Vorticity and Chaos in Heavy Ion Collisions

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Abstract

P-odd effects related to medium vorticity are discussed. In particular, we suggest studying a separation of baryonic charge due to the large baryonic chemical potential. This separation could be manifested in neutron asymmetries in heavy ion collisions in the FAIR and NICA energy range. We analyze the vorticity in various chaotic flows in detail. Chaotic flows are generalized in a nontrivial way relevant to heavy ion collisions. We pay special attention to their symmetry properties, both discrete and continuous. The bounds for vorticity production in heavy ion collisions are obtained.

Chiral Magnetic and Vortical effects

New coupling

$$e_j A_\alpha J^\alpha \Rightarrow \mu_j u_\alpha J^\alpha \tag{1}$$

CVE leads to similar (to CME) contribution to the electromagnetic current

$$J_e^\gamma = \frac{N_c}{4\pi^2 N_f}\varepsilon^{\gamma\beta\alpha\rho}\partial_\alpha u_\rho \partial_\beta(\theta \sum_j e_j\mu_j) \tag{2}$$

where N_c and N_f are the numbers of colours and flavours, respectively.

CME vs CVE

$$e_j \vec{H} \Rightarrow \mu_j \vec{\nabla} \times \vec{u} \tag{3}$$

The **generalized** CVE

$$J_i^\nu = \frac{\sum_j g_{i(j)}\mu_j}{\sum_j e_j \mu_j} J_e^\nu\,. \tag{4}$$

Inhomogenius chemical potential

$$|J_i^0| = \frac{|\vec{\nabla}\sum_j g_{i(j)}\mu_j|}{|\vec{\nabla}\sum_j e_j\mu_j|}|J_e^0| \tag{5}$$

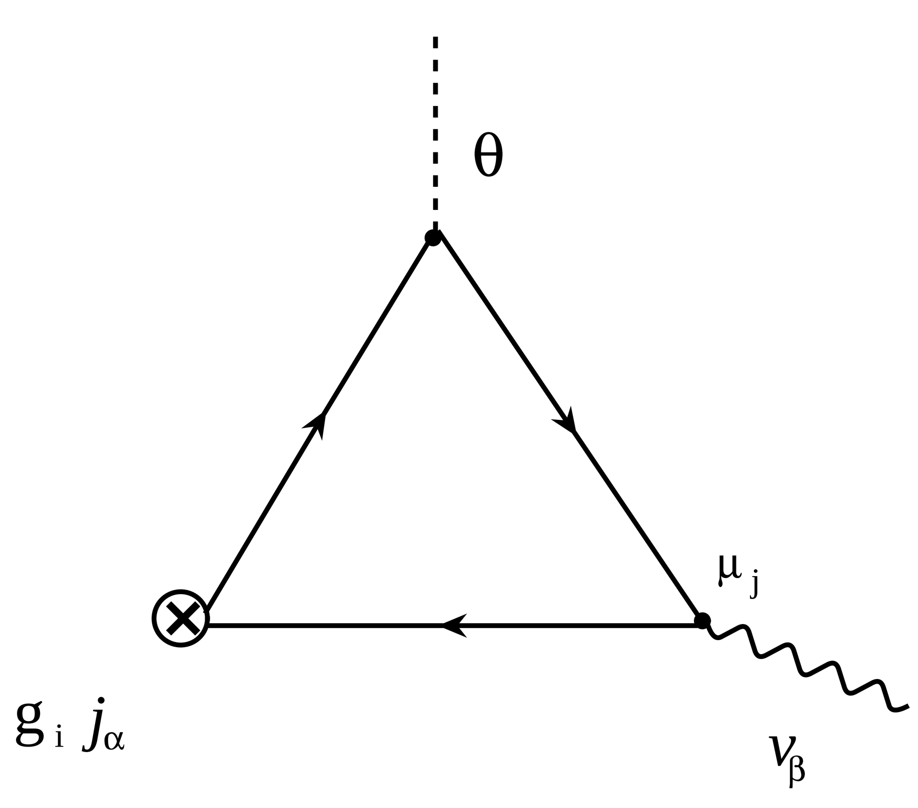

FIGURE 1: The generation of the current of the conserved charge g_i by the chemical potential μ_j.

Experiments at NICA and Neutron Asymmetries

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To collect statistics from different events one needs to construct a quadratic variable which does not depend on the varying sign of topological field fluctuations. This problem was solved in the experimental studies of CME by consideration of the angular asymmetries of *pairs* of particles with the same and opposite charges with respect to the reaction plane. Moreover, one can use three-particle correlations as well in order to avoid the necessity of fixing the reaction plane.

