Hunting for the Chiral Magnetic Effect

Jinfeng Liao
Spin: Chirality, Vorticity and Magnetic Field

Interesting interplay —> highly nontrivial phenomena!
QCD Matter under New Extreme Conditions

QCD matter under extremely strong vorticity and magnetic fields!
A Quantum Fluid of Spin

A nearly perfect fluid (of energy-momentum)

What happens to the spin DoF in the fluid???
Interdisciplinary Interests

Weyl semimetal
(non-degenerated bands)

Dirac semimetal
(doubly degenerated bands)

“Spin hydrodynamic generation”

“Fluid Spintronics”

Condensed matter, cold atomic gases, neutron stars, cosmology, plasma physics, etc
[Chiral Matter workshops @ RIKEN, NTU]
Exciting Progress: See Recent Reviews

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Review

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

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Mapping the Phases of Quantum Chromodynamics with Beam Energy Scan

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Abstract

We review the present status of the search for a phase transition and critical point as well as anomalous transport phenomena in Quantum Chromodynamics (QCD), with an emphasis on the Beam Energy Scan program at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. We present the conceptual framework and discuss the observables deemed most sensitive to a phase transition, QCD critical point, and anomalous transport, focusing on fluctuation and correlation measurements. Selected experimental results for these observables together with those characterizing the global properties of the systems created in heavy ion collisions are presented. We then discuss what can be already learned from the currently available data about the QCD critical point and anomalous transport as well as what additional measurements and theoretical developments are needed in order to discover these phenomena.

Keywords: Heavy Ion Collision, Beam Energy Scan, QCD Phase Diagram, Critical Point, Chiral Magnetic Effect

arXiv:1906.00936
Chiral Magnetic Effect
Chiral Symmetry Restoration

* 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?
Chiral Symmetry: Quantum 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
From Gluon Topology to Quark Chirality

\[ Q_w = \frac{1}{32\pi^2} \int d^4x \, (gG_a^{\mu\nu}) \cdot (\tilde{g}\tilde{G}_a^{\mu\nu}) \]

QCD anomaly: gluon topology $\rightarrow$ chirality imbalance

\[ N_5(t \to +\infty) - N_5(t \to -\infty) = \frac{g^2}{16\pi^2} \int dt d^3r \, G_a^{\mu\nu} \tilde{G}_a^{\mu\nu} \]

Net chirality $\leftrightarrow$ topo fluctuations & chiral restoration
Chiral Magnetic Effect (CME): Macroscopic Chiral Anomaly

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

Chirality & Anomaly & Topology

Electric Current

Magnetic Field

Q.M. Transport

[Kharzeev, Fukushima, Warringa, McLerran, …]
Intuitive understanding of CME:

Magnetic polarization $\rightarrow$ correlation between micro. SPIN & EXTERNAL FORCE

Chiral imbalance $\rightarrow$ correlation between directions of SPIN & MOMENTUM

Transport current along magnetic field

$$\vec{J} = \frac{Q^2}{2\pi^2} \mu_5 \vec{B}$$
Chiral Transport Theory

Usual (classical) transport equation:

\[
\left\{ \partial_t + \mathbf{v} \cdot \nabla \mathbf{x} + \mathbf{p} \cdot \nabla \mathbf{p} \right\} f^{(c)}(t, \mathbf{x}, \mathbf{p}) = C[f^{(c)}], \\
\dot{\mathbf{x}} = \mathbf{v} = \nabla \mathbf{p} E_p , \quad \dot{\mathbf{p}} = q (\mathbf{E} + \mathbf{v} \times \mathbf{B}).
\]

Chiral transport equation:

\[
\left\{ \partial_t + \mathbf{G}_x \cdot \nabla \mathbf{x} + \mathbf{G}_p \cdot \nabla \mathbf{p} \right\} f^{(q)}(t, \mathbf{x}, \mathbf{p}) = C[f^{(q)}], \\
\mathbf{G}_x = \frac{1}{\sqrt{G}} \left[ \mathbf{v} + \hbar q (\mathbf{v} \cdot \mathbf{b}_x) \mathbf{B} + \hbar q \mathbf{E} \times \mathbf{b}_x \right], \quad \mathbf{G}_p = \frac{q}{\sqrt{G}} \left[ \mathbf{E} + \mathbf{v} \times \mathbf{B} + \hbar q (\mathbf{E} \cdot \mathbf{B}) \mathbf{b}_x \right]
\]

[Son, Yamamoto; Stephanov, Yin; Chen, Wang, et al; Hidaka, Pu, Yang; Mueller, Venugopalan; Huang, Shi, Jiang, JL, Zhuang; ...]
Fluid Dynamics That Knows Left & Right

