Experimental study of local strong parity violation in relativistic nuclear collisions

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Abstract

Parity-odd domains, corresponding to non-trivial topological solutions of the QCD vacuum, might be created in relativistic heavy ions collisions. These domains are predicted to lead to charge separation along the system orbital momentum of the system created in non-central collisions. Three-particle mixed harmonics azimuthal correlator is a $\mathcal{P}$-even observable but directly sensitive to the charge separation effect. Using this observable to analyze Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ and 62 GeV, STAR detects a signal consistent with several of the theoretical expectations. Possible contributions from effects not related to parity violation are studied with existing event generators, which fail to describe the data. Future directions in studying the effect are discussed.

1. Introduction. Quantum Chromodynamics (QCD) is the theory of strong interactions. Perturbative QCD is firmly established and thoroughly tested experimentally. In the non-perturbative sector, QCD links chiral symmetry breaking and the origin of hadron masses to the existence of topologically non-trivial classical solutions describing the transitions between the vacuum states with different Chern-Simons numbers. Quark interactions with topologically non-trivial classical gluonic fields change the quark helicity and are $\mathcal{P}$ and $\mathcal{CP}$ odd. It was suggested in [1] that metastable $\mathcal{P}$ and $\mathcal{CP}$ odd domains, characterized by non-zero topological charge, might be created in ultra-relativistic heavy ion collisions. The possibility for an experimental detection of this local strong parity violation was discussed in [1, 2, 3]. More recently, it was noticed [4, 5] that in non-central collisions such domains can demonstrate themselves via the asymmetry in the emission of charged particle w.r.t. the system’s angular momentum. Such charge separation is a consequence of the difference in the number of particles with positive and negative helicities positioned in the strong magnetic field ($\sim 10^{15}$ T) of a non-central nuclear collision [4, 6], the so-called chiral magnetic effect. The same phenomenon can also be described in terms of the induced electric field that is parallel to the static external magnetic field, which occurs in the presence of topologically non-trivial vacuum solutions [7].

Since the direction of the separation may vary event by event in accord with the changing sign of the topological charge of the domain, the observation of the effect is possible only by correlation techniques. Such an observable, $\mathcal{P}$-even, but directly sensitive to the charge separation effect, has been proposed in [8] and is based on 3-particle mixed harmonics azimuthal correlations.

Phenomenologically, the charge separation can be described by adding a $\mathcal{P}$-odd sine term to the Fourier decomposition of the particle azimuthal distribution with respect to the reaction plane.
angle, $\mathcal{P}_{RP}$, which is often used in the description of anisotropic flow $[3]$:  
\[
\frac{dN_\alpha}{d\phi} \propto 1 + 2v_1 \cos(\Delta\phi) + 2v_2 \cos(2\Delta\phi) + ... + 2a_\alpha \sin(\Delta\phi) + ... ,
\]  
where $\Delta\phi = (\phi - \mathcal{P}_{RP})$ is the particle azimuth relative to the reaction plane, $v_1$ and $v_2$ account for directed and elliptic flow. Parameters $a_\alpha = -a_\beta$ describe the $\mathcal{P}$-violating effect. The sign of $a_\alpha$ varies event to event following the fluctuations in the domain’s topological charge, and on average is zero. $\langle a_\alpha \rangle = 0$. The observation of the effect is possible via correlations, e.g. $\langle a_\alpha a_\beta \rangle$, where $\alpha$ and $\beta$ denote the particle type. To measure $\langle a_\alpha a_\beta \rangle$, it was proposed $[3]$ to use the correlator:

\[
\langle \cos(\phi_\alpha + \phi_\beta - 2\mathcal{P}_{RP}) \rangle = \langle \cos(\Lambda\phi_\alpha \cos(\Lambda\phi_\beta) - \sin(\Lambda\phi_\alpha \sin(\Lambda\phi_\beta)
\]

\[
= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in}] - [\langle a_\alpha a_\beta \rangle + B_{out}] \approx -\langle a_\alpha a_\beta \rangle + [B_{in} - B_{out}].
\]

This correlator represents the difference between correlations projected onto an axis in the reaction plane and the correlations projected onto an axis perpendicular to the reaction plane. The key advantage of using such a difference is that it removes all the correlations among particles $\alpha$ and $\beta$ that are not related to the reaction plane orientation $[9, 10]$. Only the parts of such correlations that depend on azimuthal orientation with respect to the reaction plane remain as backgrounds, denoted as $[B_{out} - B_{in}]$. Note that the contribution given by the term $\langle v_{1,\alpha} v_{1,\beta} \rangle$ can be neglected because directed flow averages to zero in a rapidity region symmetric with respect to mid-rapidity, as used in this analysis.

