Chiral magnetic effect & early time dynamics

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Outline

1. Chiral magnetic effect in Heavy-Ion Collisions
   - Introduction
   - Current status & challenges

2. Chiral magnetic effect & early-time dynamics
   - New theoretical developments

3. Conclusions & Outlook
   - Isobar scan
Chiral Magnetic Effect (CME) & anomalous transport

Discovery of new kinds of conductivity for systems with (approx.) chiral fermions and chirality imbalanced
(Fukushima, Kharzeev, Warringa PRD 78 (2008) 074033)

\[
\text{Chiral Magnetic Effect: } \mathbf{j}_v \propto j_a^0 \mathbf{B}
\]

axial charge density \quad magnetic field

Several interesting effects due to interplay of axial and vector charges
Chiral Separation Effect (CSE), Chiral Magnetic Wave (CMW), …

Several manifestations of such effects beyond high-energy QCD
Discovery of CME in 3d Dirac/Weyl semi-metals
Li et al. Nature Physics (2016)
CME in Heavy-Ion Collisions

High-energy heavy-ion collisions provide an exciting environment to explore anomalous transport phenomena — Non-conservation of axial charge expected to lead to significant fluctuations e.g. due to sphaleron transitions

**Chiral Magnetic Effect:** \[ j_\nu \propto j_0^a \mathbf{B} \]

- **Axial charge density**
- **Magnetic field**

— Strong magnetic field \( eB \sim m_\pi^2 \) present in off-central collisions

— Non-conservation of axial charge expected to lead to significant fluctuations e.g. due to sphaleron transitions

Good news: Chiral magnetic effect presents exciting opportunity to further explore dynamics of QGP, e.g. topological properties
CME in Heavy-Ion collisions

Since axial charge fluctuates from event to event on average $\langle j_v \rangle = 0$, so one can only measure fluctuations

Basic idea is to look for back-to-back correlations of opposite charge particles with respect to the reaction plane

$$\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$

Even though many qualitative features of the measurements at RHIC and LHC are in line with CME expectations (e.g. centrality dependence, event-shape engineering, …), so far measurements are also subject to potentially large backgrounds

$\vec{j}_v \propto j_\alpha^0 \vec{B}$

$\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$

$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$

$\times 10^3$

% Most Central

STAR PRC 81 (2010) 054908

CME in Heavy-Ion Collisions

Quantitative theoretical understanding of anomaly induced transport phenomena (CME, CMW, ...) in heavy-ion collisions desirable to guide experimental searches

**Chiral Magnetic Effect:** \[ \vec{j}_v \propto j_a^0 \vec{B} \]

- axial charge density
- magnetic field

Quantitative description requires (at least) three ingredients

- space-time dependence of magnetic field
- information about the dynamics of axial charge changing processes in Quark-Gluon plasma
- microscopic/macroscopic description of anomalous transport
CME in Heavy-Ion collisions

Spectators in off-central collisions create a strong magnetic field $eB \sim m_{\pi}^2$ (unit conversion $m_{\pi}^2 \sim 10^{14}$ T)
(c.f. talk by V. Skokov)

Life-time of magnetic field in vacuum is very short < 1 fm/c

Expect significant fraction of the effect should take place during the pre-equilibrium stage

STAR PRC 81 (2010) 054908
Skokov, Illarionov, Toneev
Axial charge density: Not conserved in QCD due to axial anomaly

\[ \partial_\mu j^{\mu}_5, f = 2m_f \bar{q} \gamma_5 q - \frac{g^2}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a \]

Even though on average \( \langle j^0_a \rangle = 0 \) the fact that the current is not conserved should lead to space-time dependent fluctuations

\[ \text{field-strength fluctuations} \propto \vec{E} \cdot \vec{B} \]

Even though on average \( \langle j^0_a \rangle = 0 \) the fact that the current is not conserved should lead to space-time dependent fluctuations

short distance

long distance

color flux tubes

sphaleron transitions
Creation of axial charge imbalance

Early time dynamics of axial charge production can be addressed within classical Yang-Mills simulations

*Global* imbalance of axial charge is small at $\tau \sim 1/Q_s$

Kharzeev, Venugopalan, Krasnitz, PLB545 (2002) 298-306

Significant *local* imbalance of axial charge density created at $\tau \sim 1/Q$

Lappi, SS in preparation

Source term for axial charge production comparable to energy density

$$\langle tr[F_{\mu\nu}(x)\tilde{F}^{\mu\nu}(x)]tr[F_{\mu\nu}(y)\tilde{F}^{\mu\nu}(y)]\rangle \sim \frac{1}{N_c^2-1}\epsilon(x)\epsilon(y)$$

Correlation length of local domains is microscopically small $\sim 1/Q_s$
Creation of axial charge imbalance

