Quantifying the chiral magnetic effect from anomalous-viscous fluid dynamics

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Anomalous Chiral Transport in Heavy Ion Collisions from Anomalous-Viscous Fluid Dynamics

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Exciting Progress: See Recent Reviews


Outline

• Introductory Discussions
• The AVFD Framework
• Quantitative Results from AVFD
• EBE-AVFD
• Summary & Outlook
Introductory Discussions
Chiral Symmetry & SSB

**Classical symmetry:**

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

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

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

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

**Mirror Plane**

**Dirac Sea**

\[ M = m - 2G \langle \bar{\psi} \psi \rangle \]

**Constituent mass**

**Lagrangian (SM) mass**

**Axial symmetry is broken!**
The “Origin of Mass”

QCD interactions (via SSB) account for nearly all the visible mass in the Universe.

A typical person, say ~ 70 kg
* Reasonable estimate, dominantly
H2O ~ 10 protons + 8 neutrons
~ 28 u quarks + 26 d-quarks

* Mass from Higgs: ~1.7kg (~2.4%)
* Mass from QCD: ~ 68.3kg (~97.6%)

The QCD chiral symmetry is just of paramount importance!
QCD & Chiral Symmetry

* Spontaneously broken chiral symmetry in the vacuum is a fundamental property of QCD.

* A chirally symmetric quark-gluon plasma at high temperature is an equally fundamental property of QCD!

Could we see direct experimental evidence for that?
“Little Bang” in High Energy Nuclear Collision

* Quark-gluon plasma (QGP) is created in such collisions.
* It is PRIMORDIALLY HOT ~ trillion degrees ~ early universe.
* Is chiral symmetry restored?
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:**

\[
\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B} \\
dQ_5/dt = \int_X C_A \vec{E} \cdot \vec{B}
\]

* C_A is universal anomaly coefficient
* Anomaly is intrinsically QUANTUM effect

[e.g. pi0→ 2 gamma]
The Chiral Magnetic Effect

\[ \mathbf{J} = \frac{Q^2}{2\pi^2} \mu_5 \mathbf{B} \]

Chirality & Anomaly & Topology

Electric Current

Q.M. Transport

Magnetic Field
The quark-gluon plasma is a type of CHIRAL MATTER, with (approximately) chiral quarks.

Heavy ion collision environment: extremely strong magnetic field and fluid rotation!
Strong EM Fields in Heavy Ion Collisions

- Strongest B field (and strong E field as well) naturally arises!
  [Kharzeev, McLerran, Warringa; Tuichin; Skokov, et al; Bzdak-Skokov; Deng-Huang; Blochynski-Huang-Zhang-Liao; Skokov-McLerran; ...]
- "Out-of-plane" orientation (approximately)
From CME Current to Charge Separation

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

strong radial blast: position $\rightarrow$ momentum

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

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

[Kharzeev 2004; Kharzeev, McLerran, Warringa, 2008; ...]

Charge Separation or Electric Dipole in Pt Space (along out-of-plane)
Experimental Observable

charge separation ⇒ charge dept. two-particle correlation

\[ \gamma = \langle \cos(\Delta \phi_i + \Delta \phi_j) \rangle = \langle \cos \Delta \phi_i \cos \Delta \phi_j \rangle - \langle \sin \Delta \phi_i \sin \Delta \phi_j \rangle \]
\[ \delta = \langle \cos(\Delta \phi_i - \Delta \phi_j) \rangle = \langle \cos \Delta \phi_i \cos \Delta \phi_j \rangle + \langle \sin \Delta \phi_i \sin \Delta \phi_j \rangle \]

\[ \gamma = \kappa \nu_2 F - H \]
\[ \delta = F + H \]

\( H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2 \)

Many interesting proposals of new observables!

See many exp. talks at this conference.
Summarizing Exp. Search Status

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

Vary v2 for fixed B:
- AuAu v.s. UU;
- Varying event-shape;
- 2-component subtraction.

Vary B for fixed v2:
- Isobaric collisions with RuRu v.s. ZrZr

Our best guess for now:

\[ H_{\text{CME}} \to 2\alpha_1^2 \]

[STAR, PRL2014]

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

Many interesting proposals of new observables!

See many exp. talks at this conference.
Toward Quantitative Era of CME Study

* **Modeling CME & CMW with transport model (AMPT):**
  SINAP group; TAMU group; …

* **Modeling CME with chiral kinetic theory:**
  Tsinghua-IU group; TAMU group; …

* **Dynamical magneto-hydro:** Florence-Frankfurt group; BNL-SBU group; Tokyo group; …

* **Axial charge dynamics:** SYSU group; BNL-SBU group; Tsinghua-IU group; …

* **Fluid dynamical description:**
  IU group; BNL-SBU group; …

The rest of this talk will focus on the approach based on a new kind of fluid dynamics simulations: Anomalous-Viscous Fluid Dynamics (AVFD)
The AVFD Framework
Would chiral anomaly, usually considered at microscopic level, manifest itself MACROSCOPICALLY in a many-body system of chiral fermions? If so, how?

