constant. The μ_5 is a chiral chemical potential that quantifies the presence of *chirality imbalance* i.e. the difference between the numbers of RH and LH chiral fermions in the system. For a chiral QGP with nonzero $\mu_5 \neq 0$, a CME current is generated along the direction of $\vec{\mathbf{B}}$. Intuitively the CME may be understood in the following way. The magnetic field leads to a spin polarization (i.e. "magnetization") effect, with quarks' spins preferably aligned along the $\vec{\mathbf{B}}$ field direction, which implies $\langle \vec{s} \rangle \propto (Qe)\vec{\mathbf{B}}$. Quarks with specific chirality have their momentum $\vec{p}$ direction correlated with spin $\vec{s}$ orientation: $\vec{p} \| \vec{s}$ for RH quarks, while $\vec{p} \| (-\vec{s})$ for LH ones. In the presence of chirality imbalance, i.e. $\mu_5 \neq 0$, there will be a net correlation between average spin and momentum $\langle \vec{p} \rangle \propto \mu_5 \langle \vec{s} \rangle$. It is therefore evident that $\langle \vec{p} \rangle \propto (Qe)\mu_5 \vec{\mathbf{B}}$, which implies a vector current of these quarks $\vec{\mathbf{J}} \propto \langle \vec{p} \rangle \propto (Qe)\mu_5 \vec{\mathbf{B}}$.

There remains however the crucial question of how to achieve a chiral QGP with chirality imbalance in the first place. The process of creating nonzero chirality pertains to the famous *"chiral anomaly"* (or often called "triangle/axial anomaly"). This anomaly implies the breaking of axial current conservation by quantum loop effect, $\partial_\mu J^\mu_5 = C_A \vec{\mathbf{E}} \cdot \vec{\mathbf{B}}$. Therefore chirality imbalance can be created through nonzero $\vec{\mathbf{E}} \cdot \vec{\mathbf{B}}$: such fields can be either QED EM fields or QCD chromo-EM fields.

In QCD the gluon configurations with globally nonzero $\vec{\mathbf{E}} \cdot \vec{\mathbf{B}}$ are known to exist: they are the *topological solitons such as instantons and sphalerons*. These topological objects play crucial roles in our understanding of nonperturbative dynamics in QCD vacuum [13] as well as in hot QGP [14, 15, 16]. Such configurations have their global topological winding number $Q_w \sim \int \vec{\mathbf{E}} \cdot \vec{\mathbf{B}}$, and when coupled with chiral fermions, can generate definite amount of global chirality imbalance via chiral anomaly: $N_R - N_L = 2Q_w$ for each flavor of light quarks. In addition there are also strong local fluctuations of topological charge density (i.e. locally nonzero chromo $\vec{\mathbf{E}} \cdot \vec{\mathbf{B}}$) from the initial conditions in the glasma (see e.g. [17, 18]) which would similarly translate into local fluctuations of chirality imbalance. In short, the chirality imbalance is a direct manifestation of the QCD topological fluctuations and could become observable through the CME current.

Summarizing the introductory discussions, the CME is a remarkable phenomenon that stems from highly nontrivial interplay of QCD chiral symmetry, axial anomaly, and gluonic topology. The pertinent CME conductivity $\sigma_5 = C_A \mu_5$ has distinctive features by virtue of its topological origin: it is $\mathcal{T}$-even and thus non dissipative, its constant C_A is completely fixed from anomaly relations and thus takes universal value from weak to strong coupling and encompassing various physical systems. It is therefore of fundamental importance to search for the CME in experiments. The heavy ion collisions provide a unique environment where a hot chiral-symmetric QGP is created, gluonic topological fluctuations generate chirality imbalance, and very strong magnetic fields $|\vec{\mathbf{B}}| \sim m_\pi^2$ are present during the early stage of such collisions. Significant efforts have been made to look for CME signals in heavy ion collision experiments. In the rest of this contribution we give a brief overview on the status of such efforts, with an emphasis on most recent developments.