According to Refs. $[4, 5, 6]$ one expects the following features of the correlator $\langle a_\alpha a_\beta \rangle$:

- **Magnitude**: Estimates $[4]$ predicted a signal $|a| \sim N/Q_{\mathcal{P}}$, where $Q = 0, \pm 1, \pm 2, ...$ is the topological charge and $N_{\mathcal{P}}$ is the positive pion multiplicity in one unit of rapidity – the typical scale of such correlations. More accurate estimates $[5]$ including the strength of the magnetic field and topological domains production rates, were found to be close to the same number, of the order of $10^{-2}$ for mid-central collisions at top RHIC energies, which corresponds to $10^{-4}$ for the correlator $\langle a_\alpha a_\beta \rangle$.

- **Charge combinations**: In the absence of medium effects, one expects $\langle a_\alpha a_\alpha \rangle = \langle a_\alpha a_\beta \rangle = \langle a_\beta a_\alpha \rangle = \langle a_\beta a_\beta \rangle$ to be of the order unity.

- **Centrality dependence**: The correlator is expected to follow a $1/N$ dependence (typical for any kind of correlations due to clusters; $N$ is the multiplicity) multiplied by a factor accounting for the variation of the magnetic field. Thus at large centralities the effect should decrease with centrality somewhat faster than $1/N$.

- **Rapidity dependence**: The correlated particles come from a domain of the order of 1 fm, and it is expected that the correlations would have a typical hadronic width in $\Delta \eta = |\eta_\alpha - \eta_\beta|$ of the order unity.

- **Transverse momentum dependence**: Local parity violation is non-perturbative in nature and one would expect the main contribution to the signal at $p_T \lesssim 1$ GeV/$c$, but the actual limits might be affected by the radial flow.
• **Beam species dependence:** The effect should be proportional to the square \( Z^2 \) of the nuclear charge, but the atomic number \( A \) dependence is not well understood. The suppression of the back-to-back correlations should be smaller in collisions of lighter nuclei.

• **Collision energy dependence:** The effect might be stronger at lower energies, as the time integral of the magnetic field is larger. At the same time, the charge separation effect is expected to depend strongly on deconfinement and chiral symmetry restoration [6], and the signal might be greatly suppressed or completely absent at an energy below that at which a quark-gluon plasma can be formed.

### 2. Data.

The results are based on 14.7M Au+Au and 13.9M Cu+Cu events at \( \sqrt{s_{NN}} = 200 \) GeV, and 2.4M Au+Au and 6.3M Cu+Cu events at \( \sqrt{s_{NN}} = 62 \) GeV recorded with the STAR detector [11] at RHIC. Charged particle tracks were reconstructed in a Time Projection Chamber (TPC), |\( \eta \)| < 1.0, operated in a solenoidal magnetic field of 0.5 T. The main TPC is supplemented by two Forward TPCs, which cover pseudorapidity intervals 2.7 < |\( \eta \)| < 3.9. A minimum bias trigger was used during data-taking. The centrality of the collision is determined according to the recorded multiplicity of charged particles in |\( \eta \)| < 0.5. The correlations are reported for charged particle in the region |\( \eta \)| < 1.0 with \( p_t > 0.15 \) GeV/c. The results integrated over transverse momentum have a cut of \( p_t < 2 \) GeV/c.

### 3. Method.

In the three-particle correlation technique, used in this analysis, the role of the event plane is played by the third particle that enters the correlator with double the azimuth [10, 12]. Under the assumption that particle \( c \) is correlated with particles \( \alpha \) and \( \beta \) only via common correlation to the reaction plane, one has:

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

where \( v_{2,c} \) is the elliptic flow value of the particle \( c \). We check this assumption by using particles \( c \) from different detectors that exhibit different elliptic flow. Figure 1 compares the three-particle correlator divided by \( v_{2,c} \), when the third particle is selected from the main TPC with those when it is selected from the Forward TPCs, where elliptic flow is significantly smaller [13]. The shaded bands in Fig. 1 and below illustrate the systematic error due to uncertainty in \( v_2 \) measurements.

