STAR probes of local strong parity violation in heavy ion collisions

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Indiana University

Joint CATHIE/RIKEN workshop
BNL, 14-18 December, 2009
Important features of the system created in non-central heavy ion collisions (HIC)

- Overlapped area: non-uniform particle density and pressure gradient

- Large orbital angular momentum:
  \[ L \sim 10^5 \]
  Liang, JPG34:323 (2007)

- Strong magnetic field:
  \[ B \sim 10^{15} \text{ T} \quad (eB \sim 10^4 \text{ MeV}^2) \]
  \[ (\mu_N B \sim 100 \text{ MeV}) \]
  Rafelski, Müller PRL36:517 (1976)
  Kharzeev, McLerran, Warringa
  NPA803:227 (2008)
Particle production in HIC: Asymmetries wrt. the reaction plane

Anisotropic transverse flow

Initial space anisotropy of the overlapped area evolves into momentum space

Strong elliptic and directed flow. Well established collective effects, extensively studied at RHIC/SPS.


Global polarization and spin alignment

Preferential orientation of the spin of produced particles wrt. the system orbital momentum

Experimentally consistent with zero. Measured by STAR for strange hyperons ($\Lambda$, $\bar{\Lambda}$) and vector mesons ($K^*, \phi$).


Local strong parity violation

Charge separation along the magnetic field/orbital momentum

Under experimental study at RHIC. Focus of this talk.
Theoretical concept of P-violation in strong interactions
Localized in space & time solutions. Transitions between different vacua via tunneling/go-over-barrier

Quantum Chromodynamics vacuum (gluonic field energy) is periodic vs. Chern-Simons number, $N_{CS}$:

- **Instanton**
- **Sphaleron**

$N_{CS}$ (generalized coordinate)

Quark interaction changes chirality, which is a $P$ and $T$ odd transition

P/CP invariance are (globally) preserved in strong interactions.

Evidence from neutron EDM (electric dipole moment) experiments:

- Pospelov, Ritz, PRL83:2526 (1999)

$$\theta < 10^{-11}$$

If $\theta \neq 0$, then QCD vacuum breaks $P$ and $CP$ symmetry.

**but:**

In HIC formation of (local) metastable $P$-odd domains is not forbidden.

T.D. Lee, PRD8:1226 (1973)
Kharzeev, Pisarski, Tytgat, PRL81:512 (1998)

Kharzeev, Krasnitz, Venugopalan, PLB545:298 (2002)
Charge separation in HIC

Magnetic field aligns quark spins along or opposite to its direction.

Chirality:

- Left
- Right

- Spin
- Momentum

- Positive charge
- Negative charge

Right-handed quark momentum is opposite to the left-handed one.

Vacuum transitions produce local excess of left/right handed quarks:

\[ N_{\text{left}} \neq N_{\text{right}} \]

Induced electric field (parallel to B):

\[ E \sim \theta \cdot B \]

Positive and negative charges moving opposite to each other \[ \rightarrow \] charge separation in a finite volume.

Kharzeev, Zhitnitsky, NPA797:67 (2007)

Ilya Selyuzhenkov, CATHIE/RIKEN workshop 2009
Why charge asymmetry wrt. the reaction plane is P-violation?

Coordinate/momentum (vectors):
$$\vec{r} \rightarrow -\vec{r} \quad \vec{p} \rightarrow -\vec{p}$$

Orbital momentum/magnetic field (pseudo-vectors):
$$\vec{L} \rightarrow \vec{L} \quad \vec{B} \rightarrow \vec{B}$$
Experimental observable
Azimuthal distribution in case of P-violation

\[
\frac{dN_{\pm}}{d\phi} \sim 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n\Delta \phi) + 2a_{1,\pm} \sin\Delta \phi + \ldots
\]

\(v_n\) \(n\)-harmonic anisotropic transverse flow.

\(a_{1,\pm}\) asymmetry in charged particle production (consider only first harmonic).