Normal Hydrodynamics
\[ \partial_\mu J^\mu = 0 \]
\[ J^\mu = n u^\mu + \nu^\mu \]
\[ \nu^\mu = \frac{\sigma T}{2} \Delta^{\mu\nu} \partial_\nu \left( \frac{\mu}{T} \right) + \frac{\sigma}{2} E^\mu \]
Viscous Current
Diffusion
Conduction

Anomalous Hydrodynamics
\[ \partial_\mu J^\mu = C_A E^\mu B_\mu \]
Anomaly
\[ J^\nu = n u^\mu + \nu^\mu + \nu_\alpha^\mu \]
Viscous Current
Anomalous Current
\[ \nu^\mu = \frac{\sigma T}{2} \Delta^{\mu\nu} \partial_\nu \left( \frac{\mu}{T} \right) + \frac{\sigma}{2} E^\mu \]
Diffusion
Conduction
\[ \nu_\alpha^\mu = \xi B_\alpha B^\mu + \xi \omega^\mu \]
CME
CVE

[Son, Surowka; Kharzeev, Yee; Hidaka, Yang; Shi, JL, et al; ...]

A new type of hydrodynamics with macro. quantum effect!
Search for CME at RHIC & LHC
Rotating Quark-Gluon Plasma

\[ L_y = \frac{Ab\sqrt{s}}{2} \sim 10^4 \sim 5 \hbar \]

Angular momentum \(\rightarrow\) nontrivial vorticity structure and spin polarization effect

\[ P_z = \frac{A\sqrt{s}}{2} \]

Low energy

High energy

Jiang, Lin, JL, PRC2016

STAR, Nature 2017

[Talk by Ryblewski]
The angular momentum together with large (+Ze) nuclear charge → strong magnetic field!

\[ P_z = \frac{A\sqrt{s_{NN}}}{2} \]

Out-of-plane

\[ E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_{\pi}^2 \]

- Strongest B field (and strong E field as well) naturally arises!
  [Kharzeev, McLerran, Warringa; Skokov, et al; Bzdak-Skokov; Deng-Huang; Skokov-McLerran; Tuchin; ...]
- “Out-of-plane” orientation (approximately)
  [Bloczynski-Huang-Zhang-Liao]
Quantitative simulations confirm the existence of such extreme fields!

[Many interesting B-field induced effects: di-electron; polarization splitting; quarkonium v2; D meson v1; …]
Search for CME in Heavy Ion Collisions

The quark-gluon plasma is a subatomic CHIRAL MATTER.

Can we observe CME in heavy ion collisions??

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

1) (nearly) chiral quarks
2) chirality imbalance
3) strong magnetic field
From CME Current to Charge Separation

strong radial blast: position $\rightarrow$ momentum

$$\vec{J} = \sigma_5 \mu_5 \vec{B}$$

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

$$< a_{\pm} > \sim \pm < \mu_5 > B$$

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

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

Very difficult measurement:
* Zero average, only nonzero variance;
* Correlation measurement with significant backgrounds;
* Signal likely very small

charge separation ⇒ charge dept. two-particle correlation

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

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

These correlations are sensitive to CME contributions, however they are also sensitive to many non-CME backgrounds!

[F. Wang; S. Pratt; Bzdak, Koch, JL; ……]
CME & Backgrounds

**CME expectation:**

\[ \gamma_{SS} < 0, \delta_{SS} > 0 \]
\[ \gamma_{OS} > 0, \delta_{OS} < 0 \]

**Transverse Momentum Conservation (TMC)**

\[ \gamma < 0, \delta < 0 \]

**Local Charge Conservation (LCC)**

\[ \gamma_{OS} > 0, \delta_{OS} > 0 \]

**Resonance decay:**

similar to LCC

**Background contribution to gamma is due to nonzero v2!!**
Fighting with Backgrounds

A two-component decomposition model:

\[ \gamma = \kappa v_2 \ F - H \]
\[ \delta = F + H \]

F: Bulk Background
H: Possible Pure CME Signal = \((a_{1,CME})^2\)

Bzdak, Koch, JL, 2012

Many interesting proposals of new observables!

Vary \(v_2\) for fixed \(B\):
- \(AuAu\) v.s. \(UU\);
- Varying event-shape;
- 2-component subtraction.

Vary \(B\) for fixed \(v_2\):
- Isobaric collisions with \(RuRu\) v.s. \(ZrZr\)

\[ \sqrt{s_{NN}} \text{ (GeV)} \]

\[ (H_{SS} - H_{OS}) \times 10^4 \]

\(Au+Au\) 30 - 60% \(Pb+Pb\)

Experimental data
BES II error projection

STAR PRL2014
Current Experimental Status for CME

Key challenge: weak signal versus strong backgrounds.