For the studies of CVE we suggest the collider NICA which is expected to operate with average luminosity $L \sim 10^{27} cm^{-2}s^{-1}$ for $Au+Au$ collisions in the energy range $\sqrt{s_{NN}} = 4 \div 11$ GeV/n (for Au^{79+}). In one of the collision points of NICA rings the Multi Purpose Detector (MPD) will be located. MPD is proposed for a study of dense baryonic matter in collisions of heavy ions over the wide atomic mass range $A = 1 \div 197$. Inclusion of neutron detectors is also considered in the conceptual design of the MPD. The multiplicity of the neutrons in these collisions, predicted by the UrQMD model, will be about 200 in a full solid angle. With the proposed interaction rate for the detector MPD of about 6 kHz, it will be possible in a few months of accelerator running time to accumulate $\sim 10^9$ events with different centralities and measure CVE with comparable accuracy to CME or set an upper limit on the value of CVE. For the estimation of CVE we could explore the same three-particle correlator of azimuthal angles $\langle cos(\phi_\alpha + \phi_\beta - 2\phi_c)\rangle$ which was used for the detection of CME.

The crucial difference of CVE with respect to CME is due to a very small number of produced antibaryons, in particular, antineutrons. Therefore, no sign change for correlators is expected!

Fig.2 shows the distribution of these correlators for neutrons from UrQMD model events of minbias $Au + Au$ collisions at $\sqrt{s_{NN}} = 9$ GeV.

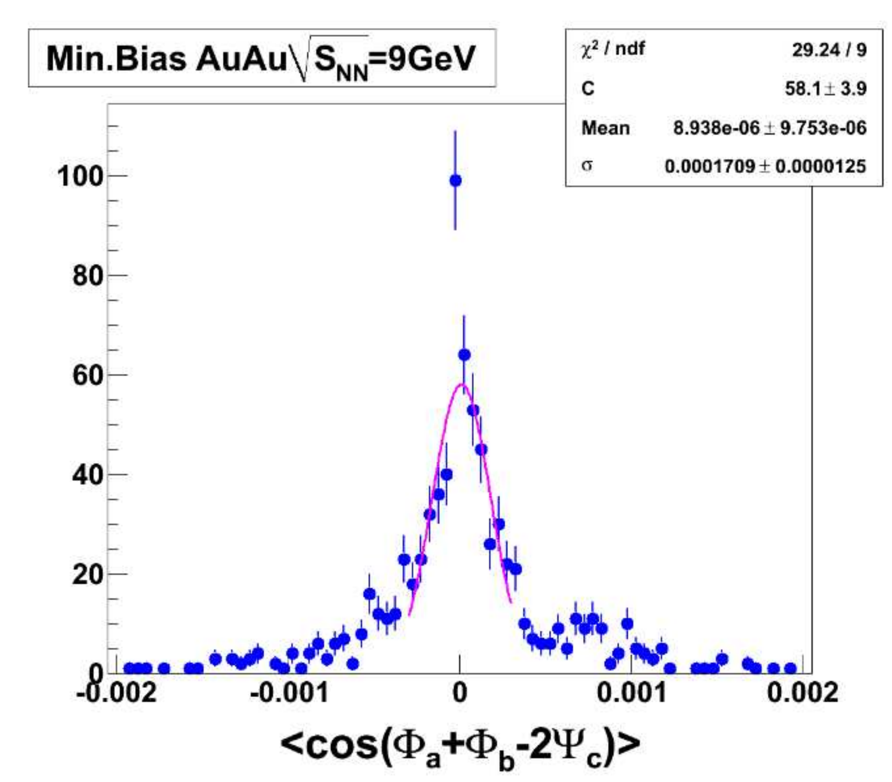
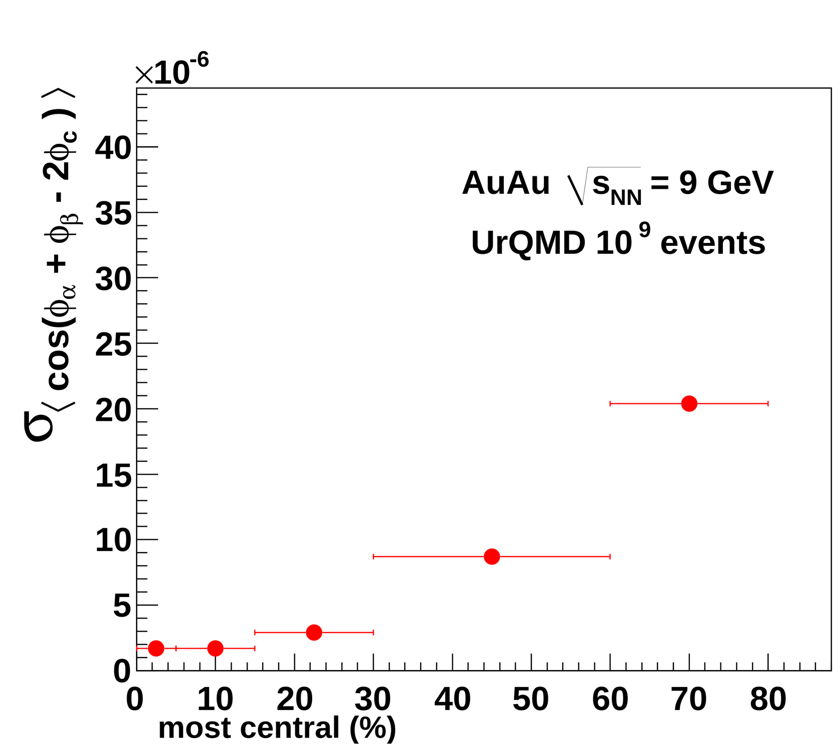


