The Chemistry of Anomalous Transport Effects

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A Very Recent Review

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

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Toward Precision Physics of Beam Energy Scan

Beam Energy Scan Theory (BEST) Collaboration
Quantitative Study of Anomalous Transport

Dynamical Evolution

CME
\[ \vec{J} = \sigma_5 \vec{B}, \]

CVE
\[ \vec{J} = \frac{1}{\pi^2} \mu_5 \mu \vec{\omega}. \]

Initial Conditions

Driving Forces

CMW
\[ (\partial_0 \pm v_B \partial_\hat{B}) \delta J_{R/L}^0 = 0. \]
\[ v_B \equiv \frac{(Qe)B}{(4\pi^2)\chi} \]

CVW
\[ (\partial_0 \pm v_\omega \partial_\hat{\omega}) \delta J_{R/L}^0 = 0. \]
\[ v_\omega \equiv \frac{\mu_0 \omega}{(2\pi^2)\chi\mu_0} \]

Observable ("Chemistry"): partons \( \rightarrow \) hadrons
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!
Measurable effects (CME, CMW, photon v2,…) are controlled by:

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

Angular momentum is conserved in time.

Quantifying Rotation of QGP

Convenient parameterization:

\[
\langle \omega_y \rangle(t, b, \sqrt{s_{NN}}) = A(b, \sqrt{s_{NN}}) + B(b, \sqrt{s_{NN}}) (0.58t)^{0.35} e^{-0.58t}
\]

\[
A = \left[ e^{-0.016b \sqrt{s_{NN}}} + 1 \right] \times \tanh(0.28b) \times [0.001775 \tanh(3 - 0.015 \sqrt{s_{NN}}) + 0.0128]
\]

\[
B = \left[ e^{-0.016b \sqrt{s_{NN}}} + 1 \right] \times [0.02388 b + 0.01203] \times [1.751 - \tanh(0.01 \sqrt{s_{NN}})]
\]

Quantitative Dynamical Evolution for CME

One example of recent attempts: Yi Yin, JL, arXiv:1504.06906

We reported CME simulations with:
anomalous hydro for charge currents
on top of (data validated) bulk VISH hydro,
and accounting for backgrounds.
Quantitative Dynamical Evolution for CME


We solve a-hydro current equations (as perturbation) on top of bulk viscous hydro:

\[
\frac{\partial \mu}{\partial J^\mu} = \partial \mu \left( n u^\mu + Q_f C A \mu_A B^\mu \right) = 0
\]

\[
\frac{\partial \mu}{\partial J_A^\mu} = \partial \mu \left( n A u^\mu + Q_f C A \mu_V B^\mu \right) = -Q_f^2 e C_A E_\mu B^\mu
\]

A clear charge separation is seen!

\[
\left[ \frac{dN^H}{d\phi} \right]_{CME} \propto \left[ 1 + 2Q^H a_1^H \sin(\phi) + \ldots \right]
\]
Quantitative Dynamical Evolution for CME

Using the particle spectra from the SAME VISH hydro, we evaluate quantitatively effect from transverse momentum conservation:

\[
\delta_{\alpha\beta}^{\text{TMC}} \pm \gamma_{\alpha\beta}^{\text{TMC}} = \left[ \langle p_\perp \rangle_\alpha (1 \pm \bar{v}_{2,\alpha}) \right] \left[ \langle p_\perp \rangle_\beta (1 \pm \bar{v}_{2,\beta}) \right] \frac{1}{N_{\text{TMC}} \langle p_\perp^2 \rangle (1 \pm \bar{v}_2)}
\]
The messages:

* B field lifetime $\sim 1\text{fm/c}$ is OK!
* Needed axial charge realistic:
  $\sim$ percent of initial entropy density,
  or $\sim (0.2\text{GeV})^3$!
* Data could be consistent with CME+backgrounds!
“Chemistry”: Hadrons out of Partons

If some phenomenon happens at parton level, they convert into hadrons following the “chemistry”.

Mesons

Baryons
Partonic Collectivity: An Excellent Example

Striking patterns with very simple explanation: parton “chemistry” for hadrons indicating partonic collectivity. — It carries decisive strength.

Anomalous transport effects are partonic level phenomena: Can we device and measure something alike?
Anomalous effects: parton level transport
—> at freeze-out, combining into identified hadron observables in specific patterns!

Common conceptions (that are NOT fully accurate):
CME —> electric charge separation
CVE —> baryonic charge separation
Plus, usually the total Q or B are measured only with proxy.
Mixing of CME and CVE

\[ \vec{J} = \frac{1}{\pi^2} \mu_5 \mu \vec{\omega} \]

vs

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

\[
\vec{J}^{2f}_Q = \frac{N_c \mu_5}{2\pi^2} \left[ \frac{5}{9} (e \vec{B}) + \frac{2}{9} (\mu \vec{\omega}) \right], \quad \vec{J}^{2f}_B = \frac{N_c \mu_5}{2\pi^2} \left[ \frac{1}{9} (e \vec{B}) + \frac{4}{9} (\mu \vec{\omega}) \right] 
\]

\[
\vec{J}^{3f}_Q = \frac{N_c \mu_5}{2\pi^2} \left[ \frac{2}{3} (e \vec{B}) + 0 \times (\mu \vec{\omega}) \right], \quad \vec{J}^{3f}_B = \frac{N_c \mu_5}{2\pi^2} \left[ 0 \times (e \vec{B}) + \frac{2}{3} (\mu \vec{\omega}) \right] 
\]

2 flavor chemistry? or 3 flavor chemistry?

