Final state effects on chiral magnetic effect in relativistic heavy-ion collisions

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Outline

- Motivation
- The AMPT model and its results
- Predictions on CME in isobar collisions
- Summary
Strong B field in HIC

The B field at the colliding time, \( t = 0 \). Biot-Savart law

\[
-eB_y \sim 2 \times \gamma \frac{e^2}{4\pi} Z v_z \left( \frac{2}{b} \right)^2 \approx 40m_{\pi}^2 \sim 10^{19}\text{Gauss}
\]

The Earths magnetic field

0.6 Gauss

A common, hand-held magnet

100 Gauss

The strongest steady magnetic fields achieved so far in the laboratory

4.5 x 10^5 Gauss

The strongest man-made fields ever achieved, if only briefly

10^7 Gauss

Typical surface, polar magnetic fields of radio pulsars

10^{13} Gauss

Surface field of Magnetars

10^{15} Gauss

http://solomon.as.utexas.edu/~duncan/magnetar.html
Chiral Magnetic Effect

• CME: Initial fluctuations of topological charge in QCD vacuum $\rightarrow$ P and CP odd metastable domains $\rightarrow$ Charge separation in the direction of magnetic field

• CME indicates that parity is locally violated in strong interactions, which shows us the vacuum nature and QCD electromagnetics.
• The STAR data are consistent with the CME expectation. → Charges are distributed asymmetrically w.r.t reaction plane, i.e. dipole charge separation.
Can CME signal survive from final interactions?

• The lifetime of B field is short. → The CME is an initial effect.
• Final state interaction effects on the CME is important.
A multiphase transport (AMPT) model

(1) initial condition

(2) parton cascade

[2<->2 elastic collisions]

(3) hadronization

(4) hadronic rescatterings

- Only resonance decays are employed to ensure charge conservation for now.

Z. W. Lin, C. M. Ko et al. PRC 72, 064901 (2005)

Z. -W. Lin et al., PRC 72 (2005) 064901

Melting AMPT Model
We include initial dipole charge separation mechanism into AMPT model. We switch the $p_y$ values of a percentage of the downward moving $u$ quarks with those of the upward moving $u$-bar quarks, and likewise for $d$-bar and $d$ quarks, where the percentage is a relative ratio with respect to the total number of quarks.

We focus on final state effects on the charge separation, including parton cascade, hadronization, resonance decays after $\vec{B}$ and $\vec{E}$ vanish quickly.
An initial charge separation ~10% can describe same-charge data in the presence of strong final state interactions. But ~10% only can describe opposite-charge correlation for 60-70%. From a percentage of charge separation of 10% in the beginning → 1-2% percentage at the end.
The AMPT result without CME is very close to the expectation of trans. mom. conservation [dashed: \(<\cos(\phi_\alpha+\phi_\beta)>=-v_2/N\)].

TMC can partly account for data, and an initial 10% dipole charge separation are needed. \(\Rightarrow\) CME+TMC (+LCC)~ experimental data
Isobars are atoms (nuclides) of different chemical elements that have the same number of nucleons.

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<th>$^{96}<em>{44}$Ru+$^{96}</em>{44}$Ru</th>
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<th>$^{96}<em>{40}$Zr+$^{96}</em>{40}$Zr</th>
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<td>Flow</td>
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<td>CME</td>
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• RHIC plans to collide isobars ($^{96}$Zr+$^{96}$Zr and $^{96}$Ru+$^{96}$Ru) at 200 GeV in Run-18 (2017-2018).
b-dependent Magnetic field

- b dependence of averaged $<B_y>$ for Ru+Ru and Zr+Zr, and other systems.
- $<B_y>$ (Ru+Ru) is larger than $<B_y>$ (Zr+Zr) by 10% at large b.

Lienard-Wiechert potentials:

$$eB(t, r) = \frac{e^2}{4\pi} \sum_n Z_n \frac{v_n \times R_n}{(R_n - R_n \cdot v_n)^3} (1 - v_n^2),$$
We apply $f\% = 1146.1A^{-4/3}B_y(b)$ to introduce the initial charge separation into Ru+Ru and Zr+Zr, by fitting the STAR data of Au+Au and Cu+Cu.

$$f\% = \frac{(N^+_{\text{upward}}-N^+_{\text{downward}})}{(N^+_{\text{upward}}+N^+_{\text{downward}})} \sim J\pi R^2/N_{\text{mult}} \sim A^{-4/3}B_y$$
If CME, a magnitude ordering that Au+Au < Zr+Zr < Ru+Ru < Cu+Cu.

The CME difference due to different B fields between Zr+Zr and Ru+Ru can be seen, even with considering FSI effects.
Summary

● The initial CME results from QCD vacuum fluctuations + large B field.

● Final state interactions reduce the CME signal, so the percentage of initial CME charge separation should be larger than that without FSI.

● Isobaric collisions will be a good test to directly see CME difference due to different B fields.
Thanks for your attention!
A domain-based charge separation better describe the STAR data.

The domain rate is consistent with the charge separation percentage in the global case.
• Parton cascade reduces charge separation significantly.
• Coalescence recovers some charge separation in part because it reduces the number of particles after combining quarks into hadrons.
• Resonance decays reduce charge separation, where local charge conservation washes out the magnitude of opposite-charge correlation.
Topological structure of QCD vacuum

Gluonic field energy

\[ N_{CS} = \frac{1}{16\pi^2} \int d^3x \epsilon^{ijk} \left( A_i^a \partial_j A_k^a + \frac{1}{3} \epsilon^{abc} A_i^a A_j^b A_k^c \right) \]

\[ Q_w = \frac{g^2}{32\pi^2} \int d^4x \ F_{\mu\nu}^a \tilde{F}_a^{\mu\nu} \sim \vec{E}^a \cdot \vec{B}^a \quad \text{P & CP ODD} \]