\(\Psi_{RP}\) reaction plane (RP) angle

\(\Delta \phi = \phi - \Psi_{RP}\) particle azimuth relative to RP

Predicted asymmetry is about 1% for mid-central collisions

→ within an experimental reach

Observable

- Charge asymmetry is too small to be observed in a single event
- Asymmetry fluctuates event by event. P-odd observable yields zero:
  \[ \langle a_{\pm} \rangle = \langle \sin (\phi_{\pm} - \Psi_{RP}) \rangle = 0 \]

- Study P-even correlations: \( \langle a_{\alpha} a_{\beta} \rangle \ ( \alpha, \beta = \pm ) \)
  Measure the difference between in-plane and out-of-plane correlations:

\[
\langle \cos (\phi_{\alpha} + \phi_{\beta} - 2 \Psi_{RP}) \rangle = \langle \cos \Delta \phi_{\alpha} \cos \Delta \phi_{\beta} \rangle - \langle \sin \Delta \phi_{\alpha} \sin \Delta \phi_{\beta} \rangle =

= \left[ \langle v_{1,\alpha} v_{1,\beta} \rangle + Bg^{(in)} \right] - \left[ \langle a_{\alpha} a_{\beta} \rangle + Bg^{(out)} \right]

\]

- Large RP-independent background correlations cancel out in \( Bg^{(in)} - Bg^{(out)} \)

\( Bg^{(in)}(Bg^{(out)}) \) denotes in- (out-of) plane background correlations

- RP-dependent (P-even) backgrounds contribute:
  \[ \rightarrow Bg^{(in)} - Bg^{(out)} \text{ term} \]
  \[ \rightarrow \langle v_{1,\alpha} v_{1,\beta} \rangle: \text{ directed flow (zero in symmetric rapidity range) + flow fluctuations} \]
Medium effects on charge correlations

P-odd domain formation (no medium)

\[ a_+ = -a_- \]

\[ \langle a_+^2 \rangle = \langle a_-^2 \rangle > 0 \]

\[ \langle a_+ a_- \rangle = -\langle a_+^2 \rangle \]

Quenching in medium

orientation flips event by event

\[ \langle a_+^2 \rangle = \langle a_-^2 \rangle > 0 \]

\[ \langle a_+ a_- \rangle \ll -\langle a_+^2 \rangle \]


Expectations for charge correlations

- Magnitude: \[ a_{\pm} = \pm \frac{4}{\pi} \frac{Q}{N_{\pm}} \]

\[ Q = N_R - N_L \] - topological charge \((Q = \pm 1, \pm 2, \ldots)\)

\(N_{\pm}\) - charged particle multiplicity \(\langle Q \rangle \sim \sqrt{N_{\pm}}\)

For midcentral Au+Au collisions (1 P-odd domain/collision):
\(N_{\pm} \sim 100\) per unit of rapidity \(\rightarrow a_{\pm} \sim 1\%\)

\[ \langle a_{\alpha} a_{\beta} \rangle \sim 10^{-4} \]

- Correlation width in rapidity: about one unit
- Localized at \(p_t < 1\) GeV/c (non-perturbative effect)
- Proportional to the magnetic field: \(a_{\pm} \sim B\)
- Stronger opposite-sign signal for a smaller colliding system (atomic number)

Kharzeev, Zhitnitsky, NPA797:67 (2007)
Measurement technique

- Goal: 2-particle correlations wrt. the reaction plane (RP):
  \[ \langle \cos(\phi_\alpha + \phi_\beta - 2 \Psi_{RP}) \rangle \]

- In experiment RP is unknown
  → estimated from azimuthal distribution of produced particles:
  \[ \langle \cos(\phi_\alpha + \phi_\beta - 2 \Psi_{RP}) \rangle = \langle \cos(\phi_\alpha + \phi_\beta - 2 \phi_c) \rangle / \nu_{2,c} \]
  \( \nu_{2,c} \) - elliptic flow of \( c \)-particle

  Implies: \( c \) and \( (\alpha, \beta) \) particles are correlated only via RP
  → validity needs to be tested experimentally

- Measuring (mixed harmonics) **3-particle azimuthal correlations**:
  \[ \langle \cos(\phi_\alpha + \phi_\beta - 2 \phi_c) \rangle = -\langle a_\alpha a_\beta \rangle \nu_{2,c} + \text{[non-parity correlations]} \]
STAR probes of P-violation
The STAR experiment

**TPC:** $|\eta| < 1.3$

(Time Projection Chamber)

**FTPCs:** $2.9 < |\eta| < 3.9$

(Forward TPC)

**ZDC SMDs:** recoil neutrons at **beam rapidity**

(Zero Degree Calorimeter - Shower Maximum Detector)

**Charged particle cuts:**

- Pseudo-rapidity $|\eta| < 1$
- Transverse momentum $0.15 < p_t < 2$ GeV/c

Data from RHIC running in year 2004/2005

<table>
<thead>
<tr>
<th>System</th>
<th>Energy, $\sqrt{s_{NN}}$</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au+Au</td>
<td>200 / 62 GeV</td>
<td>10.6 / 7 M</td>
</tr>
<tr>
<td>Cu+Cu</td>
<td>200 / 62 GeV</td>
<td>30 / 19 M</td>
</tr>
</tbody>
</table>