[Kharzeev, Son, 2010; …]
Let’s Take a Closer Look at “Chemistry”

CME

\[ \vec{J}^f = \sigma^f_5 \vec{B} \]

\[ \sigma^f_5 = Q_f \frac{N_c e^2 \mu_5}{2\pi^2} \]

More effects for u-quarks than d,s quarks

\[ \mu_u \sim 2d \sin(\phi - \Psi_2) \]

\[ \mu_{d,s} \sim -d \sin(\phi - \Psi_2) \]

\[ a_{\pi^+} = -a_{\pi^-} \sim 3a_B \]

\[ a_p = -a_{\bar{p}} \sim 3a_B \]

\[ a_{K^+} = -a_{K^-} \sim 2a_B \]

\[ a_{\Lambda} = -a_{\bar{\Lambda}} \sim 1a_B \]

\[ a_{K^+} = -a_{K^-} \sim 3a_B \]

\[ a_{\Lambda} = -a_{\bar{\Lambda}} \sim 0a_B \]
Let's Take a Closer Look at “Chemistry”

CVE

\[ \vec{f}^f = \frac{1}{\pi^2} \mu_5 (\mu_f, \vec{\omega}) \]

Depending on flavor initial conditions!!

\[ \mu_u \sim n_0^u d' \sin(\phi - \Psi_2) \]
\[ \mu_{d,s} \sim n_0^{d,s} d' \sin(\phi - \Psi_2) \]

\[ a_{\pi^+} = -a_{\pi^-} \sim (n_0^u - n_0^d)a_\omega \]
\[ a_p = -a_{\bar{p}} \sim (2n_0^u + n_0^d)a_\omega \]

2-flavor

\[ a_{K^+} = -a_{K^-} \sim n_0^u a_\omega \]
\[ a_{\Lambda} = -a_{\bar{\Lambda}} \sim (n_0^u + n_0^d)a_\omega \]

3-flavor

\[ a_{K^+} = -a_{K^-} \sim (n_0^u - n_0^s)a_\omega \]
\[ a_{\Lambda} = -a_{\bar{\Lambda}} \sim (n_0^u + n_0^d + n_0^s)a_\omega \]
Let's Take a Closer Look at “Chemistry”

<table>
<thead>
<tr>
<th></th>
<th>CME</th>
<th>2F</th>
<th>3F</th>
<th>CVE</th>
<th>2F</th>
<th>3F</th>
</tr>
</thead>
<tbody>
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<td>pion</td>
<td></td>
<td>3</td>
<td>3</td>
<td></td>
<td>-0.06</td>
<td>-0.06</td>
</tr>
<tr>
<td>proton</td>
<td></td>
<td>3</td>
<td>3</td>
<td></td>
<td>1.44</td>
<td>1.44</td>
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<tr>
<td>ch. K</td>
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<td>3</td>
<td></td>
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<tr>
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<td>1</td>
<td>0</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Assuming for AuAu:

\[ n_0^u : n_0^d \approx 0.47 : 0.53 \]
\[ n_0^s \approx 0 \]
Identified Hadrons: Patterns?!

[Poster@QM15: L. Wen]

Unfortunately, it is known that this sequential pattern includes background contributions…

Proton: $B=1$, $Q=1$
Lambda: $B=1$, $Q=0$
Pion: $B=0$, $|Q|=1$
K0s: $B=0$, $Q=0$
Example of Quantitative Attempts

\[ \gamma_{\alpha,\beta}^{\text{data}} \sim \gamma_{\alpha,\beta}^{\text{CME}} + \gamma_{\alpha,\beta}^{\text{TMC}} \]
\[ \delta_{\alpha,\beta}^{\text{data}} \sim \delta_{\alpha,\beta}^{\text{CME}} + \delta_{\alpha,\beta}^{\text{TMC}} \]

2-flavor

3-flavor

Caution:
CME only,
for same charge pair only, and
including transverse momentum conservation only.

Badly Needed Measurements

“raw info” needs to be processed!

\[ \gamma_{\alpha\beta} = \kappa v_2 \, F_{\alpha\beta} - H_{\alpha\beta} \]
\[ \delta_{\alpha\beta} = F_{\alpha\beta} + H_{\alpha\beta} \]

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

Then we can answer: any striking patterns with simple “chemistry” interpretation?
Discussions on Isobaric Collisions

New Proposal of Isobaric Collisions @ RHIC:
up to 10% variation in B field, while no variation in rotation.

\[
\begin{align*}
\text{CME} & \quad 2F & \quad 3F \\
pion & 3 & 3 \\
proton & 3 & 3 \\
\text{ch. K} & 2 & 3 \\
\text{lambda} & 1 & 0 \\
\end{align*}
\]

\[
\begin{align*}
\text{CVE} & \quad \text{RuRu} & \quad \text{ZrZr} \\
pion & 1.49 & 1.47 \\
\text{proton} & 0.49 & 0.47 \\
\text{ch. K} & 1 & 1 \\
\text{lambda} & 1 & 1 \\
\end{align*}
\]

However, the flavor initial conditions differ as well…

\[\text{[RuRu]} \sim \text{[ZrZr]} \times 1.2\]

Assuming:

\begin{align*}
\text{RuRu} & \quad n_0^u : n_0^d \simeq 0.49 : 0.51 \\
\text{ZrZr} & \quad n_0^u : n_0^d \simeq 0.47 : 0.53 \\
n_0^s & \simeq 0
\end{align*}
Summary

Driving force:
* magnetic fields: finite size proton; azimuthal corr. with P.P.
* Vorticity:

Dynamical evolution:

* It is important to study quantitatively the normal viscous transport as well as anomalous transport for contrast!
  [see talks by Y. Hatta and by S. Shi]

“Chemistry” of anomalous effects:
* entering via I.C. and freeze-out;
* qualitative patterns that can serve as critical test;
* exp. removal of backgrounds from data — must-do in my view;
* isobaric collisions crucial!