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Hydrodynamics with chiral anomaly and charge separation in relativistic heavy ion collisions

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ABSTRACT

Matter with chiral fermions is microscopically described by theory with quantum anomaly and macroscopically described (at low energy) by anomalous hydrodynamics. For such systems in the presence of external magnetic field and chirality imbalance, a charge current is generated along the magnetic field direction — a phenomenon known as the Chiral Magnetic Effect (CME). The quark–gluon plasma created in relativistic heavy ion collisions provides an (approximate) example, for which the CME predicts a charge separation perpendicular to the collisional reaction plane. Charge correlation measurements designed for the search of such signal have been done at RHIC and the LHC for which the interpretations, however, remain unclear due to contamination by background effects that are collective flow driven, theoretically poorly constrained, and experimentally hard to separate. Using anomalous (and viscous) hydrodynamic simulations, we make a first attempt at quantifying contributions to observed charge correlations from both CME and background effects in one and same framework. The implications for the search of CME are discussed.

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1. Introduction

The study of matter with chiral fermions has generated significant interest recently, encompassing a wide range of systems from condensed matter materials to hot dense nuclear matter [1]. Of particular interest, are possible anomalous effects that can manifest the microscopic quantum anomaly of chiral fermions in the macroscopic transport properties of matter. The universal nature of chiral anomaly often leads to certain universal features of such anomalous transport effects. A well-known example is the *Chiral Magnetic Effect (CME)* — the generation of a vector current $\boldsymbol{J}$ (a parity-odd vector quantity) along an external magnetic field $\boldsymbol{B}$ (a parity-even axial-vector quantity):

$$\boldsymbol{J} = C_A\, \mu_A\, \boldsymbol{B} \tag{1}$$

where μ_A is a nonzero axial chemical potential that quantifies the amount of chirality imbalance i.e. the difference in numbers of right-handed and left-handed fermions. The coefficient C_A is the universal constant originated from the chiral anomaly coefficient, e.g. $C_A = N_c e/(2\pi^2)$ for each flavor of massless quarks in QCD.

One concrete physical system where the CME may occur and get experimentally observed, is the quark–gluon plasma (QGP) — an extremely hot, deconfined form of nuclear matter that has been created and measured in high energy nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) [2–4]. Evidently three elements are needed for (1) to happen. First a chiral QGP with (approximately) massless quarks is necessary for anomaly effect. While the spontaneous breaking of (approximate) chiral symmetry is a fundamental property of QCD vacuum, it is indeed predicted by Lattice QCD simulations as well as theoretical models that such symmetry is restored at the high temperature accessible in heavy ion collisions. Furthermore a chirality imbalance $\mu_A \neq 0$ is needed. This pertains to a salient feature of QCD as a non-Abelian gauge theory: the topologically nontrivial gluonic configurations such as instantons and sphalerons that are known to be crucial for understanding nonperturbative dynamics of QCD. These configurations couple to quarks through chiral anomaly and "translate" topological fluctuations into chirality imbalance for quarks, thus creating nonzero μ_A on an event-by-event basis. Finally in a heavy ion collision, very strong magnetic field results from the incoming nuclei that are positively charged and move at nearly the speed of light. Such $\boldsymbol{B}$ field has a magnitude on the order of $eB \sim m_\pi^2$ and points approximately

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in the out-of-plane direction [5–7]. A un-ambiguous observation of CME in heavy ion collisions would therefore provide experimental evidence for a chiral symmetric QGP as well as the QCD topological configurations. In addition to the CME, various other interesting anomalous transport effects have been proposed, such as Chiral Separation Effect [8,9], Chiral Electric Separation Effect [10,11], Chiral Magnetic Wave [12–14], Chiral Vortical Wave [15]. For recent reviews see e.g. [1,16–18].

In this study we focus on the Chiral Magnetic Effect in heavy ion collisions. The CME (1) predicts a charge separation along the out-of-plane direction with excessive positive charges accumulating on one tip of the fireball and negative charges on the other tip. Such a separation can be measured by the following reaction-plane dependent azimuthal correlation observable:

$$\gamma_{\alpha\beta} = <\cos(\phi_i + \phi_j - 2\psi_{\rm RP})>_{\alpha\beta} \tag{2}$$

with $\alpha, \beta = \pm$ labeling the charged hadron species and $\phi_{i,j}$ the azimuthal angles of two final state charged hadrons. The $\Psi_{\rm RP}$ denotes reaction plane angle and for later convenience we set $\Psi_{\rm RP} = 0$. This observable has been measured at RHIC [19–22] for a variety of beam energy and centrality as well as at the LHC [23]. The measurements show highly nontrivial change-dependent azimuthal correlations, i.e. charge asymmetry is significant in high energy collisions and disappears at low energy. While some aspects of data are consistent with CME expectations, an unambiguous extraction of CME signal has been obscured due to significant background effects driven by bulk flow [24–29]. This has been clearly revealed by examining another correlation observable:

$$\delta_{\alpha\beta} = <\cos(\phi_i - \phi_j)>_{\alpha\beta} \tag{3}$$

for which data show opposite trends from CME expectations. It was found that the transverse momentum conservation and the local charge conservation can make strong contributions to these observables. For detailed discussions see e.g. [17,18].

