Quantitative Modeling of Anomalous Chiral Transport

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Outline

– A brief introduction

– Status of CME measurements

– Quantitative CME:

  Anomalous Viscous Fluid Dynamics

– Summary & Outlook
Exciting Progress: See Recent Reviews


Quark-Gluon Plasma: A Chiral Fluid

Would chiral anomaly, usually considered at microscopic level, manifest itself MACROSCOPICALLY in a fluid system of many chiral fermions? If so, how?

It is a nearly perfect liquid: around the quantum limit.

It is a hot plasma with approximately chiral quarks.
**Emergence in Hydrodynamic Context**

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\[ \mathcal{L} \rightarrow \mathcal{L} \]
## Emergence in Hydrodynamic Context

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**WHAT ABOU “HALF”-SYMMETRY???

i..e ANOMALY?!

— classical symmetry that is broken in quantum theory
Chiral Anomaly

Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

**Classical symmetry:**

\[ \mathcal{L} = i \bar{\Psi} \gamma^\mu \partial_\mu \Psi \]

\[ \mathcal{L} \rightarrow i \bar{\Psi}_L \gamma^\mu \partial_\mu \Psi_L + i \bar{\Psi}_R \gamma^\mu \partial_\mu \Psi_R \]

\[ \Lambda_A : \Psi \rightarrow e^{i \gamma_5 \theta} \Psi \]

\[ \partial_\mu J_5^\mu = 0 \]

**Broken at QM level:**

\[ \partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B} \]

\[ \frac{dQ_5}{dt} = \int_X C_A \vec{E} \cdot \vec{B} \]

* C_A is universal anomaly coefficient
* Anomaly is intrinsically QUANTUM effect
Landau Levels in Magnetic Field

\[ E_n^2 = p_z^2 + 2nB \]

Lowest-Landau-Level (LLL): LLL is chiral!
Chiral Anomaly

Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

$$dQ_5/dt = \int_x C_A \vec{E} \cdot \vec{B}$$

$$J_5^\mu = J_5^\mu_R - J_5^\mu_L$$

Illustrated with Lowest-Landau-Level (LLL) picture: the LLL is chiral!
Anomalous Transport: Chiral Magnetic Effect

* The Chiral Magnetic (CME) is an anomalous transport

\[ \vec{J} = \sigma_5 \mu_5 \vec{B} \]

In NORMAL environment, this will NOT happen.
For this to occur: need a P- and CP-Odd environment!

A (convenient) way to quantify IMBALANCE in the numbers of LH vs RH chiral fermions

\[ \mu_5 \]

\[ \text{CHIRAL MATTER!} \]

Such imbalance can be generated through chiral anomaly coupled with E-dot-B (e.g. topological fluctuations of QCD).
So How Does CME Work?

One may recognize deep connection between CME & anomaly.

The CME conductivity is
* fixed entirely by quantum anomaly
* $T$-even, non-dissipative
* universal from weak to strong coupling

We need to modify hydrodynamics!
Hydrodynamics That Knows Left & Right

conservation law:

\[ \partial_\mu J^\mu = 0 \quad \rightarrow \quad \partial_\mu J^\mu = C E^\mu B_\mu \]

constituent relation:

\[ J^\mu = n u^\mu + \nu^\mu \]

\[ \nu^\mu = -\sigma TP^{\mu\nu} \partial_\nu \left( \frac{\mu}{T} \right) + \sigma E^\mu + \xi \omega^\mu + \xi_B B^\mu \]

[Son, Surowka, 2009;…] CVE CME

In Chiral Fluid: Microscopic quantum anomaly emerges as macroscopic anomalous hydrodynamic currents!

It is the “21st century hydrodynamics”: the 1st new terms added since Navier-Stocks!

[In passing: fluid rotation induces similar effects as magnetic field]
Wrap-up: Emergence in Chiral Matter

Chiral anomaly: Basic QM dynamics of chiral fermions

Anomalous chiral transport (Chiral magnetic effect): Emergent phenomenon in **Chiral Matter**:

Quark-gluon plasma [This talk focuses on QGP.]

