Energy dependence of the chiral magnetic effect in expanding holographic plasma

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Reference: Phys. Rev C 105 (2022) 3, 034903 arXiv:2112.13857

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Abstract

Based on a holographic far-from-equilibrium calculation of the Chiral Magnetic Effect (CME) in an expanding quark gluon plasma (QGP), we study collisions at various energies. We compute the time evolution of the CME current in the presence of a time-dependent axial charge density and subject to a time-dependent magnetic field. The plasma expansion leads to a dilution of the CME current. We study distinct combinations of how the initial magnetic field and initial axial charge behave with changing initial energy as proposed in previous literature. Most scenarios we consider lead to an increasing time-integrated CME current, when increasing the initial energy. This would make it more likely to observe the CME at higher collision energies.

1. Motivation

– The existence of the Chiral Magnetic Effect in heavy ion collisions has yet to be conclusively established.
– STAR's recent report [1] of no signal satisfying pre-blind criteria necessitates a deeper understanding of the background, no theory predicted observed ratios.
– Uncertainty still surrounds collision geometries, the magnetic field evolution, and energy dependence of input parameters for hydrodynamic models such as the axial charge density.

2. Holographic Model

Einstein gravity coupled to $U(1)_V \times U(1)_A$ [2]

$$S = \frac{1}{16\pi G_N}\int \mathrm{d}^5x\sqrt{-g}\left(R - 2\Lambda - \frac{L^2}{4}F_{\mu\nu}F^{\mu\nu} - \frac{L^2}{4}F^{(5)}_{\mu\nu}F^{\mu\nu}_{(5)} + \frac{\alpha}{3}\epsilon^{\mu\nu\rho\sigma\tau}A_\mu\left(3F_{\nu\rho}F_{\sigma\tau} + F^{(5)}_{\nu\rho}F^{(5)}_{\sigma\tau}\right)\right) + S_{ct}$$

Boundary conditions on asymptotically AdS metric

$$\lim_{r\to\infty}\frac{1}{r^2}g_{\mu\nu} = \mathrm{diag}\left(-1,1,1,\tau^2\right)$$

enforces boost invariant expansion in dual theory where we work in Milne coordinates $x^i = (\tau, x_1, x_2, \xi)$

Field theory magnetic field

$$B^a = \frac{1}{2}\epsilon^{abcd}u_b F_{cd} \qquad B^1 = \frac{B_0}{\tau}$$

3. Ansatz and solutions

Metric: **Coordinates:** $x^\mu = (\tau, x_1, x_2, \xi, r)$

$$\mathrm{d}s^2 = 2\mathrm{d}v\left(\mathrm{d}r - \frac{1}{2}A(v,r)\mathrm{d}v\right) + S(v,r)^2 e^{H_1(v,r)}\mathrm{d}x_1^2 + S(v,r)^2 e^{H_2(v,r)}\mathrm{d}x_2^2 + L^2 S(v,r)^2 e^{-H_1(v,r)-H_2(v,r)}\mathrm{d}\xi^2$$

Axial gauge field: $\xrightarrow{\text{Dual to}}$ **Axial Current:**

$$A_\mu = (-\phi(v,r)/L, 0,0,0,0) \qquad \langle J^a_{(5)}\rangle = \frac{1}{2\kappa^2}\left(\frac{q_5 L}{\tau}, 0,0,0\right)$$

Vector gauge field: $\xrightarrow{\text{Dual to}}$ **Vector Current:**

$$V_\mu = \frac{1}{L}(0, -V_x(v,r), \xi B, 0, 0) \qquad \langle J^a\rangle = \frac{1}{2\kappa^2}(0, 2V_2(\tau), 0, 0)$$

Goal: Compute numerical solutions for given initial data via characteristic formulation [3] of general relativity and extract behavior of dual vector current $\langle J^1\rangle$ for various models of the energy dependence of the magnetic field and axial charge density.

Model axial charge density dependence on initial energy via flux tube model [4]

$\sqrt{s}$ [GeV]	19	27	39	64	200	2750
$\langle J^0_{(5)}\rangle$ [10^{-3}GeV^3]	1.2	1.4	1.6	1.9	2.7	6.6

Magnetic field strength also depends on the initial collision energy as well as on the colliding nuclei (distribution of protons and neutrons, shape etc.) [5]

$\sqrt{s}$[GeV]	19	27	39	64	200
eB	$0.095m_\pi^2$	$0.135m_\pi^2$	$0.195m_\pi^2$	$0.32m_\pi^2$	$1m_\pi^2$

4. Cases

Investigate energy dependence of CME while varying energy dependence of initial data.

Example:

Case I – vary energy density holding $B(\tau_0)$ and $\langle J^0_{(5)}(\tau_0)\rangle$ fixed on initial time slice.

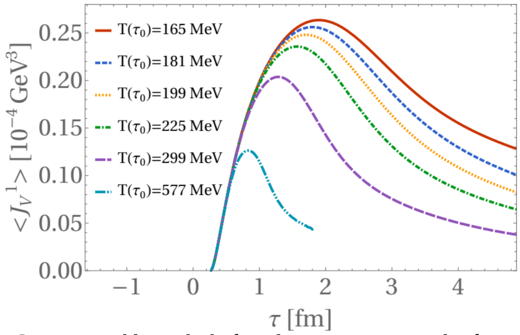
Case VI – vary energy density while varying $B(\tau_0)$ and $\langle J^0_{(5)}(\tau_0)\rangle$ with initial energy on initial time slice.

Compute charge flow through a surface as a measure of integrated CME current arriving at detectors

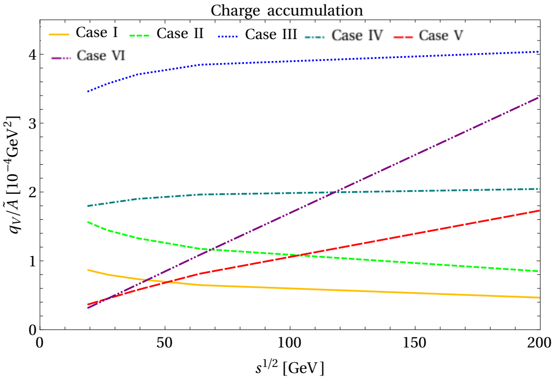
$$q_V = \int \mathrm{d}t \int \langle\vec{J}\rangle\cdot\mathrm{d}\vec{A}$$

5. Results

Case I – Time dependence of the CME current



– Current quickly peaks before decreasing as a result of expansion.
– Increasing initial energy leads to decreasing peak amplitude.



Conclusions:
– Four of six cases display increasing CME signal with increasing energy.
– Comparison with [6] shows case I is the best fit with current experimental data.
– Improvements to our analysis can include deviations away from boost invariant evolution, magnetic fields with different time dependence, non-homogeneous axial charge density, radial flow and higher harmonics in transverse plane.

References

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