Estimation of electric conductivity of the QGP via asymmetric heavy-ion collisions

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Abstract

We propose a new way of estimating the electric conductivity of the QGP via asymmetric collisions like Cu-Au collisions. We show that, in off-central Cu+Au collisions, a sizable strength of electric field directed from Au nucleus to Cu nucleus is generated in the overlapping region, because of the difference in the number of electric charges between the two nuclei. This electric field would induce an electric current in the matter created after the collision, which result in a dipole deformation of the charge distribution. The directed flow parameters $v_1^{\pm}$ of charged particles turn out to be sensitive to the charge dipole and provide us with information about electric conductivity of the quark gluon plasma.

Introduction & basic idea

Strong electromagnetic fields in heavy-ion collisions

- Strong magnetic fields in off-central collisions

$$e|\boldsymbol{B}| \sim m_\pi^2 \sim 10^{14}\ \mathrm{T}$$

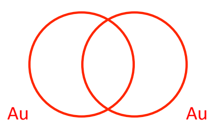
Neutron stars: $10^8\ \mathrm{T}$

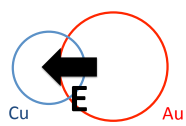
Magnetars: $10^{11}\ \mathrm{T}$

- Strong electric fields also exist

$$e|\boldsymbol{E}| \sim m_\pi^2$$

- In symmetric collisions, electric fields direct randomly
- In asymmetric collisions, electric fields tend the Cu nuclei because of the charge difference btw. Au & Cu nucleus





Number of charges

Cu: 29

Au: 79

Theoretical estimate of the electric conductivity

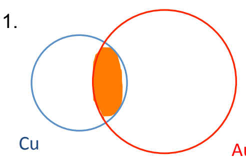
$$\sigma = BC_{\mathrm{EM}}T$$

$C_{\mathrm{EM}} \equiv \sum_f e_f^2$

- Lattice QCD: $B \simeq 0.4$, $B \simeq 7$
- pQCD: $B \sim 10^2$

Basic idea

1.



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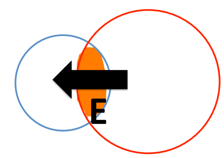

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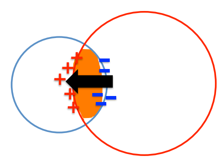


1. QGP is created in the overlapping region of Au & Cu nuclei
2. An electric field that tends the Cu nucleus is applied
3. The charge distribution is modified as a result of charge transport

The magnitude of "charge dipole" reflects the electric conductivity of the QGP!

Analysis

Event-by-event electromagnetic fields in Cu-Au collisions

- Protons inside nuclei produce electromagnetic fields
- Lienard-Wiechert potential

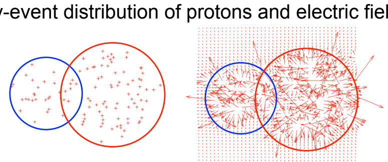
$$|e|\vec{E}(t,\vec{x}) = \alpha_{\mathrm{EM}} \sum_n \frac{1-v_n^2}{R_n^3\left[1-(\vec{R}_n \times \vec{v}_n)^2/R_n^2\right]^{3/2}} \vec{R}_n$$

$$|e|\vec{B}(t,\vec{x}) = \alpha_{\mathrm{EM}} \sum_n \frac{1-v_n^2}{R_n^3\left[1-(\vec{R}_n \times \vec{v}_n)^2/R_n^2\right]^{3/2}} \vec{v}_n \times \vec{R}_n$$

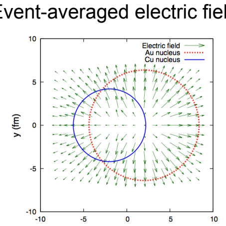
$\vec{R}_n \equiv \vec{x} - \vec{x}_n(t)$

$\vec{x}_n(t)$: positions of protons

- Distributions of protons inside nuclei are sampled from the Woods-Saxon distribution
- Event-by-event distribution of protons and electric field



- Event-averaged electric field



- $b = 4$ fm
- Tendency to direct from Au to Cu
- $e|\boldsymbol{E}| \sim m_\pi^2$

Observable sensitive to the electric conductivity

- Charge-dependent directed flow

$$v_1^{\pm} = v_1 \pm A d'_e$$

$$A \equiv (\bar{N}_+ - \bar{N}_-)/(\bar{N}_+ + \bar{N}_-) \qquad \bar{N}_\pm \equiv \int \frac{d\phi}{2\pi}\frac{dN_\pm}{d\phi}$$

$$d'_e = \frac{1}{\bar{N}_+ - \bar{N}_-}\int r dr d\phi\ \cos\phi \left[j_e^0(r,\phi) - j^0_{e,\vec{E}=\vec{B}=0}(r,\phi)\right]$$

Order-of-magnitude estimate of the value of $v_1^{\pm}$

- Number of transported charges

$$Q = \int_0^\tau dt \int_S \vec{J}\cdot d\vec{S} = \int_0^\tau dt \int_S \sigma\vec{E}\cdot d\vec{S}$$

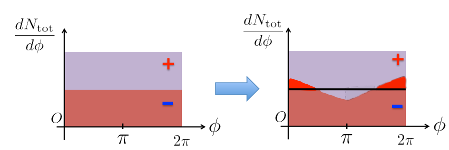
- Neglecting the space-time dependences of the conductivity,

$$Q \sim \sigma\tau \int_S \vec{E}\cdot d\vec{S}$$

electric flux $\sim \frac{Z_{\mathrm{Au}} - Z_{\mathrm{Cu}}}{2}\frac{|e|}{\epsilon}$

- Number of transported charges and Ad'_e

$$\frac{Q}{|e|} = -\frac{1}{2}\int_{-\pi/2}^{\pi/2} d\phi\ \frac{d(N_+ - N_-)}{d\phi} = -2Ad'_e\left(\bar{N}_+ + \bar{N}_-\right)$$

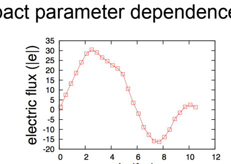


$$Ad'_e \sim -\frac{\sigma\tau}{N_{\mathrm{tot}}|e|}\int_S \vec{E}\cdot d\vec{S} \qquad N_{\mathrm{tot}} \equiv 2\pi\left(\bar{N}_+ + \bar{N}_-\right)$$

- If we choose parameters as $T \sim 200\ \mathrm{MeV}$, $\tau \sim 1\ \mathrm{fm}/c$, $N_{\mathrm{tot}} \sim 10^3$

$$Ad'_e \sim -B \times 10^{-3}$$

- Impact parameter dependence of the electric flux



More quantitative analysis needed!

- charge transport on a hydrodynamic background