- Dirac & Weyl Semimetals
  - ZrTe$_5$
  - Na$_3$Bi,
  - Cd$_3$As$_2$

- TaAs, NbAs, NbP, TaP
Status of CME Measurements
Strong EM Fields in Heavy Ion Collisions

- Strongest B field (and strong E field as well) naturally arises!
  [Kharzeev, McLerran, Warringa; Skokov, et al; Bzdak-Skokov; Deng-Huang; Bloczynski-Huang-Zhang-Liao; Skokov-McLerran; Tuchin; ...]
- “Out-of-plane” orientation (approximately)
Azimuthally fluctuating magnetic field and its impacts on observables in heavy-ion collisions

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\textbf{ABSTRACT}

The heavy-ion collisions can produce extremely strong transient magnetic and electric fields. We study the azimuthal fluctuation of these fields and their correlations with the also fluctuating matter geometry (characterized by the participant plane harmonics) using event-by-event simulations. A sizable suppression of the angular correlations between the magnetic field and the 2nd and 4th harmonic participant planes is found in very central and very peripheral collisions, while the magnitudes of these correlations peak around impact parameter $b \sim 8$–$10$ fm for RHIC collisions. This can lead to notable impacts on a number of observables related to various magnetic field induced effects, and our finding suggests that the optimal event class for measuring them should be that corresponding to $b \sim 8$–$10$ fm.
Event-By-Event Magnetic Fields


Deng & Huang, arXiv:1201.5108

Proton is a finite size object!
Event-By-Event Magnetic Fields

Measurable effects (CME, CMW, photon v2,...) are controlled by:

\[
\langle (eB)^2 \cos(2\Psi_B) \rangle
\]

From CME Current to Charge Separation

\[ \vec{J} = \sigma_5 \mu_5 \vec{B} \]

strong radial blast: position \( \rightarrow \) momentum

\[ \frac{dN_\pm}{d\phi} \propto \ldots + a_\pm \sin(\phi - \Psi_{RP}) \]

\[ < a_\pm > \sim \pm < \mu_5 > B \]

[Kharzeev 2004; Kharzeev, McLerran, Warringa, 2008; \ldots]
Charge Separation Observable

\[ \frac{dN_{\pm}}{d\phi} \propto \ldots + a_{\pm} \sin(\phi - \Psi_{RP}) \]

\[ \langle a_{\pm} \rangle \sim \pm \langle \mu_5 \rangle B \rightarrow 0 \]

The dipole flips e-by-e and averages to zero (no global P-violation)

[Voloshin, 2004]

\[ \gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \]
\[ = [\langle \nu_{1, \alpha} \nu_{1, \beta} \rangle + B_{\text{in}}] - [\langle a_\alpha a_\beta \rangle + B_{\text{out}}] \]

known to be very small

The hope was: these two cancel out to be negligible...

As it was pointed out later, the backgrounds turn out to be NOT negligible...

[STAR 2009]

[2009~2010: Wang; Bzdak, Koch, JL; Pratt, Schlichting; ...]
Clearly there are flow driven background contributions: need to develop ways of suppressing such correlations!
Separation of CME & Flow-Driven Background

**Event shape selection method** [Bzdak, Skokov; Wang]

[STAR2013, by Purdue group]  
[STAR2015@QM15]
Separation of CME & Flow-Driven Background

Making sense of data in a two-component picture

[Bzdak, Koch, JL, 2012; Blocynski, Huang, Zhang, JL, 2013]

H: “CME Signal”
F: “Flow Driven Background”

[STAR PRL 2014]
[also measured by ALICE@LHC]

Encouraging experimental evidence for CME in QGP — can we quantitatively compute CME signal?

\[
\begin{align*}
\gamma & = \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) \rangle = \kappa v_2 F - H \\
\delta & = \langle \cos(\phi_1 - \phi_2) \rangle = F + H,
\end{align*}
\]
Summarizing Exp. Status

Main challenge: flow-driven background v.s. CME signal

Vary $v_2$ for fixed $B$:
- $\text{AuAu}$ v.s. $\text{UU}$;
- Varying event-shape;
- 2-component subtraction.

Vary $B$ for fixed $v_2$:
- Isobaric collisions with $\text{RuRu}$ v.s. $\text{ZrZr}$

Our best guess for now:

Caveat: Additional backgrounds from resonance decay in subtracting $v_2$ backgrounds

[Wang, Zhao, 1608.06610]
Quantitative CME from Anomalous Viscous Fluid Dynamics
Early Attempts at CME Modeling

[Hirono, Hirano, Kharzeev, arXiv:1412.0311]
* 3+1D ideal hydro
* event-by-event simulations
* full current evolution
* glasma initial condition

[Yi Yin, JL, arXiv:1504.06906; PLB2016]
* OSU hydro: data validated
* linearized current evolution
* quantifying background in same hydro

