Chiral Electric Separation Effect

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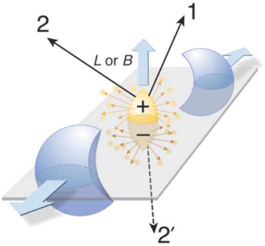
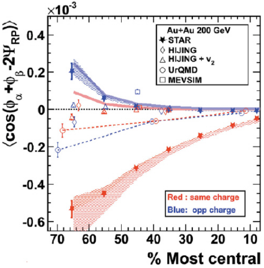
Chiral magnetic effect

- Heavy-ion collisions generate strong magnetic fields.
- Chirality imbalance + magnetic field = chiral magnetic effect (CME) **(Kharzeev 2004, Kharzeev, Mclerran, Warringa, Fukushima 2007-2008)**:

$$\mathbf{J}_V = \frac{N_c e}{2\pi^2}\mu_A \mathbf{B}$$

- Phenomenology: charge-charge azimuthal correlation. **Voloshin 2004, STAR@RHIC 2009-2015, ALICE@LHC 2012-2014**





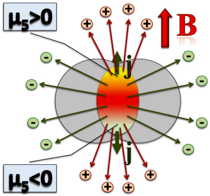
- Signal for local parity violation of QCD?! Need more theoretical and experimental studies on the backgrounds.

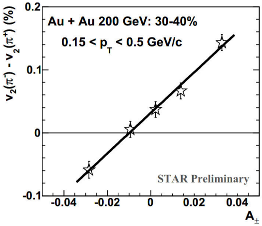
Chiral separation effect

- A dual effect to chiral magnetic effect: chiral separation effect (CSE) **(Son and Zhitnitsky 2004, Metlitski and Zhitnitsky 2005)**

$$\mathbf{J}_V = \frac{N_c e}{2\pi^2}\mu_A \mathbf{B} \;\Rightarrow\; \mathbf{J}_A = \frac{N_c e}{2\pi^2}\mu_V \mathbf{B}$$

- The coupled evolution of CME and CSE induces massless collective modes, Chiral magnetic wave (CMW) **(Kharzeev and Yee 2011)**
- CMW $\Rightarrow$ electric quadrupole in QGP$\Rightarrow$ $v_2(\pi^-) - v_2(\pi^+) \propto A_\pm$ with $A_\pm = (N_+ - N_-)/(N_+ + N_-)$**(Burnier, Kharzeev, Liao, and Yee, 2011)**





- STAR measurements (2012-2015) qualitatively coincides with CMW. But need to study and substrac the background effects.

E-induced anomalous transport?

- Question: Can strong E-field induce anomalous transport?

	$\mathbf{E}$	$\mathbf{B}$
$\mathbf{j}_V$	σ	$\frac{e}{2\pi^2}\mu_A$
$\mathbf{j}_A$	???	$\frac{e}{2\pi^2}\mu_V$

$$j_A^\mu = \sigma_5 E^\mu ???$$

- Can σ_5 be nonzero?
- j_A^μ is P-even while E^μ is P-odd $\Rightarrow \sigma_5 \propto \mu_A$ to balance the parity; j_A^μ is C-even while E^μ is C-odd $\Rightarrow \sigma_5 \propto \mu_V$ to balance the charge conjugation $\Rightarrow$ if σ_5 is nonzero it must be

$$\sigma_5 \propto \mu_V \mu_A .$$

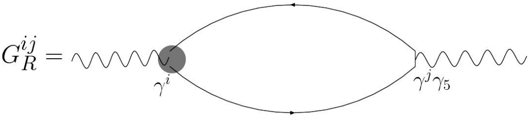
- If σ_5 is nonzero, the E-field induces a axial current and thus a chirality separation. This effect can be called chiral electric separation effect (CESE)

Chiral Electric Separation Effect (I)

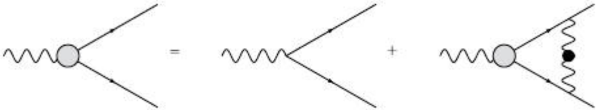
- Perform a concrete calculation to hot QED plasma.
- Apply Kubo formula:

$$\begin{aligned} \mathbf{j}^{\mu}_{A}(\omega,\mathbf{k}) &= \sigma_5 i\omega \mathbf{A}(\omega,\mathbf{k}) \\ \Rightarrow \sigma_5 &= \lim_{\omega\to 0}\lim_{\mathbf{k}\to 0}\frac{i}{3\omega}\sum_{i=1}^{3} G_R^{ii}(\omega,\mathbf{k}) \\ G_R^{ij}(x) &= -i\theta(x)\langle[J_A^i(x), J_V^j(0)]\rangle. \end{aligned}$$

- Leading-log approximation, fermion propagates in axial background so that $\mu_A \neq 0$



where the effective vertex is (dotted lines: HTL propagators)



Chiral Electric Separation Effect (II)

- At leading plus subleading order in $\mu_{V,A}/T$ expansion, we obtain result leading-log in e **(XGH and Liao, PRL110(2013)232302)**

$$\sigma_5 \approx 20.499\frac{\mu_V\mu_A}{T^2}\frac{T}{e^3\ln(1/e)} \propto \frac{\mu_V\mu_A}{T^2}\sigma$$

