Particle correlators and possible local parity violation in nuclear collisions

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Abstract. The complex topology structure of the vacuum of quantum chromodynamics (QCD) can lead to local violation of the $P=CP$ invariance of strong interactions. The preliminary estimations of magnetic field and correlators within the model of chiral magnetic effect are presented for types of nuclei and collision energies corresponded to RHIC and the LHC beams. These correlators characterized the asymmetry of the emission of charged particles with respect to the reaction plane in non-central nucleus-nucleus collisions are calculated for two various nuclear densities, namely, for approach of rigid sphere and for two-component Fermi model. The centrality dependence is under consideration for correlators integrated over other kinematic parameters. The correlator magnitudes depend on collision energy weakly for Cu + Cu and Au + Au collisions. The same-charge correlator shows noticeable increasing with growth of atomic number for symmetric collisions. Also magnetic field and centrality dependence of correlator are obtained for asymmetric Cu + Au collisions.

1. Introduction
The Lagrangian of QCD contains natural terms that can break the $P=CP$ symmetry [1]. But the experimental data show us the global $P=CP$ symmetry conservation in the strong interactions that means the $P=CP$ breaking terms should be close to zero (fine-tuned problem). There is a fundamental connection between geometry and fundamental properties of QCD Lagrangian. The vacuum of QCD is a very complicated matter with rich structure, which can corresponds to the fractal-like geometry [2]. At zero temperature, transition between metastable domains of QCD vacuum which possess of various properties with respect to the $P=CP$ symmetries is the tunneling through a potential barrier [3] but at finite temperatures such transitions can be classical called also sphalerons [4]. In the last case, the temperature of the physical system should be larger than the typical energy of sphaleron in QCD $\Lambda_{QCD} \approx 0.2$ GeV [5].

In the presence of background Abelian electromagnetic field the sphalerons and / or decays of metastable domains of QCD vacuum can lead to the separation of secondary charged particles toward the magnetic field. This phenomenon called also chiral magnetic effect (CME) [6] is the experimental manifestation of the local topologically induced $P=CP$ parity violation in the strong interactions.

2. Magnetic field in heavy-ion collisions
The magnetic field for nucleus-nucleus collisions can be obtained, for instance, using the Lienard–Wiechert potentials. This approach is described in detail elsewhere [6]. In the paper the...
**Figure 1.** Dependence of the strength of magnetic field on proper time in nucleus-nucleus collisions at the origin ($x'_\perp = 0$) and central pseudorapidity ($\eta = 0$): $Au + Au$ at $\sqrt{s_{NN}} = 200$ GeV, $Cu + Cu$ at $\sqrt{s_{NN}} = 200$ GeV, $Cu + Au$ at $\sqrt{s_{NN}} = 200$ GeV, $Pb + Pb$ at $\sqrt{s_{NN}} = 200$ GeV, $Cu + Au$ at $\sqrt{s_{NN}} = 200$ GeV, and $Pb + Pb$ at $\sqrt{s_{NN}} = 200$ GeV. The solid lines show $eB(\tau)$ for central collisions, dashed lines – for mid-central, dotted lines – for peripheral. Thin lines correspond to the limit case of the rigid sphere, thick lines – to the Fermi parametrization.

The strength of the magnetic field ($eB$) in collisions of various ion beams is compared for two parameterizations of nuclear density, namely, the sphere with sharp boundary, i.e. rigid sphere [6] and the following equation within the framework of two-component Fermi model

$$\rho_i^F(x'_\perp) \propto \varepsilon[1 + \exp(-\varepsilon/a)]^{-1} \theta_i(\varepsilon^2), \quad \varepsilon(x'_\perp) \equiv \sqrt{R_i^2 - [x'_\perp \pm b/2 \mp (R_i^2 - R_i^2) e_\perp / 26]}^2$$  \tag{1}$$

Here $b$ is the impact parameter, $R_i$ – the radius of the nucleus moved along of the $z$-axis in the positive ($i = 1$) and negative ($i = 2$) directions, $a$ is the cutoff factor, $\kappa_i \equiv R_i/a$, the nuclear densities are normalized to unit as well in [6]. It would be stressed that the Eq. (1) is valid for asymmetric, in general case, nucleus-nucleus collisions. The strength of Abelian magnetic field is studied for two parameterizations of nuclear density for wide set of nucleus-nucleus collisions at RHIC and the LHC energies ($\sqrt{s_{NN}}$), namely, for $Cu + Cu$ at $\sqrt{s_{NN}} = 22.6$, $Cu + Au$ at $\sqrt{s_{NN}} = 200$ GeV, $Pb + Pb$ at $\sqrt{s_{NN}} = 200$ GeV, $U + U$ at $\sqrt{s_{NN}} = 193$ GeV. The preliminary $eB$ dependence on proper time ($\tau$) obtained for several collision types and $\sqrt{s_{NN}}$ is shown in Fig. 1 for central ($b/R = 0.7$), mid-central ($b/R = 1.15$) and peripheral ($b/R = 2.0$) interactions. At large $\tau$ as expected in accordance with...
the $eB$ increases significantly with the decrease of the collision energy in both the $Au + Au$ (Fig. 1a, b) and the $Cu + Cu$ (Fig. 1c, d) with opposite behaviour of peak $eB$ values at very small $\tau$. The $eB$ shows the much more sharper decrease for $Pb + Pb$ collisions at the LHC energy for small $\tau$ (Fig. 1f) than that for highest RHIC energy $\sqrt{s_{NN}} = 200$ GeV. As seen the transition from the simplest case of the rigid sphere to the more realistic Fermi distribution for nuclear density leads to some decrease of the strength of magnetic field especially for RHIC energies.