Many-body physics of chiral anomaly: General interest and broad impact!
- e.g. semimetals, neutrinos in supernovae,
- Compact stars, cosmology, plasma physics, ...
# Emergence in Hydrodynamic Context

<table>
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<tr>
<th>Symmetry</th>
<th>Micro. Conservation Law</th>
<th>Emergent Macro. Hydro</th>
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<td>translational invariance</td>
<td>energy and momentum conserved</td>
<td>$\partial_\mu T^{\mu\nu} = 0$</td>
</tr>
<tr>
<td>phase invariance</td>
<td>charge conserved</td>
<td>$\partial_\mu J^\mu = 0$</td>
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$\mathcal{L} \rightarrow \mathcal{L}$

Diagram showing the transformation $\mathcal{L}$ to $\mathcal{L}$ with $|M|^2$ at the center, pointing to $P1$, $P2$, $P3$, and $P4$.
Emergence in Hydrodynamic Context

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WHAT ABOU “HALF”-SYMMETRY???
i..e ANOMALY?!
— classical symmetry that is broken in quantum theory
Hydrodynamics That Knows Left & Right

conservation law:
\[ \partial_\mu J^\mu = 0 \rightarrow \partial_\mu J^\mu = C E^\mu B_\mu \]

constituent relation:
\[ J^\mu = n u^\mu + \nu^\mu \]
\[ \nu^\mu = -\sigma T P^{\mu \nu} \partial_\nu \left( \frac{\mu}{T} \right) + \sigma E^\mu + \xi \omega^\mu + \xi_B B^\mu \]

It would be remarkable to actually “see” this new hydrodynamics at work in real world materials!

Microscopic quantum anomaly emerges as macroscopic anomalous hydrodynamic currents!

[Son, Surowka, 2009;…]CVE CME
The AVFD Framework

AVFD: Anomalous-Viscous Fluid Dynamics

Initial Conditions: Bulk + EM field + N₅

Bulk Evolution

Normal & Anomalous Current Transport

Hadron Distribution

arXiv:1611.04586
arXiv:1711.02496
The AVFD Framework

Anomalous-Viscous Fluid Dynamics

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

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

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

CME

Viscous Effect

\[ \Delta^\mu_\nu \partial_\nu (\nu_{R,L}^\mu - \nu_{NS}^\mu) = - \frac{1}{\tau_{rlx}} (\nu_{R,L}^\mu - \nu_{NS}^\mu) \]

\[ \nu_{NS}^\mu = \frac{\sigma}{2} \frac{T_\sigma}{\Delta^\mu} \frac{\mu}{\frac{\mu}{T} + \frac{\sigma}{2} q E^\mu} \]

on top of VISH2+1D -- OSU Group

[We now also have MUSIC-AVFD!]
The AVFD At Work

[Jiang, Shi, Yin, JL, arXiv:1611.04586.]

**Zero B Field**

$$n^u_V @ \tau = 0.60 \text{ fm/c}$$

**Nonzero B Field**

$$n^u_V @ \tau = 0.60 \text{ fm/c}$$
The AVFD At Work

[Jiang, Shi, Yin, JL, arXiv:1611.04586.]

**Right-Handed Density**

$\eta^u_R @ \tau = 0.60 \text{ fm/c}$

**Left-Handed Density**

$\bar{\eta}^u_L @ \tau = 0.60 \text{ fm/c}$
The AVFD At Work

[Jiang, Shi, Yin, JL, arXiv:1611.04586.]

**U Flavor Density**

\[ n^u_V \] @ \( \tau = 0.60 \text{ fm/c} \)

**D Flavor Density**

\[ n^d_V \] @ \( \tau = 0.60 \text{ fm/c} \)
The Charge Separation from AVFD

\[ n^u_R \text{ (GeV}^3\text{)} \]

\[ n^u_L \text{ (GeV}^3\text{)} \]

\[ \tau = 3.0 \text{ fm/c} \quad B \neq 0 \]

\[ \tau = 3.0 \text{ fm/c} \quad B \neq 0 \]

**B field \( \otimes \mu_5 \Rightarrow \text{current} \Rightarrow \text{dipole (charge separation)}**

\[ \frac{dN_{\pm}}{d\phi} \propto 1 + 2 a_{1\pm} \sin(\phi - \psi_{RP}) + \ldots \]
The Charge Separation from AVFD

\[ E \frac{dN}{d^3p}(x^\mu, p^\mu) = \frac{g}{(2\pi)^3} \int_{\Sigma_{fo}} p^\mu d^3\sigma_\mu f(x, p) \]

**B field \( \otimes \mu_5 \Rightarrow \text{current} \Rightarrow \text{dipole (charge separation)}**

\[ \frac{dN_\pm}{d\phi} \propto 1 + 2 a_1^\pm \sin(\phi - \psi_{RP}) + \ldots \]