**RP reconstruction with TPC, FTPCs and ZDC SMDs**
Detector effects

Acceptance corrections (re-centering):

\[
\sin n \phi \rightarrow \sin n \phi - \langle \sin n \phi \rangle
\]
\[
\cos n \phi \rightarrow \cos n \phi - \langle \cos n \phi \rangle
\]

Poskanzer, Voloshin, PRC58:1671 (1998)

<table>
<thead>
<tr>
<th>symbol</th>
<th>((a, \beta)) charges</th>
<th>c-particle</th>
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</thead>
<tbody>
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<td>opposite sign, (+) (-)</td>
<td>positive</td>
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<td>same sign, (+) (+)</td>
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<td>same sign, (-) (-)</td>
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</table>

- After corrections: consistent results for all charge combinations
- Conclude from a number of tests: 
  \(\rightarrow\) detector effects are not responsible for observed correlations.
Testing sensitivity to 2-particle correlations wrt. RP

\[ \langle \cos (\phi_\alpha + \phi_\beta - 2 \phi_c) \rangle / \nu_{2,c} \]

\[ \langle \cos (\phi_\alpha + \phi_\beta - 2 \phi_c) \rangle \]

Au+Au@200GeV

<table>
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<td>☢️</td>
<td>same sign</td>
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<td>☣️</td>
<td>opposite sign</td>
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<td>☣️</td>
<td>opposite sign</td>
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</table>

\[ \nu_{2,c} \] correction gives consistent result with TPC/FTPC c-particle (similarly ZDC-SMD)

→ Probing 2-particle correlations wrt. RP

• Same- and opposite-sign correlations consistent with P-violation
Modeling physics backgrounds

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_{2,c} \]

<table>
<thead>
<tr>
<th>symbol</th>
<th>model</th>
<th>c-particle</th>
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<tr>
<td>▼</td>
<td>HIJING</td>
<td>true reaction plane</td>
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<tr>
<td>△</td>
<td>HIJING + (v_2)</td>
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<td>■</td>
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\(\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_{2,c} \)

\(v_{2,c}\) correction systematics

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Note: cluster production is not well modeled by event generators

- Non-zero background correlations, but different from observed signal
- HIJING produce data-like opposite-sign 3-particle correlations:
  \(\rightarrow\) opposite-sign signal can be diluted by effects not related to RP orientation
Pseudo-rapidity and transverse momentum dependence

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2 \Psi_{RP}) \rangle \]

Typical “hadronic” width.
Consistent with P-violation

\[ \left| \eta_\alpha - \eta_\beta \right| \]

\[ \left[ p_{t,\alpha} + p_{t,\beta} \right]/2 \]

The signal extends to higher transverse momenta?

**Au+Au@200GeV**
Centrality: 30-50%
Energy and system size dependence

\[ \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \]

**@ 200 GeV**

**@ 62 GeV**

### Opposite sign correlations:

Stronger for a smaller (Cu+Cu) system. In agreement with P-violation, but large uncertainties due to possible RP-independent correlations.

### \( \nu_{2,c} \) correction systematics
Summary

- local P-odd domains predicted in nuclear collisions:  
  → charge separation along the system’s orbital momentum

- 3-particle azimuthal correlations are sensitive to local P-violation:  
  → STAR measurements reveal non-zero signal

  *Published 12/14/2009 in* PRL: 103, 251601 (2009)  
  *Details submitted to* PRC: 0909.1717 [nucl-ex]

- Observable is P-even:  
  susceptible to contributions from P-conserving backgrounds

- So far could not explain the same sign correlations.  
  Signal can not be described with existing background models.

- Qualitatively data agrees with predictions for local P-violation  
  (though the signal persists to higher $p_t$ than expected)

  Detailed calculations for the  
  P-violating signal and backgrounds are needed

- P-violation and future RHIC program:  
  Critical point search (beam energy scan),  
  Identified particle correlations, isobaric beams.
"Physics" viewpoint by Berndt Müller

Viewpoint

Physics 2, 164 (2009)
DOI: 10.1103/Physics.2.164

Looking for parity violation in heavy-ion collisions

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Published December 14, 2009

The STAR detector at RHIC has measured a signal that may indicate parity violation occurs in metastable regions of the superdense matter.