As a by-product [1],

$$\sigma \approx \frac{T}{e^3\ln(1/e)}\left(15.6952 + 7.76052\frac{\mu_V^2+\mu_A^2}{T^2}\right)$$

- For thermal QCD with two flavor quarks, consider an axial current $j_A^\mu = \bar{\psi}Q_A\gamma^\mu\gamma_5\psi$ with Q_A a flavor matrix and Q_e charge matrix: **(Jiang, XGH, and Liao, PRD91(2015)045001)**

$$\sigma_5 \approx T\frac{\mathrm{Tr_f}Q_eQ_A}{g^4\ln(1/g)}14.5163\frac{\mu_V\mu_A}{T^2}$$

- The CESE was also confirmed by holographic calculations: **(Pu, Wu, and Yang 2014)**

[1] Good check: put $\mu_V = \mu_A = 0$, it recovers the result of **Arnold,Moore,Yaffe 2000**

Chiral Electric Separation Effect (III)

- Collective modes by CESE, CME, and CSE.
- The complete electromagnetic response of a chiral matter:

$$
\begin{aligned}
j_V^\mu &= \sigma E^\mu + \frac{e}{2\pi^2}\mu_A B^\mu, \\
j_A^\mu &= \sigma_5 E^\mu + \frac{e}{2\pi^2}\mu_V B^\mu.
\end{aligned}
$$

- Coupled evolution of vector and axial currents leads to several collective modes **(XGH and Liao, PRL110(2013)232302)**:
  - If $\mathbf{B} = B\hat{z}$ and $\mathbf{E} = 0$: two Chiral magnetic waves along $\mathbf{B}$

    $$\omega = \pm\sqrt{(v_\chi k_z)^2 - (e\sigma_0/2)^2} - i(e\sigma_0/2)$$

  - If $\mathbf{B} = 0$ and $\mathbf{E} = E\hat{z}$ + A-background: two Chiral electric waves

    $$\omega = \pm\sqrt{(v_e k_z)^2 - (e\sigma_0/2)^2} - i(e\sigma_0/2)$$

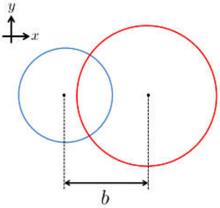
  - If $\mathbf{B} = 0$ and $\mathbf{E} = E\hat{z}$ + V-background: one Vector density wave and one Axial density wave along E-field

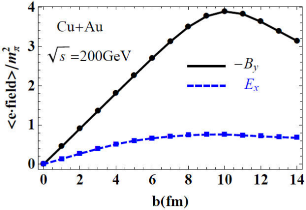
    $$
    \begin{aligned}
    \omega_V &= v_v k_z - ie\sigma_0, \\
    \omega_A &= v_a k_z
    \end{aligned}
    $$

- These collective excitations transport chirality and charge, and leads to novel charge azimuthal distribution $\Rightarrow$

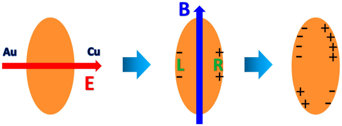
Chiral Electric Separation Effect (IV)

- Possible implication. In-plane E-field in AuCu collisions. **(Deng & XGH, PLB742(2015)296)**





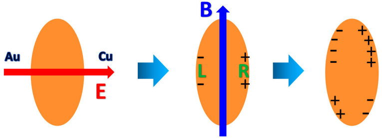
- In-plane dipole due to usual Ohm conduction + out-of-plane dipole due to CME + quadrupole due to CESE and CME in Cu + Au collisions.



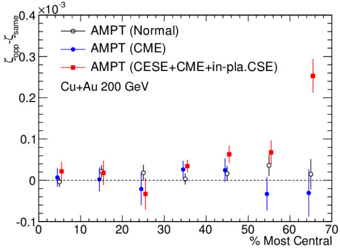
$$f_1(q,\phi) \propto 1 + 2v_1^0\cos(\phi-\psi_1) + 2qd_E\cos(\phi-\psi_E) + 2\chi q d_B\cos(\phi-\psi_B)$$
$$+2v_2^0\cos[2(\phi-\psi_2)] + 2\chi q h_B\cos[2(\phi-\psi_c)] + \text{higher harmonics}$$

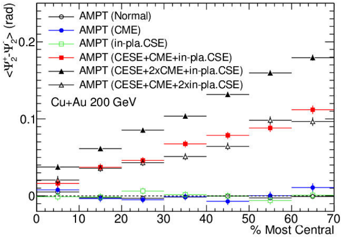
Chiral Electric Separation Effect (V)

- Signals for CESE in Cu + Au: $\zeta_{\alpha\beta} = \langle \cos[2(\phi_\alpha + \phi_\beta - 2\psi_{\rm RP})] \rangle$ and Ψ_2^q (the event-plane for hadrons of charge q).



- $\Delta\zeta = \zeta_{opp} - \zeta_{same}$ and $\Delta\Psi = \langle |\Psi_2^+ - \Psi_2^-| \rangle$ sensitive to CESE, survive final interaction **(Ma and XGH, PRC 91(2015)054901)**





- Possible backgrounds for $\Delta\zeta = \zeta_{opp} - \zeta_{same}$: local charge conservation, chiral magnetic wave. Need more studies.