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Chiral vortaic effect and neutron asymmetries in heavy-ion collisions

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We study the possibility of testing experimentally signatures of P-odd effects related to the vorticity of the medium. The chiral vortaic effect is generalized to the case of conserved charges different from the electric one. In the case of baryonic charge and chemical potential, such an effect should manifest itself in neutron asymmetries measured by the Multipurpose Detector at the Nuclotron-Based Ion Collider Facility accelerator complex. The required accuracy may be achieved in a few months of accelerator running. We also discuss polarization of the hyperons and P-odd correlations of particle momenta (handedness) as probes of vorticity.

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I. INTRODUCTION

The local violation [1] of discrete symmetries in strongly interacting QCD matter is now under intense theoretical and experimental investigation. The renowned chiral magnetic effect (CME) uses the (C) P-violating (electro)magnetic field emerging in heavy-ion collisions to probe (C) P-odd effects in QCD matter.

There is an interesting counterpart of this effect, the chiral vortaic effect (CVE) [2,3] owing to coupling to P-odd medium vorticity. In its original form [2] this effect leads to the appearance of the same electromagnetic current as the CME. Here we suggest a straightforward generalization of the CVE resulting in generation of all conserved-charge currents. In particular, we address the case of the *baryonic* charge and the corresponding asymmetries of baryons, especially neutrons (not affected by the CME), which can be measured by the Multipurpose Detector (MPD) [4] at the Nuclotron-Based Ion Collider Facility (NICA) [5] at the Joint Institute for Nuclear Research.

II. CHIRAL MAGNETIC AND VORTAIC EFFECTS

The basic point in the emergence of the CME is the coupling of the topological QCD field θ[1] to the electromagnetic field A_α controlled by the triangle axial-anomaly diagram. A similar interaction of θ with the velocity field V_α exists in relativistic hydrodynamics, owing to the new coupling

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

involving the chemical potentials μ_j (for various flavors j) and the current J^α. It also provides the complementary description [6] of the recently found contribution of fluid vorticity to the anomalous nonconserved current [7]. Note that the similarity between the effect of the magnetic field and that of rotation mentioned in Ref. [2] is very natural, as rotation is related by the equivalence principle to the so-called *gravitomagnetic* field (see, e.g., Ref. [8] and references therein).

The CVE leads to a similar (to the CME) contribution to the electromagnetic current:

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

where N_c and N_f are the numbers of colors and flavors, respectively. If variation of the chemical potential is neglected, the charge induced by the CVE for a given flavor can be obtained from that owing to CME by substitution of the magnetic field with the curl of the velocity: $e_j \vec{H} \to \mu_j \vec{\nabla} \cdot \vec{V}$.

To estimate the vorticity, one may appeal [2] to the Larmor theorem relating the magnetic field to the angular velocity of a rotating body, which in turn is proportional to the vorticity. As a result, for $\mu \sim 500$ MeV (in the NICA energy range), the order of magnitude of the CVE should be the same as that of the CME.

On one hand, the CVE provides another source for the observed consequences of the CME, relating to both light and strange [9] quarks (regarded as the heavy ones [10]). On the other hand (this is the basis of the following discussion), the CVE leads also to the separation of charges different from the electric one. This becomes obvious if the current is calculated from the triangle diagram, where quark flavors j carry various charges $g_{i(j)}$ (see Fig. 1). The calculation may also be performed following Ref. [2] by varying the effective Lagrangian with respect to the external vector field. In that case this vector field can be not only the electromagnetic potential [2] (entering the Lagrangian describing the interaction with the real electromagnetic field) but also an arbitrary (auxiliary) field coupled to any conserved charge.

If variation of the chemical potential in Eq. (2) is neglected, the current of that charge g_i selecting the specific linear combination of quark triangle diagrams is related to electromagnetic one as follows (see Fig. 1):

$$J_i^\nu = \frac{\sum_j g_{i(j)} \mu_j}{\sum_j e_j \mu_j} J_e^\nu. \tag{3}$$

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[1] Its effect is potentially much larger than the effects of CP violation responsible, for example, for neutron electric dipole moment.

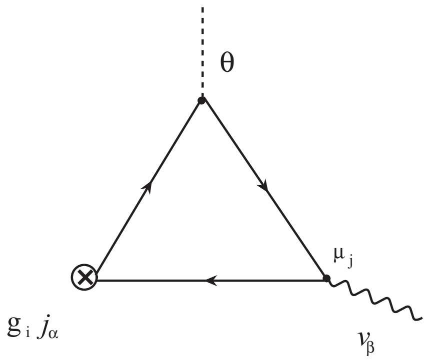

FIG. 1. Generation of the current of the conserved charge g_i by the chemical potential μ_j.

In another extreme case of dominance of chemical potential gradients (assumed to be collinear), one gets the relation

$$|J_i^0| = \frac{|\vec{\nabla} \sum_j g_{i(j)} \mu_j|}{|\vec{\nabla} \sum_j e_j \mu_j|} |J_e^0|, \tag{4}$$

which might be useful, for example, for the mixed-phase [17] description.

In particular, the high baryonic chemical potential (actually the largest one that is achievable in accelerator experiments [11]), appearing in the collisions at comparatively low energies at the FAIR and NICA (and possibly SPS and RHIC in low-energy scan mode) facilities, may result in the separation of the baryonic charge. Of special interest are manifestations of this separation in *neutron* asymmetries with respect to the production plane, as soon as the neutrons, from the theoretical side, are not affected by the CME,[2] and from the experimental side, there is a unique opportunity to study neutron production and asymmetries with the MPD at the NICA. Besides that, the noticeable strange chemical potential in the NICA energy range (see, e.g., Ref. [12] and references therein) might result in the strangeness separation.

