Search for Chiral & Vortical effects at RHIC

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Relativistic Heavy Ion collisions can produce large electro-magnetic fields and angular momentum → what are the observable consequence?

I will focus on RHIC measurements and particularly from STAR on the search for Vortical & Chiral effects

200 GeV : U+U, Cu+Cu, p+Au, d+Au Ru+Ru, Zr+Zr, 7.7-200 GeV : Au+Au BES
Search for vortical effects
Angular momentum in HICs

Collisions of two relativistic nuclei generate large angular momentum ($\vec{J}$). $\vec{J}$ points perpendicular to the plane of beam axis & impact parameter ($b$).
Angular momentum in HICs

Large angular momentum leads to local vorticity ($\vec{\omega}$) in the created medium.

Vorticity:

$$\vec{\omega} \equiv \frac{1}{2} \nabla \times \vec{v} \approx \frac{1}{2} \frac{\partial v_z}{\partial x}$$
Global polarization due to vorticity

Angular momentum ($\mathbf{J}$) $\rightarrow$ Vorticity ($\mathbf{\omega}$) $\rightarrow$ Polarization (spin orbit coupling)

- quarks
- anti-quarks

$\mathbf{L}$: left-handed  $\mathbf{R}$: right-handed

How to observe this?
#1 : Measure the direction of angular momentum

We know the beam direction, and by measuring beam fragments (BBC low $\sqrt{s}$ & ZDC high $\sqrt{s}$) we know the event-by-event direction of $\vec{J}$.

The vector joining the two beam fragments give the direction of impact parameter $\vec{b}$ & $\vec{J}$.
#2: measure the spin polarization of particles

Measuring spin of particles in not easy but we can make use of the parity-violating decay of hyperons such as Lambdas

\[ \Lambda \rightarrow p + \pi^- \]
(\(BR: 63.9\%, c\tau \sim 7.9 \text{ cm}\))

In Lambda decays the proton momentum direction is correlated to the spin polarization direction of Lambda

\[
\frac{dN}{d\Omega^*} = \frac{1}{4\pi} (1 + \alpha_H \mathbf{P}_H \cdot \mathbf{p}_p^*)
\]

\(\mathbf{P}_H\): \(\Lambda\) polarization
\(\mathbf{p}_p^*\): proton momentum in the \(\Lambda\) rest frame
\(\alpha_H\): \(\Lambda\) decay parameter

\(\alpha^\Lambda = -\alpha^\bar{\Lambda} = 0.642 \pm 0.013\)

The Feynman Lectures on Physics, Volume III, chapter 17-5
Measurements by STAR

The polarization of $\Lambda$:

$$\overline{P}_H \equiv \langle \vec{P}_H \cdot \hat{J}_{\text{sys}} \rangle = \frac{8}{\pi \alpha_H} \left\langle \cos \left( \phi^*_p - \phi \hat{J}_{\text{sys}} \right) \right\rangle \frac{R_{\text{EP}}^{(1)}}{R_{\text{EP}}}$$

- **BBCE** (Beam fragment)
- **TPC** (Tracking)
- **BBCW** (Beam fragment)
- Also TOF used for particle ID

Proton angle in $\Lambda$ rest-frame ($\Lambda$ spin)

Direction of $\hat{J}$

Resolution of $\phi \hat{J}_{\text{sys}}$
What’s new: more precise measurements

Measurements in Au+Au collisions from STAR & discovery of most vortical fluid with BES-I data

Non-zero significant polarization $P_{H}(\Lambda)$ & $P_{H}(\bar{\Lambda}) > 0$, hint of $P_{H}(\Lambda) > P_{H}(\bar{\Lambda})$

Improved significance (150 more data), non-zero polarization (<1%) observed in Au+Au 200 GeV

Opens a path for more differential studies & phenomenology
What’s new: reaction plane dependence

Strongest polarization is seen for Lambdas emitted (in-plane) where the vorticity is expected to be the largest.
What’s new: Longitudinal polarization

How about this (polarization along beam axis?)

This has been observed

Impact parameter

Angular momentum

Beam

A

B
What’s new: Longitudinal polarization

Pressure gradient $\rightarrow$ anisotropic expansion $\rightarrow$ gradient in transverse velocity $\rightarrow$ vorticity

How about this (polarization along beam axis?)
What’s new: Longitudinal polarization

Pressure gradient → anisotropic expansion → gradient in transverse velocity → vorticity

How about this (polarization along beam axis?)
What’s new: Longitudinal polarization

Pressure gradient $\rightarrow$ anisotropic expansion $\rightarrow$ gradient in transverse velocity $\rightarrow$ vorticity

Polarization projected onto beam axis changes sign w.r.t. to the direction of the elliptic anisotropy $\Psi_2$
What’s new: Longitudinal polarization

Pressure gradient $\rightarrow$ anisotropic expansion $\rightarrow$ gradient in transverse velocity $\rightarrow$ vorticity

Beam

Polarization projected onto beam axis changes sign w.r.t. to the direction of the elliptic anisotropy $\Psi_2$