Given the importance of CME and given the presently unclear situation in experimental search, what is critically needed is a quantitative modeling of both the CME signal and the pertinent background effect that would allow a meaningful comparison with data. Let us identify a number of outstanding challenges faced in such effort: (1) a description of CME in the hydrodynamic framework that is built on top of state-of-the art, data-validated bulk evolution for heavy ion collisions; (2) a quantification of the influence of key theoretical uncertainties like initial axial charge fluctuations and magnetic field lifetime on the CME signal; (3) an evaluation of background contribution consistently in the same bulk evolution framework; (4) predictions for further measurements that can help verify theoretical assumptions in the modeling. It is the purpose of this Letter to report a significant step forward in addressing these outstanding questions and thus substantially advancing the search of CME in heavy ion collisions

2. CME signal from anomalous hydrodynamics

The Chiral Magnetic Effect (1) implies anomaly-induced contributions to hydrodynamic currents, and a first step one needs to take is to integrate CME contribution with the usual viscous hydrodynamical simulation of heavy ion collisions. The theoretical foundation for this integration has been laid down recently. Fluid dynamical equations with chiral anomaly, i.e. *anomalous hydrodynamics*, have been derived [30]. (For out-of-equilibrium situation, see [31] in which anomaly effects are incorporated in the framework of kinetic theory.) Explorative attempts were recently made to apply them for phenomenological modelings in heavy ion collisions [32–34]. In this work, we adopt the approach similar to that in [33], which treats the fermion currents as perturbations and solves anomalous hydro equations for these currents on top of the data-validated viscous hydrodynamic background. The equations read:

$$\partial_\mu J^\mu = \partial_\mu \left(n u^\mu + Q_f C_A \mu_A B^\mu\right) = 0 \tag{4}$$

$$\partial_\mu J^\mu_A = \partial_\mu \left(n_A u^\mu + Q_f C_A \mu_V B^\mu\right) = -Q_f^2 e C_A E_\mu B^\mu \tag{5}$$

where E_μ, B_μ are covariant form of electromagnetic fields. Note these equations are for each quark flavor with corresponding charge Q_f. The flow field u^μ and local temperature are taken from background hydro solution by "VISH2 + 1", a 2 + 1 viscous hydrodynamics code assuming boost invariance [35]. The quark susceptibility at given (local) temperature that relates density with chemical potential is taken from lattice results [36]. The evolution is followed by a slightly generalized Cooper–Frye freeze-out procedure (see [33] for technical details) that accounts for nontrivial charge transport. Starting from an initial condition of nonzero axial charge density, these equations indeed lead to a spatial separation of positive and negative charges on the freeze-out surface along $\boldsymbol{B}$ direction. Combined with strong radial flow this leads to an event-wise azimuthal distribution of charged hadrons of the following form:

$$\left[\frac{dN^H}{d\phi}\right]_{\rm CME} \propto [1 + 2Q^H a_1^H \sin(\phi) + \ldots] \tag{6}$$

where "H" labels the species of the hadron, e.g. $H = \pi^\pm, K^\pm, \ldots$. The a_1^H, computed from the anomalous hydro equations, quantifies a CME-induced out-of-plane charge separation. This gives a contribution to observable (2) and observable (3) by $\gamma_{\alpha\beta}^{CME} = -\delta_{\alpha\beta}^{CME} = -Q^{H_\alpha} Q^{H_\beta} (a_1^{H_\alpha} a_1^{H_\beta})$. The quantitative results depend on two key input factors in the simulation, which we discuss below.

The first is the initial axial charge density that could be generated from gluon topological fluctuations which is a most significant theoretical uncertainty. A plausible strategy is to study its influence on CME signal and to put constraint on such uncertainty through data comparison. A reasonable assumption is to have initial axial density per each flavor of light quarks to be proportional to initial entropy density s_I, with a proportionality constant $\lambda_A \equiv (n_A/N_f)/s_I \approx Q_A/(N_f S)$ where Q_A is the total initial axial charge while S the total entropy. We note in the linearized regime (owing to the fact that these density fluctuations are all small), this smooth average initial condition is essentially equivalent to event-wise localized axial density "lump" with a probability distribution proportional to initial entropy density, and thus is not so much different from the event-by-event simulations in [34]. In our modeling the CME signal is found to linearly depend on parameter λ_A, i.e. $a_1^H = \lambda_A \tilde{a}_1^H$.

The second is the magnetic field $\boldsymbol{B}$. While its peak magnitude at initial impact of collision has been determined [5–7], its subsequent time evolution is affected by the created partonic medium and not fully understood at the moment [37]. The CME results crucially depend upon the lifetime of $\boldsymbol{B}$ field and it is vital to understand such dependence. We take $\boldsymbol{B}$ to be homogeneous in transverse plane and use a parametrization $eB(\tau) = (eB)_0/[1 + (\tau/\tau_B)^2]$, with (centrality-dependent) peak value $(eB)_0$ from [7], and study how the CME signal depends on the lifetime τ_B.

In short the CME signal is controlled by the two key parameters: λ_A that characterizes initial axial charge as well as the magnetic lifetime τ_B. In Fig. 1 we show our results for such dependence. Note throughout the paper we focus on RHIC AuAu collisions at $\sqrt{s} = 200$ GeV.

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