Many new measurements at RHIC and LHC:
gamma correlator + certain procedure to constrain backgrounds

Lacey, Magdy, et al: R-correlator consistent with a1~1% at RHIC

Current data provide encouraging hints, esp. @ RHIC energy!

Need quantitative modeling of signal+bkg to help exp search!
Chiral Magnetic Wave

CMW $\rightarrow$ charge quadrupole of QGP $\rightarrow$ elliptic flow splitting


$\nu_2^- - \nu_2^+ = r_e A$

charge quadrupole due to CMW transport

A consistent trend as CME: Turning-off at low energy

[STAR, PRL2015]
Quantitative Modeling of CME
Integrate CME into Bulk Evolution

* Approach based on fluid dynamics (AVFD)
  — our focus here

* Approach based on transport models.
  — AMPT based
    (Guoliang Ma, Yugang Ma, and collaborators)
  — Chiral kinetic transport based
    (Che-ming Ko and collaborators)
Beam Energy Scan Theory (BEST) Collaboration

CME Working Group

- Initial conditions
- Dynamical magnetic fields
- Non-equilibrium anomalous transport coefficient
- Fluid dynamics framework with anomalous current
- Quantification of both signal and backgrounds
Axial Charge Initial Conditions

In the glasma framework:
* Computed topological Chern-Simons number evolution
* Extracted significant non-equilibrium sphaleron rate
* Anomalous transport during the pre-thermal stage

[Mcace, Schtloting, Venugopalan, PRD2016; 
Mace, Muller, Schtloting, Sharma, PRD2017]

Will be integrated into the initial condition for further modeling of CME during hydro stage
Dynamical Magnetic Fields

A significant step forward toward full magneto-hydrodynamics (MHD)
Code package available:
https://bitbucket.org/bestcollaboration/heavy-ion-em-fields

[ Gursoy, Kharzeev, Rajagopal, Shen, et al, PRC2018]

A viable and practical way to integrate dynamical B field!
Dynamical Magnetic Fields

* Ideal RMHD simulations (ECHO-QGP) [Inghirami, et al, 1609.03042]

* Phenomenological constraint from hyperon-anti-hyperon polarization [Schafer-Muller, 1806.10907; Guo-Liao-Wang, 1904.04704; Guo-Shi-Feng-Liao, 1905.12613]

It seems plausible for $t_B \sim 0.5 \text{ fm/c}$ at 200 GeV.
Establishment of Anomalous-Viscous Fluid Dynamics (AVFD): Hydrodynamical realization of CME in HIC.

[newest developments: EBE-AVFD; AVFD+axial dynamics; AVFD+LCC]

We now have a versatile tool to quantitatively understand and answer many important questions about CME in heavy ion collisions!

AVFD Framework

Note: bulk properties fully data-validated

[arXiv:1611.04586; arXiv:1711.02496]
The Charge Separation from AVFD

Chirality imbalance $\rightarrow$ R/L asymmetry $\rightarrow$ charge asymmetry

$B$ field $\otimes \mu_5 \Rightarrow$ current $\Rightarrow$ dipole (charge separation)

$\frac{dN_{\pm}}{d\phi} \propto 1 + 2 a_{1\pm} \sin(\phi - \psi_{RP}) + ...$

$H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2$
AVFD for AuAu Collisions

CME is quantitatively viable for describing relevant experimental observable.

AVFD provides the tool to quantify various features of CME signals.

One Example: Flavor Dependence

Kaons are sensitive to anomalous transport of s-quarks.
Theory analysis (S. Lin, D. Hou, …): \( u,d \sim s \)
Event-By-Event AVFD

Include EBE fluctuations:
- Initial Conditions
- Statistic @ Freeze-out
- Hadron Cascade (~ half of all bkg.)

Important for better understanding:
* Interplay between signal and BKG;
* Experimental analysis methods
EBE-AVFD for Testing Observables

New a key tool for understanding different observables’ responses and sensitivity to signal and backgrounds

Lacey, Nagdy, et al

Tang
Implementing Local Charge Conservation (LCC)

To quantify background correlations in state-of-art hydro framework

[Schenke, Shen, Tribedy, 2019]

New development of particlization: the best way to quantify LCC

[Koch, Oliinychenko, 2019]
EBE-AVFD+LCC: Event Shape Engineering

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

First time: full characterization of signal + known major backgrounds

\[ P_{LCC} = 0.00, 0.33, 0.67, 1.00 \]

Isobaric Collision
A Decisive Experiment: Isobaric Collisions

New opportunity of potential discovery: Isobaric Collision @ RHIC

~2 billion data collected successfully in RHIC 2018 run; processing and analysis underway!