[Early applications to CMW: Hirano, Hirono, … 2012; Yee, Yin, 2012]
Anomalous-Viscous Fluid Dynamics (AVFD)

\[ D_\mu J_R^\mu = + \frac{N_c q^2}{4\pi^2} E_\mu B^\mu \quad D_\mu J_L^\mu = - \frac{N_c q^2}{4\pi^2} E_\mu B^\mu \]

\[ J_R^\mu = n_R u^\mu + \nu_R^\mu + \frac{\sigma}{2} E^\mu + \frac{N_c q}{4\pi^2} \mu_R B^\mu \]

\[ J_L^\mu = n_L u^\mu + \nu_L^\mu + \frac{\sigma}{2} E^\mu - \frac{N_c q}{4\pi^2} \mu_L B^\mu \]

\[ d \nu_{R,L}^\mu = (\nu_{NS}^\mu - \nu_{R,L}^\mu) / \tau_{rlx} \]

on top of 2+1D VISHN

\[ D_\mu T^{\mu\nu} = 0 \quad n = 0 \]

B field + \mu_A \Rightarrow charge separation

\[ \frac{dN_{\pm}}{d\phi} \propto 1 + 2 a_{1,\pm} \sin(\phi - \psi_{RP}) + \ldots \]
Chiral Viscous Fluid Dynamics Simulations

[Jiang, Shi, Yin, JL, 2016.]
Chiral Viscous Fluid Dynamics Simulations

[Jiang, Shi, Yin, JL, 2016.]
Dependence on Viscous Parameters

Charge separation could vary within a factor of 2 for a reasonable and broad range of values.

Relaxation time $\tau$:
0.3/T (bottom) $\rightarrow$ 2.0/T (top)

A “standard” choice:
$\sigma = 0.3 \times T$
$\tau = 0.5 / T$
Charge separation has a strong dependence on B field lifetime.

Dependence on B Field Lifetime
Charge separation is VERY sensitive to initial axial charge density.

Charge separation is NOT sensitive to initial vector charge density.
Discussions on Choice of B and N5

About B field Lifetime — Logically three possibilities:

1. $\tau_B \gg \tau_{\text{hydro}}$ —— It appears unlikely.
2. $\tau_B \sim \tau_{\text{hydro}}$ —— We will use this.
3. $\tau_B \ll \tau_{\text{hydro}}$ —— CME has to occur pre-hydro.

About initial axial charge density:
[c.f. Hirono,Hirano,Kharzeev,2014; Mueller, Schaefer, 2010; Kharzeev, Krasnitz,Venugopalan]

$$\langle n_5 \rangle \simeq \frac{Q_s^4}{16\pi^2} \frac{\sqrt{N_{co.}}}{A} \left( \pi \rho^2 \right)$$
With realistic initial axial charge density and short magnetic lifetime, data could be described.

[Jiang, Shi, Yin, JL, 2016.]
Is Strangeness Chiral?

Kaon charge separation is very sensitive to potential contributions from anomalous transport in strangeness sector.
Pre-Hydro CME?

$\tau_B << \tau_{\text{hydro}}$ —— CME has to occur pre-hydro.

The CME can certainly occur in non-equilibrium setting in the pre-hydro stage:

1. direct production in $E_{\text{dot}B}$ glasma fields [Fukushima; Mace, Schlichting,…]

2. Chiral kinetic transport [see afternoon discussions]

How to incorporate pre-hydro CME contribution?
—> As initial conditions for hydro!

No-pre-hydro CME: $J^\mu(\tau_{\text{hydro}}) \rightarrow J^0 \propto s$, $\vec{J} = 0$

Pre-hydro CME could modify initial conditions in two ways:

- dipole in density $\delta J_0 \sim \lambda s \sin \phi$
- anomalous 3-current $\vec{J} \sim \lambda s \hat{y}$
Pre-Hydro CME?

A “proof-of-principle” study in our hydro simulation tool:

Pre-hydro CME could propagate through the bulk evolution process and survive into final charge separation signal.

Hydro simulation could quantify such signal, given the initial conditions.
Summary & Outlook
Summary

Microscopic chiral anomaly emerges as anomalous chiral transport in chiral matter (e.g. QGP): Chiral Magnetic Effect, Chiral Magnetic Wave, Vortical Effects, ...

There is experimental progress in suppressing flow background and extracting CME signal: need more work; need quantitative modeling.

We report an anomalous-viscous fluid dynamics framework which provides sophisticated modeling for CME in high energy collisions.

Detailed AVFD studies, with reasonable parameters and initial conditions, predict CME signals that could quantitatively explain data.
Outlook

Mainly a to-do-list within the BEST CME efforts:

* A detailed study of CMW (ongoing)
* Event-by-event simulations (first batch of events obtained)
* Sophisticated modeling for isobaric collisions (ongoing)
* Change background hydro to 3+1D viscous hydro
* To be coupled with sophisticated pre-hydro modeling
* Ideal test tool for future full-fledged modeling code
* ……