Beyond very early times sphaleron transitions in and out-of equilibrium dominate axial charge production on long time/distance scales

Strong color-fields at early times can lead to an enhancement of sphaleron transition rate during the pre-equilibrium stage

Mace, SS, Venugopalan PRD93 (2016) no.7, 074036

Different mechanisms identified to create sizable fluctuations of axial charge density at early times, but further progress required to quantify effects

Since axial charge is not conserved, knowledge of “initial condition” for axial charge is in general not sufficient to describe subsequent space-time evolution

Still a major source of uncertainty in theoretical description of CME
CME & early-time dynamics

Different theoretical approaches have been developed to study anomalous transport (CME, CMW, ...) in and out-of-equilibrium.

Since early-time dynamics of heavy-ion collisions involves different degrees of freedom at different times, combination of different theoretical approaches required to describe pre-equilibrium dynamics of anomalous transport.
Non-equilibrium lattice description

- Discretize theory on 3D spatial lattice using the Hamiltonian lattice formalism

- Solve operator Dirac equation in the presence of classical SU(N) and U(1) gauge fields

\[ i\gamma^0 \partial_t \hat{\psi} = (-i\slashed{D}^s_W + m)\hat{\psi} \]

- Compute expectation values of vector and axial currents to study anomalous transport processes

\[ j^\mu_v(x) = \langle \hat{\psi}(x)\gamma^\mu\hat{\psi}(x) \rangle \quad j^\mu_a(x) = \langle \hat{\psi}(x)\gamma^\mu\gamma^5\hat{\psi}(x) \rangle \]

So far first results on small lattices (24 x 24 x 64) in a clean theoretical setup

SU(N): Isolated sphaleron transition    U(1): constant magnetic field
Non-equilibrium CME dynamics

Axial charge $j_5^0$
Vector current $j^\vec{z}_V$
Vector charge $j_V^0$

Sphaleron transition induces local imbalance of axial charge density
Non-zero magnetic field $B_z$ leads to vector current $j^\vec{z}_V$ in z-direction
Vector current $j^\vec{z}_V$ leads to separation of electric charges $j_V^0$ along the z-direction

N.Mueller, SS, S. Sharma PRL 117 (2016) no.14, 142301
Non-equilibrium CME dynamics

Axial charge $j_5^0$

Vector current $j_V^z$

Vector charge $j_\Lambda^0$

Sphaleron transition induces local imbalance of axial charge density

Non-zero magnetic field $B_z$ leads to vector current $j_V^z$ in z-direction

Vector current $j_V^z$ leads to separation of electric charges $j_\Lambda^0$ along the z-direction

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N.Mueller, SS, S. Sharma PRL 117 (2016) no.14, 142301
Non-equilibrium CME dynamics

Vector charge imbalance $j^0_V$ generates an axial current $j^z_5$ so that axial charge also flows along the B-field direction.

Axial charge $j^0_5$  Vector current $j^z_V$  Vector charge $j^0_V$

Emergence of a Chiral Magnetic shock-wave of vector charge and axial charge propagating along B-field direction.

N. Mueller, SS, S. Sharma PRL 117 (2016) no.14, 142301
Non-equilibrium CME dynamics

Vector charge imbalance $j^0_V$ generates an axial current $j^z_5$ so that axial charge also flows along the B-field direction.

Axial charge $j^0_5$  Vector current $j^z_V$  Vector charge $j^0_V$

Emergence of a Chiral Magnetic shock-wave of vector charge and axial charge propagating along B-field direction.

Vector charge imbalance $j^0_V$ generates an axial current $j_5^-$ so that axial charge also flows along the B-field direction.

Emergence of a Chiral Magnetic shock-wave of vector charge and axial charge propagating along B-field direction.

Non-equilibrium CME dynamics

Clear separation of electric charge $\mathbf{j}_V^0$ along the B-field direction
Validity of constitutive relations

Simulation results indicate approach towards constant value with a finite relaxation time.

Besides providing a field theoretical description of early time dynamics, microscopic simulations can also be compared to macroscopic description e.g. in anomalous hydrodynamics.

Since lifetime of magnetic field is short this effect should also be incorporated in more phenomenological approaches.