**\( H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2 \)**
Detailed Results from AVFD

arXiv:1611.04586

arXiv:1711.02496
The Influence of the Magnetic Field

Strong influence by B field evolution; Significant theoretical uncertainty!
The Axial Charge Initial Condition

Very sensitive to initial axial charge;
Significant theoretical uncertainty!
The Influence of the Viscous Transport

First calibration for the influence of the viscous transport on charge separation signal!

\[
\Delta_{\mu \nu} \mathcal{d} \nu_{R,L} = -\frac{1}{\tau_{rlx}} (\nu_{R,L}^{\mu} - \nu_{NS}^{\mu})
\]

\[
\nu_{NS}^{\mu} = \frac{\sigma}{2} T \Delta_{\mu \nu} \partial_{\nu} \frac{\mu}{T} + \frac{\sigma}{2} q \, E^{\mu}
\]
AVFD Predictions v.s Experimental Data

\[ B(\tau) = \frac{B_0}{1 + (\tau/\tau_B)^2} \]

\[ \tau_B = 0.6\text{fm}/c \]

\[ \sqrt{\langle n_5^2 \rangle} \approx \frac{Q_s^4 (\pi \rho_{\text{tube}}^2 \tau_0)}{16\pi^2 A_{\text{overlap}}} \sqrt{N_{\text{coll}}} \]

**Nice agreement; But read them in perspective!**

<table>
<thead>
<tr>
<th>Centrality bin</th>
<th>10-20%</th>
<th>20-30%</th>
<th>30-40%</th>
<th>40-50%</th>
<th>50-60%</th>
</tr>
</thead>
<tbody>
<tr>
<td>( eB_0(m_\pi^2) )</td>
<td>2.34</td>
<td>3.10</td>
<td>3.62</td>
<td>4.01</td>
<td>4.19</td>
</tr>
<tr>
<td>( n_5/s )</td>
<td>0.065</td>
<td>0.078</td>
<td>0.095</td>
<td>0.119</td>
<td>0.155</td>
</tr>
</tbody>
</table>

Table 1. Centrality dependence of magnetic field peak strength and the initial chirality imbalance. The \( n_5/s \) shown here is obtained with a saturation scale \( Q_s^2 = 1.25\text{GeV}^2 \).
Using Isobaric Collisions for CME Search

(a) Diagram showing the reaction of $^{96}_{44}$Ru + $^{96}_{44}$Ru resulting in $^{96}_{40}$Zr + $^{96}_{40}$Zr.

(b) Graph showing trends in $eB/m^2$ with respect to centrality for Ru and Zr.

(c) Diagram highlighting the importance of Charge Asymmetry Correlation Measurement.

(d) Graph illustrating the significance of $R_s - R_{e^-}$ with the background level, showing cases 1 and 2 with a projected line for 400 M events.
The Magnetic Fields and Signals of Isobars

Note: B field projected onto participant plane!

Expected variation of signal, 10~20%
Toward Event-by-Event Simulations

Include EBE fluctuations:
- Initial Conditions
- Statistic @ Freeze-out
- Hadron Cascade

Important for better understanding:
* Interplay between signal and BKG;
* Experimental analysis methods
Fluctuations and Angular De-Correlation

Angular de-correlation between B field and geometry is very important!

Azimuthally fluctuating magnetic field and its impacts on observables in heavy-ion collisions

John Blóczyński, Xu-Guang Huang*, Xilin Zhang, Jinfeng Liao
Fluctuations and Angular De-Correlation

* CME signal totally independent of v2?  
  **NO!**

* For event-shape engineering, B field is approximately constant across different shapes within same centrality?  
  **NO!**

* In small systems / central collisions, no B field effect at all?  
  **NO!**

*Unfortunately, signal and BKG entangle more deeply than we’d hope. Both theorists and experimentalists need to be very careful!*
Binning Events Could Be Tricky!

Au-Au @ 200GeV 50-60%

The multiplicity and B-EP de-correlation change with event shape!
EBE-AVFD Results

Au-Au @ 200GeV 50-60%

The CME signal is also correlated with event shape!
EBE-AVFD Results: Gamma(1,1,2)

Au-Au @ 200GeV 50-60%

\[ n_5/s = 0.2 \]
\[ n_5/s = 0.1 \]
\[ n_5/s = 0.05 \]
\[ n_5/s = 0.0 \]
EBE-AVFD Results: Slope & Intercept

The intercept is SENSITIVE to CME signal!

The slope contains both BKG and signal!
EBE-AVFD Results: Gamma(1,2,3)

Good linear dependence;
The slope is insensitive to CME signal.
Summary & Outlook
Summary

**AVFD:**
A versatile tool for an era of quantitative study of CME in heavy ion collisions
Toward Full-Fledged EBE-AVFD: Stay Tuned!

EM field computed from proton configuration

$n_5$ computed from initial binary collisions