FIGURE 2: Distribution of three neutrons correlator for Au+Au collisions at $\sqrt{s_{NN}} = 9$ GeV/n for UrQMD event generator.

We should mention that UrQMD model predicts the number of neutrons in each event within the mid-rapidity range is much smaller than the number of charged particles. Hence, in order to determine CVE with the same value of precision as for CME case at RHIC , we need to have a much larger number of events. For the rough estimation, while $\sim 15\,M$ of events were sufficient at RHIC for targeted precision in the CME case, at NICA we need $\sim 1000\,M$ of events for the same precision in CVE measurements, which could be accumulated in a few months of NICA/MPD running time. The possible magnitude of the statistical errors for the three-particle correlator with 10^9 of collected events is shown in the following figure:



Relativistic Chaotic Flows

A.S. Sorin and O.V. Teryaev, work in preparation

The special role in the generation of vorticity w_i is played by the (P-violating) Beltrami flows

$$\omega_i \equiv \epsilon_{ijk}\,\partial_j\, v_k = m\, v_i \tag{6}$$

for which the Bernoulli condition is satisfied in the $3D$ region

$$\partial_i\, \phi = 0\,. \tag{7}$$

Here, for isentropic flows

$$\phi = w + \frac{v^2}{2} \tag{8}$$

where

$$\partial_i\, w = \frac{1}{\rho}\,\partial_i\, p\,. \tag{9}$$

The validity of the $3D$ Bernoulli equation is the necessary condition of the Lagrangian (streamline) chaos.

We generalize the notion of the isentropic Beltrami flows to the relativistic case

$$\epsilon^{\mu\nu\alpha\beta}\,\eta_\mu\,\partial_\alpha\,\frac{w\,u_\beta}{\rho} = m\left(g^{\nu\mu} - \frac{\eta^\nu\,\eta^\mu}{\eta^2}\right)\frac{w\,u_\mu}{\rho}\,. \tag{10}$$

Here, ρ is the baryon charge density, u_μ is the fluid four-velocity, and η_μ is the constant four-vector characterizing the generalized quasi-steady flows

$$\eta^\mu\,\partial_\mu\,\frac{w\,u_\nu}{\rho} = 0\,. \tag{11}$$

Then one can show that the relativistic-covariant Bernoulli condition is valid in $4D$ space-time region

$$\partial_\mu\,\frac{w\,u^\nu\,\eta_\nu}{\rho} = 0 \tag{12}$$

for the relativistic inviscid fluid. The solutions of these equations and their role in the generation of the vorticity and chaotic thermalization will be discussed elsewhere.

Outlook

The large chemical potential might result in meson decays forbidden in the vacuum, like C-violating $\rho \to 2\gamma$ or recently considered CP-violating $\eta \to 3\pi$.

Vorticity may be related to the global rotation of hadronic matter, an interesting observable by itself. Its calculations in the framework of various models are very desirable, as well as studies of its possible relations with other collective effects due to non-centrality of heavy ion collisions, like directed (v_1) and elliptic (v_2) flows.

Another interesting problem is the possible manifestation of vorticity in the polarization of Λ particles. The experimental tests at RHIC did not show any significant effect. One may think that such a polarization can emerge due to the anomalous coupling of vorticity to the (strange) quark axial current via the respective chemical potential, being very small at RHIC but substantial at FAIR and NICA energies. In that case the Λ polarization at NICA due to triangle anomaly can be considered together with other probes of vorticity.

One can expect that the polarization is proportional to the anomalously induced axial current

$$j_A^\mu \sim \mu^2\left(1 - \frac{2\,\mu\,n}{3\,(\epsilon + P)}\right)\epsilon^{\mu\nu\lambda\rho}\,u_\nu\,\partial_\lambda u_\rho \tag{13}$$

where n and ϵ are the corresponding charge and energy densities and P is the pressure. Therefore, the μ-dependence of the polarization has to be more strong than that of CVE leading to the effect rapidly increasing with decreasing energy. This option may be explored in the framework of the program of polarization studies at NICA performed in the both collision points as well as at the low-energy scan program at RHIC.

Comparative studies of CME and CVE exploiting the different sign structure of correlators mentioned above will be very important.

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