A Viewpoint on:
Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation
B. I. Anisov et al.
Download PDF (Free)

Article is available at http://physics.aps.org/articles/v2/104

When two heavy nuclei collide at high energy, they create strongly interacting matter at energy densities far above that of normal nuclei. This has been the route for creating new phases of matter composed of quarks and gluons for almost a decade at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in the US. The measurements performed on collisions between two gold (Au - Au) or two copper (Cu - Cu) nuclei or between two protons (p - p), with center-of-mass energies up to 200 GeV per nucleon pair, have shown that superdense, strongly interacting matter has an extraordinarily low shear viscosity (compared to its entropy) and is extremely opaque with respect to unbound quarks and gluons. [1 , 2]

Now, writing in Physical Review Letters, the STAR collaboration, whose detector is based at RHIC, reports results that may constitute evidence for the violation of parity—a fundamental symmetry that says that the physics of a system and its mirror image should be the same—in local domains of hot, strongly interacting matter [3]. Although the theory of quantum chromodynamics (QCD), which governs the strong interactions, does permit parity violation, experiments have so far put stringent limits on its presence.

Collisions between heavy nuclei produce some of the strongest magnetic fields that can be generated under laboratory conditions [4]. The moving nucleus generates a coherent magnetic field that, being long-lived, acts as an "external" field on the quarks and gluons that make up the nucleus. Interesting effects arise when the magnetic field breaks the natural symmetries of the strong interaction between quarks. Magnetic fields are "odd" under time reversal—a charge moving backward in time creates a field in the opposite direction to the forward moving charge—and the presence of a magnetic field breaks time reversal symmetry in a quantum system. This aspect has been widely employed in the study of quantum chaos and has found many applications in condensed matter physics, such as in the quantum Hall effect.

Experimentally, the strong interactions respect space and time reflection symmetry to a very high degree: this has been established by precise experiments that set limits on the anomalous electric dipole moment (EDM) of the neutron [5]. Yet the equations of QCD permit terms that violate...
Backup slides
Results with ZDC SMD and two particle correlations

\[ \langle \cos (\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \]

\[ \langle \cos (\phi_\alpha - \phi_\beta) \rangle = \langle \cos \Delta \phi_\alpha \cos \Delta \phi_\beta \rangle + \langle \sin \Delta \phi_\alpha \sin \Delta \phi_\beta \rangle \]

\[ \Delta \phi_{\alpha,\beta} = \phi_{\alpha,\beta} - \Psi_{RP} \]

Correlations with (first harmonic)
ZDC-SMD event plane from recent 2007 data yield
similar result to TPC/FTPC

STAR AuAu 200 GeV
- recentering, FF
- recentering, RFF
- no recent., FF
- no recent., RFF

ArXiv:0909.1717 [nucl-ex]

STAR Preliminary: ZDC SMD, y2007

Physics backgrounds

Reaction plane (RP) dependent:

- Directed flow (vanishes in symmetric eta-range), flow fluctuations:

\[ \langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\phi_{c}) \rangle_{flow} = \langle v_{1,\alpha} v_{1,\beta} \rangle v_{2,c} \]

- Global polarization (zero from measurement)

- RP dependent fragmentation ("flowing clusters"):

\[ \langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\Psi_{RP}) \rangle_{clust} = A_{clust} \langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\phi_{clust}) \rangle_{clust} v_{2,clust} \]

RP independent 3-particle correlations:

Can be removed by better RP determination
Different multiplicity scaling \(1/N_{ch}^2\) compared to P-violation

- Jet fragmentation, resonances, multi-particle clusters

- HBT, Coulomb effects, etc.
Detector effects study

- Track momenta distortions due to the charge buildup in the TPC at high accelerator luminosity
  → *Results for low/high luminosity runs are consistent*

- Dependence on reconstructed position of the collision vertex
  → *No vertex dependence found*

- Displacement of track hits when it passes the TPC central membrane
  → *Results from different half-barrels of the TPC are consistent*

- Feed-down effects from non-primary tracks (i.e. resonance decay daughters)
  → *Results for dca < 1 cm and dca < 3 cm are consistent*

- Electron contribution checked via dE/dx cut
  → *Effect is negligible*

- Studied a correlator similar to parity observable
  → *but with the reaction plane angle rotated by π/4*

- Variation depending on the charge of the third particle used to reconstruct the reaction plane and changes of the STAR magnetic field polarity
  → *Variations does not change the observed signal*
Charge correlations and $N_{\text{part}}$ scaling @200GeV

Correlations multiplied by $N_{\text{part}}$ to remove dilution in more central collisions

Opp-sign correlations scale with $N_{\text{part}}$

Same sign signal is suggestive of correlations with the reaction plane

Stronger opposite charge correlations in Cu+Cu at the same $N_{\text{part}}$

<table>
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3-particle HIJING