Mace, Mueller, SS, Sharma, PRD 95 (2017) no.3, 036023
Quark mass dependence

Explicit violation of axial charge conservation for finite quark mass

\[ \partial_\mu j^\mu_a(x) = 2m\langle \hat{\psi}(x)i\gamma_5\hat{\psi}(x) \rangle - \frac{g^2}{16\pi^2} F^a_{\mu\nu} \tilde{F}^\mu\nu \]

leads to damping of axial charge

Since CME current is proportional to axial charge density it will also be reduced

\[ \vec{j}_\nu \propto j^0_a \vec{B} \]

Significant reduction of the charge separation signal by factor \(~5\) already for moderate quark masses

\[ \rightarrow \text{unlikely that strange quarks contribute significantly} \]
CME & early-time dynamics

New theoretical tools to calculate early time dynamics of anomalous transport starting to become available

- non-equilibrium lattice simulations
- chiral kinetic theory
- anomalous hydrodynamics

Strong fields → quasi-particles → perfect fluid

~1 fm/c

generation of anomalous axial and vector currents

strong magnetic fields present

transport and interactions with medium

Challenge for the future will be to extend pre-equilibrium calculations to realistic heavy-ion environment
Anomalous hydrodynamics

Eventually the early time dynamics has to be matched to an extended version of usual hydrodynamic description of space-time evolution

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

including the dynamics of axial (L/R) currents

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

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

Significant progress in recent years in development of anomalous hydrodynamic models

M.Hongo, Y.Hirono, T.Hirano (2013); H.-U.Yee, Y.Yin (2014); Y.Hirono, T.Hirano, D.Kharzeev (2014); S.Shi Y.Jiang, E.Lilleskov, Y.Yin, J.Liao (2016); …
Anomalous hydrodynamics

Based on flexible assumptions about axial charge distribution and magnetic field, models allow for a direct comparison with experiment (c.f. talk by S. Shi)

Effectively axial charge is treated as a conserved quantity in present phenomenological models

Choice of initial conditions for axial/vector charges/currents provides significant source of uncertainty

-> Despite significant advances quantitative predictions still require further theoretical progress
Experimental future — Isobars

Basic idea: By colliding different species of ions with same mass but different charge, one can vary the signal (~B) without changing the background

Projections based on 1.2 B events for each collision type (Zr+Zr, Ru+Ru) (c.f. talk by L. Wen)

Deng, Huang, Ma, Wang, PRC 94 041901 (2016)

If background contributes less than 80% to $\Delta \gamma$ expect $5\sigma$ significance for unambiguous discovery
Conclusions

Chiral magnetic effect & anomalous transport phenomena provide an exciting opportunity to study new aspects of the QGP dynamics

Concepts developed in context of RHIC/LHC have already had a tremendous impact on the broader physics community

Despite significant progress on theory side, quantitative description of CME in heavy-ion collision remains a challenge

Combination of different theoretical methods required

Even though has proven challenging to disentangle possible signatures of CME & backgrounds in heavy-ion experiments, upcoming decisive test in RHIC Isobar Scan

New insights into Chiral Magnetic Effect & underlying QCD dynamics
Backup
Potential Backgrounds

Backgrounds unrelated to the chiral magnetic effect may be able to explain the observed charge separation*

Flow boost collimates pairs more strongly in-plane than out of plane known backgrounds are expected to go as $v_2$

Difficult to draw definitive conclusions without better models, and an independent lever arm for magnetic field and $v_2$
Beam Energy Dependence of Charge Separation

Initial attempts at subtracting the background

Significant charge separation ($\Delta \gamma$) observed at all energies

Subtracting estimate of flow modulated background indicates residual signal is:
- absent at 7.7 GeV
- maximum near 20 GeV
- falling with energy
- marginal at 2.76 TeV

Background subtracted assuming factorization:

$$H = \frac{\kappa \nu_2 \delta - \gamma}{1 + \kappa \nu_2}$$

$$\delta = \langle \cos(\Delta \varphi) \rangle$$

Bzdak, Koch and Liao, Lect. Notes Phys. 871, 503
Testing CME with p+Pb and Pb+Pb

Widths in p+Pb, in peripheral Pb+Pb and in Au+Au are all similar

A surprising coincidence? a natural occurrence? or do all have the same origin in a non-CME background?
\( \gamma \) correlation in p+Au and d+Au

- Sizable \( \Delta \gamma \) in p+Au and d+Au w.r.t 2\(^{nd}\) -order event plane (EP) \( \psi_2 \) from TPC, the magnitude is similar to or higher than Au+Au
- \( \Delta \gamma \) disappears in p+Au when \( \eta \) gap is introduced between EP and particles of interest: \( \Delta \gamma \) in TPC EP results mostly from short range correlation.

![Graph showing correlation between different reactions and event planes.](image)

- Time Projection Chamber: \(|\eta| < 1\)
- Beam-Beam Counter: \(3.8 < |\eta| < 5.2\)
- Zero Degree Calorimeter: \(6 < |\eta|\)

HT (High Tower): trigger on electromagnetic energy
U+U?

Why we need U+U collisions?
- To disentangle the signal and the background by varying the background (trying to minimize flow background by selecting the most central collisions in UU)

Projected B-field vs $\varepsilon_2$ can provide a natural explanation to data.