![Figure 1](image-url)
The upper (in magnitude) limit is obtained with \( v_2(4) \) and the lower limit from \( v_2(2) \), the midpoint is calculated using \( v_2(FTPC) \) \cite{13, 14}. Whenever \( v_2(4) \) values are not available the upper limits are obtained assuming that the measurements with FTPC suppress only 50% of the non-flow contribution.

A very good agreement between the same charge correlations in Fig. 1 justifies the assumption Eq. 3. But the opposite charge correlations are too small in magnitude to conclude on validity of the factorization. Similarly, in the most peripheral collisions, the statistical errors are large, which also prohibits making a definite conclusion. In these cases, the factorization can be broken due to contribution of three-particle clusters, which we estimate with the help of event generators. We proceed below assuming \( \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{RP}) \rangle = \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_2, \) but indicate in all plots the HIJING \cite{15} direct three-particle correlation results. The latter can be considered as an estimate of the systematic uncertainty from correlations not related to the reaction plane. (Using the event generator UrQMD yields both opposite-charge and same-charge correlations at least a factor of two lower than those predicted by HIJING.) Note that in principle such uncertainty can be suppressed by taking particle \( c \) farther in rapidity from the particles \( \alpha \) and \( \beta \).

4. Results. Figure 2 presents the correlator \( \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{RP}) \rangle \) for Au+Au and Cu+Cu collisions at \( \sqrt{s_{NN}}=200 \text{ GeV} \). \((+,+\)\) and \((-,-\)\) correlations are found to be the same within statistical errors and are combined together as same-charge correlations. Opposite-charge correlations are relatively smaller than same-charge correlations. This observation led to the proposal that back-to-back correlations may be suppressed due to the opacity of the medium as discussed in the introduction. The difference in magnitude between same and opposite sign correlations is considerably smaller in Cu+Cu than in Au+Au, qualitatively in agreement with the scenario of stronger suppression of the back-to-back correlations in Au+Au collisions. In Fig. 2 and below, error bars show the statistical errors. Note again that presenting the results in this section we assume the factorization of correlator, Eq. 3. The possible error due to this assumption is denoted by the thick lines in Figs. 2 and subsequent figures. Figure 2 shows results for collisions at \( \sqrt{s_{NN}}=62.4 \text{ GeV} \). The signal is similar in magnitude, with slightly more pronounced opposite-charge correlations compared to those at \( \sqrt{s_{NN}}=200 \text{ GeV} \). This is consistent with weaker suppression of opposite-charge correlations in the less dense 62 GeV system.

The correlations are weaker in more central collisions compared to more peripheral collisions, which partially can be attributed to dilution of correlations which occurs in the case of particle production from multiple sources. The somewhat stronger correlations in Cu+Cu collisions than in Au+Au for the same centrality also may have similar explanation. To compensate for the dilution effect we show in Fig. 3 results multiplied by the number of participants. The decrease of the correlations in most central collisions is expected as the magnetic field weakens. The same and opposite sign correlations clearly exhibit very different behavior. The opposite sign correlations in Au+Au and Cu+Cu collisions are found to be very close at similar values of \( N_{part} \) in rough qualitative agreement with the picture in which their values are mostly determined by the suppression of back-to-back correlations.

Figure 4 shows the dependence of the signal on the difference in pseudorapidities of two particles, \( \Delta \eta = |\eta_\alpha - \eta_\beta| \), for 30-50% centrality. The signal has a typical hadronic width of about one unit of pseudorapidity. Figure 4 shows the dependence of the signal on the sum of the transverse momentum (magnitudes) of the two particles for these same centralities. The signal is not concentrated in the low \( p_t \) region as naively might be expected for \( P \)-violation effects. We find also that the correlation depends very weakly on \( |p_{t,\alpha} - p_{t,\beta}| \) (not shown). This excludes
Figure 2: $\langle \cos(\phi_a + \phi_\beta - 2\Psi_{R/P}) \rangle$ in Au+Au and Cu+Cu collisions at (a) $\sqrt{s_{NN}} = 200$ GeV and (b) $\sqrt{s_{NN}} = 62$ GeV. Thick solid (Au+Au) and dashed (Cu+Cu) lines represent possible non-reaction-plane dependent contribution from many-particle clusters as estimated by HIJING.