Key idea: contrasting two systems with identical bulk, varied magnetic fields.

Insight from initial conditions:
joint cut on Multiplicity-Eccentricity

Isobars: How to Choose Identical Systems?

Eccentricity is guaranteed the same!

B field differs by 12~20%!

Joint multiplicity-geometry cut:
Vanishing difference in bulk properties,
Sizable difference in magnetic fields!!!
Analyzing Actual EBE-AVFD Events for Isobars

Millions of EBE-AVFD events: Subject to joint-cut

\[ 64 < N_{ch, |y|<1} < 96 \]
\[ 0.1 < q_2 < 0.3 \]

Post-selection double-check: Identical v2!

 Guaranted to have two identical sample of isobar events for contrast!
AVFD Predictions for Isobars

-1 < $\eta$ < 1
64 < $N_{ch}$ < 96
0.05 < $v_2^{\text{ref}}$ < 0.25

Statistics: $10^7$ events in AVFD simulation
~ $3 \times 10^8$ events in experiment

Look for absolute difference between isobars (after joint-cut)!
Look for consistency between delta- and gamma-correlators!

Summary & Outlook
Summary: Toward Synergy of Key Ingredients

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

An exciting time: things are converging!
Outlook: Isobaric Collisions

- Many observables: consistency?
- Very important: understanding observables & their relations!!
- Use sophisticated modeling tools (signal+bkg.) to help

Exciting time (~2020): Stay tuned!
Backup Slides
Exp. Search for CME

Flavor dependence is very interesting!

Talks by: H. Huang, F. Wang, R. Lacey, A. Tang, G. Wang, J. Zhao, Q. Shou
Exp. Search for CME

New observables

Lacey, Magdy, et al

A. Tang
CME <=> Chiral Anomaly

Anomaly --> \[ \partial^\mu j^\mu_5 = \frac{q^2}{2\pi^2} E \cdot B \]
\[ \frac{dN_5}{dtd^3x} = \frac{q^2}{2\pi^2} E \cdot B \]

Chirality --> \[ \int d^3x j_{el} \cdot E = \mu_5 \frac{dN_5}{dt} = \frac{q^2\mu_5}{2\pi^2} \int d^3xB \cdot E \]

\[ E \to 0 \]
\[ j_{el} = \left(\frac{q^2\mu_5}{2\pi^2}\right)B \]

* This is a non-dissipative current!
* Indeed the chiral magnetic conductivity is P-odd but T-even!
(In contrast the Ohmic conductivity is T-odd and dissipative.)

CME is macroscopic chiral anomaly — a remarkable phenomenon!
Demonstrating the AVFD

Upper: NO magnetic field
Lower: with B field (along y+ direction)
Demonstrating the AVFD

Upper: Left-Handed (LH), with B field (along y+ direction)
Lower: Right-Handed (RH), with B field (along y+ direction)
Magnetic Filed Induced Polarization

\[ S^\mu = -\frac{1}{8m} \epsilon^{\mu \nu \rho \sigma} p_\nu \varpi_{\rho \sigma} \]

For Lambda:

\[ \varpi_{\rho \sigma} \rightarrow \left[ \varpi_{\rho \sigma} - 2 \left( \frac{0.61}{2M_p} \right) \frac{eF_{\rho \sigma}}{T} \right] \]

For anti-Lambda:

\[ \varpi_{\rho \sigma} \rightarrow \left[ \varpi_{\rho \sigma} + 2 \left( \frac{0.61}{2M_p} \right) \frac{eF_{\rho \sigma}}{T} \right] \]

[Yu Guo, Shengqin Feng, Shuzhe Shi, JL, 1905.12613]
Magnetic Field Induced Polarization

For this to work:
Requires long-lived late time magnetic field.

Where does that come from??

[Yu Guo, Shengqin Feng, Shuzhe Shi, JL, 1905.12613]
Connecting Magnetic Field and Fluid Rotation

\[ e\vec{B} = \frac{e^2}{4\pi} nA\vec{\omega} \]

Important at low beam energy!

\[ 100 \times (P_\Lambda - P_n) \]

\[ \sqrt{s_{NN}} \text{ (GeV)} \]

EBE-AVFD+LCC: Event Shape Engineering

Filled: w/ CME
Open: w/o CME

\[ P_{\text{LCC}} = 0.00, 0.33, 0.67, 1.00 \]

First time: full characterization of signal + known major backgrounds