3. Correlators of the charged particles

In the framework of CME model the theoretical correlator is given by [7, 8]

$$\langle K_{\alpha\beta}^T \rangle = \frac{\pi^2}{16} \frac{\langle \Delta_\alpha \Delta_\beta \rangle}{\langle N_\alpha N_\beta \rangle} = \kappa \alpha_s \left( \frac{\pi R}{2} \sum_f q_f^2 \right)^2 \int \frac{d^2 x_\perp}{S_{\perp}} \int_{\tau_0} \tau_f d\tau [eB(\eta, \tau)]^2. \quad (2)$$

Here $\varepsilon_{\pm \pm} = -0.5, \xi_{\pm \pm} = 0.5, \xi_{\pm}(x_\perp, \lambda) = \sum_i \xi_i(x_\perp, \lambda), \xi_{\pm}(x_\perp, \lambda) = \prod_i \xi_i(x_\perp, \lambda), \alpha_s$ – renormalized strong coupling constant, $N_\alpha$ – multiplicity of particles with electric charge sign $\alpha$ in event, $q_f$ – electric charge (in units of $e$) of quark with flavor $f$, $\Delta_\alpha$ is the difference between total charges with fixed sign $\alpha$ on each side of the reaction plane, numerical coefficient $\kappa \sim 1$, $x_\perp$ – position of nucleon from one of the colliding nuclei in the plane perpendicular to the beam axis, $S_{\perp}$ – area of overlap region of colliding nuclei in the transverse plane, functions $\xi_{\pm}(x_\perp, \lambda)$ take into account the suppression effect via screening length $\lambda$ [6]. The correlators $\langle \Delta_\alpha \Delta_\beta \rangle$ are calculated for set of collision types and energies indicated above. The variation of the type of nucleus and $\sqrt{s_{NN}}$ allow the investigation of the energy and atomic number dependencies of $\langle \Delta_\alpha \Delta_\beta \rangle$ as well as the influence of both the parametrization of nuclear density and the $\lambda$ on correlator values. The preliminary results are shown in Figs. 2 and 3.

![Figure 2](image-url)
The larger \( \lambda \) leads to noticeable increase of same-charge correlator \( \langle \Delta^2 \rangle \) in \( Au + Au \) collisions at some fixed \( \sqrt{s_{NN}} \) (Fig. 2). On the other hand as seen in Fig. 2 the values of \( \langle \Delta^2 \rangle \) depend weakly on collision energy for wide range of \( \sqrt{s_{NN}} = 7.7 - 200 \) GeV. It should be noted that the growth of multiplicity of secondary particles with increase of \( \sqrt{s_{NN}} \) leads to the same decrease of the magnitudes of \( \langle K^T_{\alpha \beta} \rangle \) as well as of corresponding experimental observables for higher energy nucleus-nucleus collisions. Therefore the energy dependence of \( \langle \Delta^2 \rangle \) obtained here agrees with expectations from [6, 7, 8]. In general the correlator values for same-charged particle pairs are smaller for Fermi parametrization than that for approach of rigid sphere at corresponding centralities. But the type of parametrization for nuclear density influences on the \( \langle \Delta^2 \rangle \) mostly for central collisions and this influence decreases for more peripheral collisions. The correlator values change weakly with increasing of atomic number (Fig. 3) at least for same-charge pair in heavy ion (\( Pb + Pb \) and \( U + U \)) collisions.

4. Conclusion

The strength of magnetic field in nucleus-nucleus collisions as well as multiplicity-independent correlators within the framework of the chiral magnetic effect are calculated for two parameterizations of nuclear density, namely, for rigid sphere and for two-component Fermi model. The calculations are made for wide set of beam types and collision energies. The more realistic Fermi distribution leads to some decrease of the strength of magnetic field especially for RHIC energies. For the first time the estimations of the magnetic field are calculated in asymmetric \( Cu + Au \) collisions. The correlator magnitudes depend on collision energy weakly for \( Cu + Cu \) and \( Au + Au \). Comparison of correlator values with experimental observables is in the progress.

References

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Figure 3. Centrality dependence of the correlator \( \langle \Delta^2 \rangle \) for \( Pb + Pb \) collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV (a) and for \( U + U \) at \( \sqrt{s_{NN}} = 193 \) GeV (b) for various screening lengths and parameterizations for nuclear density.