Figure 3: Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}=200$ GeV. The correlations are scaled with the number of participants and shown as a function number of participants. Thick lines as in Fig. 2.
quantum interference or Coulomb effects as possible explanations for the signal. There are no specific theoretical predictions on this dependence, though naively one would expect that the signal should not extend to large values of $|p_t,\alpha - p_t,\beta|$.

5. Physics background. The correlator $\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$ is a $P$-even observable and can exhibit a non-zero signal for effects not related to $P$-violation. Among those are processes in which particles $\alpha$ and $\beta$ are products of a cluster (e.g. resonance, jet, di-jets) decay, and the cluster itself exhibits elliptic flow [10] or decays (fragments) differently when emitted in-plane compared to out-of-plane. If “flowing clusters” are the only contribution to the correlator, one can write:

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \frac{N_{\text{clus, event}} N_{\text{pairs, event}}}{N_{\text{pairs, event}}} \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{\text{clus}}) \rangle_{\text{clus, v2,clus}},$$

(5)

where $\langle \ldots \rangle_{\text{clus}}$ indicates that the average is performed only over pairs consisting of two daughters from the same cluster. Estimates of the contribution of “flowing resonances”, based on Eq. 5 and reasonable values of resonance abundances and values of elliptic flow, indicate that they should not produce a fake signal.

To study the background contribution in greater detail we used event generators MEVSIM [16], UrQMD [17] and HIJING [15]. The results are presented in Fig. 5. MEVSIM includes only correlations due to elliptic flow and resonance ($\phi, A, \rho, \omega,$ and $K^*$) decay. HIJING is also run with an added “afterburner” to add elliptic flow as experimentally observed. No generator gives qualitative agreement with the data; the model values of $\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$ are significantly smaller in magnitude than what is seen in the data, and the correlations calculated in these models tend to be very similar for same and opposite sign correlations. In Fig. 5, UrQMD points are connected by dashed lines to illustrate that the “reference line” for strong parity correlations might be not at zero.

Here, we also mention that such effects as directed flow fluctuations and global polarization [20, 21] should not have any significant contribution to the measurements.
6. Future directions. Taking into account the importance of the question, one can envision a dedicated program for establishing the nature of the signal and further detail study. From the theoretical point of view, the calculation of the dependence on centrality and system system size looks fully doable though requires significant computing and man power (e.g. 3d hydrodynamics is needed for the calculation of the magnetic field). Detailed predictions on the transverse momentum and particle type dependence of the effect also will be essential in differentiating it from possible “background” contributions. A good theoretical understanding of the “background” correlations itself is also required, as at present all event generators lack a good description of correlation results.

A number of future experiments and analyses are naturally suggested by STAR results. One of them is the dependence of the signal on the energy of the colliding ions, which can be addressed, for example, during the RHIC beam energy scan. The charge separation effect is expected to depend strongly on the formation of a quark-gluon plasma [6], and the signal might be greatly suppressed or completely absent at an energy below that at which a quark-gluon plasma can be formed. Identified and multiparticle correlations studies also will be available with larger statistics. Those will be important to test a specific predictions, e.g. such as topological cluster decays in equal number of $q\bar{q}$-pairs of all flavors. The charge separation dependence on the magnetic field [6] can be tested with collision of isobaric nuclei, such as $^{96}_{44}$Ru and $^{96}_{40}$Zr that were used at GSI [22]. Collision of isobaric nuclei will be also very interesting in relation to the directed flow studies (in the latter case one needs asymmetric collisions).

Correlation measurements from RHIC [19] and earlier measurements at ISR (see review [19]) indicate that cluster formation plays an important role in multiparticle production at high energies. These clusters, with a size inferred in [18] to be 2.5–3 charged particles per cluster, may account for production of a significant fraction of all particles. It will be interesting and important to establish how these clusters are related to the topological clusters as suggested in [23] and [24] (“turning points”). Note recent progress in describing of the soft Pomeron as a multi-instanton ladder [25], which also suggests an important role played in multiparticle production.
by topologically nontrivial gluonic configurations.

