MAGNETIC FIELD IN HIC IN Au-Au, Cu-Cu AND ISOBAR COLLISIONS

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March 2, 2016
Introduction

Magnetic field at early stage and evolution

Magnetic field of isobars

Outlook and Conclusions
Magnetic field of hadronic scale, \( eB \sim m_{\pi}^2 \), may be responsible for number of observables

Besides CME/CMW: photon azimuthal anisotropy. Signal is proportional to \( B^2 \cos 2(\Psi_B - \Psi_{PP}) \)

- Synchrotron radiation  

- Conformal Anomaly  

- Chiral anomaly  

- Extension on Conformal Anomaly: dilepton production  
  Ho-Ung Yee, Phys. Rev. D88 (2013) 2, 026001

- Isobars may be crucial to test effect of magnetic field

- Systematical studies are needed

- Most of this talk: magnetic field at \( t = 0 \).
In first approximation, colliding nuclei are two positive charges moving with ultra-relativistic velocities in opposite directions.

Two currents in opposite direction. Magnetic fields of the two sources add up, while electric fields nearly cancel each other.

Out-of-plane direction of magnetic field:
\[ \langle eB_y \rangle \sim m^2 \pi, \quad \langle eB_x \rangle \sim \langle eB_z \rangle \sim 0 \]
\[ \langle eE_x \rangle \sim \langle eE_y \rangle \sim \langle eE_z \rangle \sim 0 \]

Charge distribution in nuclei is not uniform. Lumpy distribution of electric charge in colliding nuclei results in nonzero randomly oriented magnetic field even in central collisions.
Formation of conducting medium may increase magnetic field lifetime

Full 3+1D anomalous hydro + Maxwell equations

For now modification of Maxwell equations: \( \mathbf{j} = \sigma_{\text{Ohm}} \mathbf{E} + \sigma \chi \mathbf{B} \) and switching \( \sigma \)'s at \( t = 0 \)

Little information about \( \sigma \)'s at very early stage, approximated by \( \sigma_{\text{LQCD}} \)

Numerical solution of Maxwell equations with external current defined by participants. Conductivity is switched on at \( t = 0 \) in finite volume.

Conductivity does increase lifetime, but field magnitude is small.

*Talk by K. Tuchin*
Similar result for Milne coordinates \((\tau, x_\perp, \eta)\) and expanding fireball

This is not final conclusion!

Formation of knots of magnetic flux

Assuming non-trivial linking, conservation of helicity results in conservation of total magnetic energy

Power law decay of \(B\): \(t^{-1/2}\) instead of \(t^{-2}\)

Talk by Y. Hirono
Properties of $B$ at initial state

- Magnetic field life time is uncertain
- Nonetheless we still can answer some important questions:
  - How homogeneous is $B$?
  - Direction of $B$ vs direction of reaction plane?
  - Does naive Z scaling holds for system of different sizes?
  - Does nucleus deformation change $B$?
**Definitions**

- Average magnetic field in $y$ direction $\langle B_y \rangle$
- Average magnitude squared $\langle B^2 \rangle$
- Observable related average $O = \langle B^2 \cos[2(\Psi_B - \Psi_{PP})]\rangle$
- For all of above $\int d^2x_\perp$ over $R = 0.25$ fm
- Centrality instead of impact parameter
IMPORTANCE OF CENTRALITY

Talk by J. Liao


V.S. 2016
Calculated at geometrical center of participants

Reminder:

\[ \langle O \rangle = \langle B^2 \cos(2(\Psi_B - \Psi_{PP})) \rangle \]

Expected linear dependence of \( B_y \) on centrality and quadratic dependence of \( \langle O \rangle \) and \( B^2 \)

0-5%: significant contribution of \( B_x \) to magnitude of \( B \)

0-5%: non-zero \( \langle O \rangle \)
**Homogeneity of $B$: $x$ direction**

- How homogeneous $B$ in HIC?
- Consider
  
  $$O(r) = [eB(r)]^2 \cos[2(\Psi_B(r) - \Psi_{PP})]$$

- Correlation function
  
  $$C(r) = N^{-1}\langle \delta O(r)\delta O(0) \rangle$$

- Center is defined by participants
- Correlation length in $x$-direction is about 2.5 fm. Almost independent of centrality.
Homogeneity of $B$: $y$ direction

- Correlation length in $y$-direction is extremely large.
- What does this mean and why is it important?
Sphaleron transitions and directions of $B$

- Assume two regions separated by 2-3 fm contributing to observable
- Same conditions (i.e. winding number)
- Magnetic field, its directions relative to participant plane is strongly correlated
- Signal is double of individual contribution
Sphaleron transitions and directions of $B$

- Decorrelation is significant if the distance larger than 2.5 fm
- Signal is half of individual
**Observables in Au and Cu**

- Naive expectations for observables related to
  \[ \langle O \rangle \propto Z^2 \]

- \( Z_{Au}^2 / Z_{Cu}^2 = 7.4 \)

- Experimental signal for CME observables has different trend:
  \( \gamma_{Cu} > \gamma_{Au} \):

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![Graph](chart.png)
• Charge ratio $Z^2_{Au}/Z^2_{Cu} = 7.4$
• Significant deviation due to difference in nuclei geometry
• Non-monotonous behavior as function of centrality
**Observables in Au and Cu: dilution effect**

- If signal is extracted from two particle correlation function (say $\gamma$'s): dilution effect is inevitable
- Assuming that number of correlated pairs is proportional to total number of particles, dilution brings factor $\kappa/N_{\text{ch}}$
Non-trivial charge dependence in Cu-Cu and Au-Au collisions. Should we worry about isobars?

Consider $A = 96$ and vary $Z$ for fixed centrality.

Isobars of interest $Z = 40$ and 44. Ratio squared 1.21.

MC for $\langle O \rangle$ approximately follows naive scaling!

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**Diagram:**

A graph comparing the ratio of $\langle O \rangle(Z,\%) / \langle O \rangle(Z=35,\%)$ for different centrality bins. The ratio increases with $Z$ and is consistent across different centrality bins, indicating a naive scaling.

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**Further Reading:**

- VSokov@bnl.gov
- B in HIC QCD Workshop 18/23
Isobars Zr and Ru are expected to be deformed

Electron scattering

\[ \beta_2(Zr) = 0.08 \quad \beta_2(Ru) = 0.158 \]

Model calculation

\[ \beta_2(Zr) = 0.217 \quad \beta_2(Ru) = 0.053 \]

Contradicting results.
Is of any significance for $B$?

Centrality classes do not change for different $\beta$ (unless very central events are considered)

$B$ does not vary as well!
Normalized by $B_y^2$ of $Z = 40$ at $0 - 5\%$
**Isobrars: Comparison to Au and Cu**

![Graph showing comparison of isobrars for different elements: Cu, Zr, Ru, and Au. The graph plots \( \langle Q \rangle / \langle N_{ch} \rangle \) against centrality. The data points indicate a trend where the values for Cu and Zr are generally higher than those for Ru and Au.](#)
Conclusions

- At given centrality, naive scaling of magnetic field on $Z$ breaks down for systems with vastly different geometries.
- Dilution effect is significant.
- For systems with same $A$: $B^2 \cos 2(\Psi_B - \Psi_{PR})$ is proportional to $Z^2$. This supports 20% difference in magnetic field related observables for isobars Zr and Ru.
- In wide range of centralities, magnetic field is independent on nuclear deformation.
- $^{96}_{42}Mo$ ?!