Hydro calculation predicts opposite trend

Becattini and Karpenko PRL 120, 012302 (2018)
Search for chiral effects
Heavy ion collisions are the right place

**#1: Non-conservation of chirality:** Collisions generate fluctuating parallel chromo E & B fields

\[ E \parallel B \parallel \hat{z} \\Rightarrow \quad dQ_5/dt \propto E \cdot B \]

**#2: A deconfined medium of massless fermions (chiral symmetry restoration)**

**#3: Creation of strong magnetic-field ~10^{18} Gauss**

Kharzeev, McLerran, and Warringa 0711.0950, Skokov, Illarionov, Toneev 0907.1396, McLerran, Skokov, 1305.0774
The Chiral Magnetic Effect

The B-field will align the spins due to magnetic moments

\[ \langle \vec{p} \rangle \propto (Qe) \mu_5 \vec{B} \]

\[ \vec{J} \propto \langle \vec{p} \rangle \propto (Qe) \mu_5 \vec{B} \]

Kharzeev, McLerran, Warringa 0711.0950

P Tribedy, GHP@APS, April 10-12, 2019
The Chiral Magnetic Effect

There could be two different possibilities:
- Excess right handed
- Excess left handed

With B-field
- The B-field will align the spins due to magnetic moments
- No net effect

\[
\langle \vec{p} \rangle \propto (Qe) \mu_5 \vec{B}
\]

\[
\vec{I} \propto \langle \vec{p} \rangle \propto (Qe) \mu_5 \vec{B}
\]

Kharzeev, McLerran, Warringa
0711.0950

P Tribedy, Rutgers Nuclear Physics Seminars
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\[\text{L : left-handed} \quad \text{R : right-handed}\]
The Chiral Magnetic Effect

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\[ \mathbf{I} \propto \langle \mathbf{p} \rangle \propto (Qe)\mu_5\mathbf{B} \]

\( n_R < n_L \)

Kharzeev, McLerran, Warringa 0711.0950, Kharzeev, Liao, Voloshin, Wang 1511.04050

P Tribedy, Rutgers Nuclear Physics Seminars
The first measurements at RHIC: 200 GeV Au+Au

Charge separation perpendicular to $\Psi_2$

$$\gamma^{+-} = \langle \cos(\phi_1^+ + \phi_2^- - 2\Psi_2) \rangle$$

Elliptic Anisotropy

The very first measurements indicated non-zero charge separation increasing in peripheral events
The first measurements at RHIC: BES data

Charge separation vanishes at the lowest energy

L. Adamczyk et al. (STAR Collaboration), PRL 113 (2014) 052302.

Expectation consistent disappearance of deconfinement / chiral symmetry restoration ?
Beyond the simple cartoon picture of CME

Axial charge profile
Lappi, Schlichting, 1708.08625

Magnetic field map
Belmont, Nagle, 1610.07964

(Peripheral Pb+Pb)

Fluctuations, quenching & collective expansion should be dominant
Beyond the simple cartoon picture of CME

Axial charge profile
Lappi, Schlichting, 1708.08625

Magnetic field map
Belmont, Nagle, 1610.07964

Fluctuations, quenching & collective expansion should be dominant
Magnetic field vs. collision centrality

Effect of B-field should vanish in peripheral events
Signal should vanish in peripheral events

Effect of B-field should vanish in peripheral events

Large charge separation in peripheral A+A & p/d+A

First seen at LHC in p+Pb & peripheral Pb+Pb
Why so large signal in p+A, peripheral A+A?

$\Delta \eta$ dependence of charge separation $\rightarrow$ di-jets dominate peripheral A+A & p+A

$\langle \cos(\phi_1 + \phi_2 - 2\phi_3) \rangle \times N_{\text{part}}$

0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005

0-100% p+Au 200 GeV

0.4
0.8
1.2
1.6

$\Delta \eta_{12}$

Di-jet fragmentation

HBT, Coulomb

Reaction plane independent background in p/d+A mimics CME

STAR preliminary

p+Au is baseline for peripheral A+A but not central A+A

P Tribedy, GHP@APS, April 10-12, 2019
One more attempt using Au+Au & U+U collisions

B-field scaled by ellipticity

Hydro + local charge conservation

Maximum possible background

Minimum possible background

Schenke, Shen, PT 1901.04378
One more attempt using Au+Au & U+U collisions

**B-field scaled by ellipticity**

![Graph showing B-field scaled by ellipticity for Au+Au and U+U collisions. The data points are compared with theoretical predictions.](image)

*Figure 1*:

**Hydro + local charge conservation**

![Graph showing hydrodynamic simulations with local charge conservation.](image)

*Figure 2*:

Interesting but an experimental baseline for background needed (w.r.to $\Psi_3$ plane)

**STAR Data**

![Graph showing STAR data comparison.](image)

*Figure 3*: 

Schenke, Shen, PT 1901.04378
Decisive tests of Chiral Effects
Better and controlled experiment : Isobar collisions

10% larger B-field in Ru+Ru but same background as Zr+Zr

3.1B events for both Ru+Ru, Zr+Zr collected over 8 weeks
Blind analyses is ongoing by the STAR collaboration
Summary

Very exciting time for RHIC

1) New high statistics measurements of vortical effects, STAR upgrade with new detectors will improve measurements of Lambda polarization

2) Comprehensive set of measurements on CME, CMW, several new approaches to quantify CME signals but no decisive tests yet

3) Isobar data taking was a success, bind analysis is ongoing by STAR

Things I couldn’t cover: CMW, CSE
Interplay of Chiral & Vortical effects
Thank You
Backup
Recent attempts to quantify the fraction of signals

Several estimations of possible signal fraction of CME, large uncertainties and also some model dependence is needed.