7. Summary. Charge separation due to quark interaction with topologically non-trivial gluonic configurations in a strong magnetic field of non-central heavy ion collision may provide a unique opportunity for a direct observation of the topological structure of QCD. The predictions are well within reach of the experiment. STAR has performed analysis of \( \text{Au} + \text{Au} \) and \( \text{Cu} + \text{Cu} \) collisions at \( \sqrt{s_{NN}} = 200 \) and 62 GeV using three-particle correlations that are directly sensitive to the local \( P \)-violation effects in heavy-ion collisions. The results are reported for different particle charge combinations as a function of collision centrality, particle separation in pseudorapidity, and particle transverse momentum. Qualitatively the results agree with the magnitude and gross features of the theoretical predictions for local \( P \)-violation in heavy-ion collisions, but the signal persists to higher transverse momenta than expected \[6\]. The particular observable used in the analysis is \( P \)-even and might be sensitive to non-parity-violating effects. None of the studies we have performed so far have revealed a background source that can explain the observed same-sign correlations.

Better theoretical calculations of the expected signal and potential physics backgrounds in high energy heavy-ion collisions are essential for confirmation and experimental study of this phenomenon.

A very exciting future program dedicated to detail study of the effect is emerging.

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References

[1] D. Kharzeev, R. D. Pisarski and M. H. G. T"ytgat, Phys. Rev. Lett. 81, 512 (1998) [arXiv:hep-ph/9804221].
[2] D. Kharzeev and R.D. Pisarski, Phys. Rev. D 61, 111901 (2000).
[3] S. A. Voloshin, Phys. Rev. C 62, 044901 (2000).
[4] L. E. Finch, A. Chikanian, R. S. Longacre, J. Sandweiss and J. H. Thomas, Phys. Rev. C 65, 014908 (2001).
[5] D. Kharzeev, Phys. Lett. B 633, 260 (2006).
[6] D. Kharzeev and A. Zhitnitsky, Nucl. Phys. A 797, 67 (2007).
[7] D. Kharzeev, L. D. McLerran and H. J. Warringa, Nucl. Phys. A 803, 227 (2008).
[8] J. Fukushima, D. E. Kharzeev and H. J. Warringa, Phys. Rev. D 78, 074033 (2008).
[9] S. A. Voloshin, Phys. Rev. C 70, 057901 (2004).
[10] N. Borghini, P. M. Dinh and J. Y. Ollitrault, Phys. Rev. C 66, 014905 (2002).
[11] J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 92, 062301 (2004) [arXiv:nucl-ex/0310029].
[12] K. H. Ackermann et al. [STAR Collaboration], Nucl. Instrum. Meth. A 499, 624 (2003).
[13] S. A. Voloshin, A. M. Poskanzer and R. Snellings [arXiv:0809.2949] [nucl-ex].
[14] J. Adams et al. [STAR Collaboration], Phys. Rev. C 72, 014904 (2005) [arXiv:nucl-ex/0409033].
[15] M. Gyulassy and X.-N. Wang, Comput. Phys. Commun. 83, 307 (1994); X.N. Wang and M. Gyulassy, Phys. Rev. D 44, 3501 (1991).
[16] R. L. Ray and R. S. Longacre, [arXiv:nucl-ex/0008009].
[17] S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998) [Prog. Part. Nucl. Phys. 41, 225 (1998)].
[18] B. Alver et al. [PHOBOS Collaboration], Phys. Rev. C 75, 054913 (2007).
[19] L. Foa, Phys. Rept. 22, 1 (1975).
[20] Z. T. Liang and X. N. Wang, Phys. Rev. Lett. 94, 102301 (2005).
[21] S. A. Voloshin, [arXiv:nucl-th/0410089].
[22] B. Hong [FOPI Collaboration], Phys. Rev. C 66, 034901 (2002); Nucl. Phys. A 721, 317 (2003).
[23] D. Kharzeev, A. Krasnitz and R. Venugopalan, Phys. Lett. B 545, 298 (2002) [arXiv:hep-ph/0109253].
[24] D. M. Ostrovsky, G. W. Carter and E. V. Shuryak, Phys. Rev. D 66, 036004 (2002) [arXiv:hep-ph/0204224].
[25] D. E. Kharzeev, Y. V. Kovchegov and E. Levin, Nucl. Phys. A 690, 621 (2001) [arXiv:hep-ph/0007182].