Chiral vortical and magnetic effects in anomalous hydrodynamics

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Outline

• Motivation

• Hydro Set and Initial Conditions

• Numerical Results

• Conclusion
Motivation

• Chiral effects in HIC: still in focus and debate

• $\gamma$ correlation of identified particles?

• In low energy and peripheral collisions, CVE is stronger than CME

• Hydrodynamics simulation of CVE is necessary
3+1D Anomalous Ideal Hydrodynamics

with chiral magnetic effect

\[ \partial_\mu T^{\mu\nu} = e F^{\nu\lambda} j_\lambda \]
\[ \partial_\mu j^\mu = 0 \quad j^\mu = n u^\mu + \kappa_B B^\mu \]
\[ \partial_\mu j_5^\mu = -C E_\mu B^\mu \quad j_5^\mu = n u_5^\mu + \xi_B B^\mu \]

EOS: ideal massless quark-gluon gas

\[ \epsilon = 3p = \frac{19\pi^2}{12} T^4 + \frac{9}{2} (\mu^2 + \mu_5^2) T^2 + \frac{9}{4\pi^2} (\mu^4 + 6\mu^2 \mu_5^2 + \mu_5^4) \]

Transport Coefficients

\[ e\kappa_B = C\mu_5 (1 - \frac{\mu_5 n_5}{\epsilon + p}) \quad e\xi_B = C\mu (1 - \frac{\mu n}{\epsilon + p}) \]

Determined by requiring entropy does not decrease [1,2].

Two more coefficients if including CVE:

\[ e^2 \kappa_\omega = 2C\mu\mu_5 (1 - \frac{\mu n}{\epsilon + p}) \quad e^2 \xi_\omega = C\mu^2 (1 - \frac{2\mu_5 n_5}{\epsilon + p}) \]

Magnetic Field

Exponentially decaying Gaussian distribution:

\[ eB_y(\tau, \eta, x, y) = eB_0 \frac{b}{2R} \exp \left( - \frac{x^2}{\sigma_x^2} - \frac{y^2}{\sigma_y^2} - \frac{\eta^2}{\sigma_\eta^2} - \frac{\tau}{\tau_B} \right) \]

\[ eB_0 = 0.5 GeV^2 \quad \sigma_x = 0.8(R - \frac{b}{2}) \]

\[ \sigma_y = 0.8 \sqrt{R^2 - (b/2)^2} \quad \sigma_\eta = \sqrt{2} \]

Recent magneto-hydrodynamics simulation[1] gave time evolution very similar to exponential decay

Initial Conditions

• MC-Glauber model is sufficient for CME simulation but gives zero initial vorticity

• HIJING model has been used to describe vorticity of initial system[1] but has no chiral charge distribution

γ Correlation of Identified Particles with CME for RHIC 200GeV Au-Au Collisions

p-π opposite-sign (red line) and same-sign (blue line) correlation in comparison with experimental data (dots)

A lot of other contributions are cancelled out in OS-SS correlation
$\gamma$ Correlation of Identified Particles with CME for RHIC 200GeV Au-Au Collisions

$\pi-\pi$ OS-SS correlation (line) in comparison with experimental data (dots)

possible indication of strong CVE in more peripheral collisions
Comparison of CVE and CME Contributions

Simulation of pion and proton $a_1$ with different effects included, for RHIC 200Gev Au-Au 40~50% centrality collisions

<table>
<thead>
<tr>
<th></th>
<th>$\pi$</th>
<th>$p$</th>
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</thead>
<tbody>
<tr>
<td>None(Glauber)</td>
<td>$-0.0007 \pm 0.0019$</td>
<td>$-0.0058 \pm 0.0063$</td>
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<tr>
<td>None</td>
<td>$-0.0023 \pm 0.0014$</td>
<td>$-0.0120 \pm 0.0038$</td>
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<tr>
<td>CME</td>
<td>$0.0013 \pm 0.0013$</td>
<td>$-0.0027 \pm 0.0042$</td>
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<tr>
<td>CVE + CME</td>
<td>$0.0048 \pm 0.0018$</td>
<td>$0.0109 \pm 0.0044$</td>
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- CVE calculated as perturbation
- Initial chiral charge taken as proportional to temperature
- None-zero background comes from fluctuation in HIJING events
Conclusion and Outlook

• We calculated $\gamma$ correlation of protons and pions for RHIC 200Gev Au-Au Collisions.

• We also made a comparison of CVE and CME contribution in a given condition.

• Both show signs of strong CVE contribution

• More observables: electric quadrupole, $\Lambda$ polarization, different collision energy…

• Improvements: resonance decay…

• CVE hydrodynamics: initial condition, stable evolution…
γ Correlation of Identical Particles with CME for RHIC 200GeV Au-Au Collisions

\[ \gamma \text{ Correlation} \]

p-p correlation (line) in comparison with experimental data (dots)