Results using a new observable to study CME looks interesting.

STAR Collaboration, Ye, QM 2018

Magdy, QM 2018

Au+Au $\sqrt{s_{NN}} = 200$ GeV (20-50%)

Fraction of CME-like signal

$\Psi_{RP}/\Psi_{PP}$ (TPC full)

$\Psi_{RP}/\Psi_{PP}$ (TPC sub-evt)

$m_{\text{inv}} > 1.5$ GeV/$c^2$ (TPC full)

Low $m_{\text{inv}} +$ ESE (TPC sub-evt)

$\Delta\gamma_{112}$ ESE ($\Delta\gamma_{123}$ similar)

$\langle N_{\text{ch}} \rangle \sim 30$

STAR Preliminary

$R_{\Psi_2}(\Delta S)$

$\Delta S'$
Why is this so exciting?

Baryon number violation in early universe $\rightarrow$ matter-antimatter asymmetry

Non-trivial topologies of gauge fields $\rightarrow$ violation of P & CP

Baryogenesis (Electroweak)

$\partial_\mu J_B^\mu \neq 0$

“Chirality-genesis” (QCD)

$\partial_\mu J_5^\mu \neq 0$

Can we observe in the hot & dense QCD medium of heavy ion collisions?
Another source is flowing resonance

Flowing resonances can mimic CME in mid-central A+A

Neutral resonance yield

Charge separation

One can subtract the resonance contribution if the invariant mass distribution for CME is known

P Tribedy, GHP@APS, April 10-12, 2019
Another source of background: flowing cluster

$+\text{pos} - \text{neg} \ 0 : \text{neutral}$

No charge dependent correlations

Background due to neutral resonance decay, local charge & momentum conservation

Flowing neutral cluster that produces charge pair will mimic CME
Finally, the current theoretical effort in tracking the longitudinal asymmetry and decorrelation effects. In turn, this information will elucidate the space-time picture of the QGP, which is expected to be very different. By correlating this information with the pseudorapidity coverage in the STAR detector, it becomes possible to study the differential transverse flow in forward rapidity, where the response of FTPC in 2012 shows the removal of FTPC. The projected future capabilities of TPC+fTPC (2001-2012) include extended capabilities like TPC-FTPC (2001-2012) and TPC-TPC (2001-2012), as shown in the figure. The STAR detector is expected to have a large acceptance, including 3+1D hydrodynamic models. The pseudorapidity coverage in the STAR detector prior to the 2019 EPD can be seen on the left panel, while the right panel shows the projected future capabilities. The color legend includes iTPC 2019- (p_T, charge, PID), FTS 2021- (p_T, charge), FCS 2021- (E_T, n^0, γ), and EPD 2019- (hits).
Chiral Separation Effect & Chiral Magnetic Wave
The Chiral Magnetic Wave: driven by CSE

This phenomena is driven by excess quarks over anti-quarks does not require initial $\mu_5$

\[
\frac{dN^{\pm}}{d\phi} \propto v_2^{\pm} \cos(2\phi^{\pm})
\]
Search for the chiral magnetic wave at RHIC

L. Adamczyk et al. (STAR Collaboration) Phys. Rev. Lett. 114, 252302
Qi-Ye Shou QM 2018

Observation at RHIC is consistent to CMW expectation

\[ A_{ch} = \frac{N_+ - N_-}{N_+ + N_-} < 0, \quad v_2(\pi^+) > v_2(\pi^-) \]

\[ A_{ch} = \frac{N_+ - N_-}{N_+ + N_-} > 0, \quad v_2(\pi^+) < v_2(\pi^-) \]

Unlike LHC, at RHIC effect \( v_2 >> v_3 \)
Chiral and Vortical effects
Chiral separation effect and spin polarization

CSE enhances spin polarization along global angular momentum

\[ A_{ch} = \frac{N_+ - N_-}{N_+ + N_-} > 0 \]

More spin polarized along \( \vec{B} \parallel \vec{\omega} \)

\[ A_{ch} = \frac{N_+ - N_-}{N_+ + N_-} < 0 \]

More spin polarized opps to \( \vec{B} \parallel \vec{\omega} \)
The connection between CSE and polarization

Global polarization of $\Lambda$ and $\bar{\Lambda}$ studied w.r.to charge asymmetry $A_{ch}$

Very first measurement looks promising, need more statistics