III. EXPERIMENTS AT THE NICA AND NEUTRON ASYMMETRIES

The numerical smallness of this expected vortaic effect makes searching it on an event-by-event basis highly improbable. To collect statistics from different events, one needs to construct a quadratic variable that does not depend on the varying sign of topological field fluctuations.

This problem was solved in experimental studies of the CME [13–16] 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, to avoid the necessity of fixing the reaction plane.

We suggest using similar correlations for baryonic charge. However, this method is not directly applicable in the case of baryon charge separation because of the very small number of antibaryons produced, in particular, antineutrons.[3] Nevertheless, the two-particle correlation for neutrons might still be used as one of the probes of the CVE. In the case of three-particle correlations the third particle should not necessarily be the neutron and could also be a charged particle.

Note that comparison of the aforementioned correlations for various particles could be very useful. Namely, the direct effect of the CVE is negligible for pions, owing to the rather low chemical potential, so that only the CME contributes. In contrast, for neutrons the correlations are caused entirely by the CVE, while for protons one should have both such effects. In the case that the correlations emerged for reasons other than the CVE and CME to quadratic order, then their simultaneous observation would be an important test of their actual existence.

For studies of the CVE we suggest the NICA collider,[4] 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+}). The MPD [4] will be located in one of the collision points of the NICA rings. The 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 [18], will be about 200 in a full solid angle. The number of registered neutrons in each event depends on the event centrality and varies in the range $10 \div 150$ with a reasonable efficiency, ∼60% for neutron detection. With a proposed interaction rate for the MPD of about 6 kHz [4], it will be possible, in a few months of accelerator running time, to accumulate $\sim 10^9$ events with different centralities and measure the CVE with an accuracy comparable to that for the CME or set an upper limit on the value of the CVE. For estimation of the CVE we could explore the same three-particle correlator of azimuthal angles,

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle, \tag{5}$$

which was used for detection of the CME [13–16].

Figure 2 shows the distribution of correlators, Eq. (5), for neutrons from UrQMD model events of minbias Au + Au collisions at $\sqrt{s_{NN}} = 9$ GeV. In each event the correlator was obtained by taking two of the neutrons [α and β in Eq. (5)] from the midrapidity range ($|\eta| < 3$) and the third one [c in Eq. (5)] was taken from the high-rapidity range ($|\eta| > 3$). The correlator mean value is equal to 0, owing to the absence of neutron asymmetry in the model simulation as shown in Fig. 2.

We should mention that the UrQMD model predicts that the number of neutrons in each event within the midrapidity range is much smaller than the number of charged particles. Hence, to determine the CVE with the same value of precision as for the CME case at the RHIC [16], we need to have a much larger

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[2] Let us stress that the CME leads to the separation of all conserved charges (including baryonic ones) of electrically charged particles only.

[3] Note that the opposite-sign charge correlations for the CME are also very low [16].

[4] The value of the CME at the NICA is under intense discussion [17].

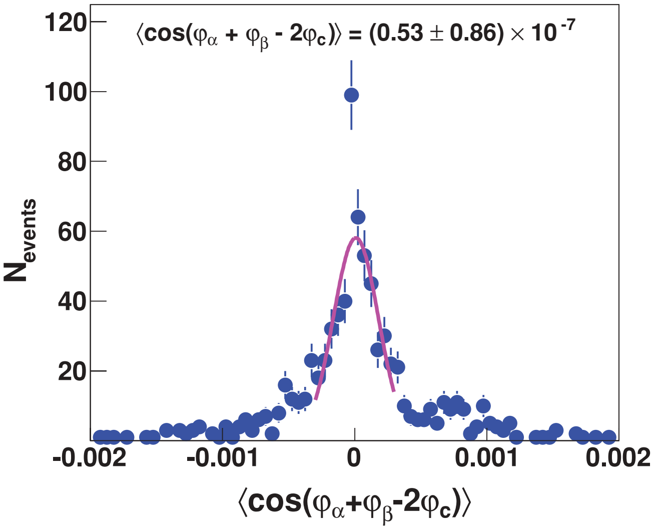

FIG. 2. (Color online) Distribution of three-neutron correlators for Au + Au collisions at $\sqrt{s_{NN}} = 9$ GeV/n for the UrQMD event generator.

number of events. For the rough estimation, while $\sim 15 \times 10^6$ events were sufficient at the RHIC for targeted precision in the CME case, at the NICA we need $\sim 1000 \times 10^6$ 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 a three-particle correlator with 10^9 collected events is shown in Fig. 3.

At the moment, only estimation of statistical errors for correlator (5) can be performed, and more thorough investigation of systematic and measurement errors (such as detector acceptance and inefficiencies and effects of particle clustering) should be carried out with experimental data obtained from the real detector. It may be pointed out that the main contribution to the background for correlator (5) comes from particle flow, and in the NICA energy range elliptic flow of charged (and neutral) particles is less than that at RHIC energies. Therefore, one would expect that the background of the flow effect for neutral particles used in CVE calculations should also be lower than that for charged particles in the CME in high-energy collisions. More detailed estimates taking into account also neutron detector acceptances and efficiencies will be discussed elsewhere.

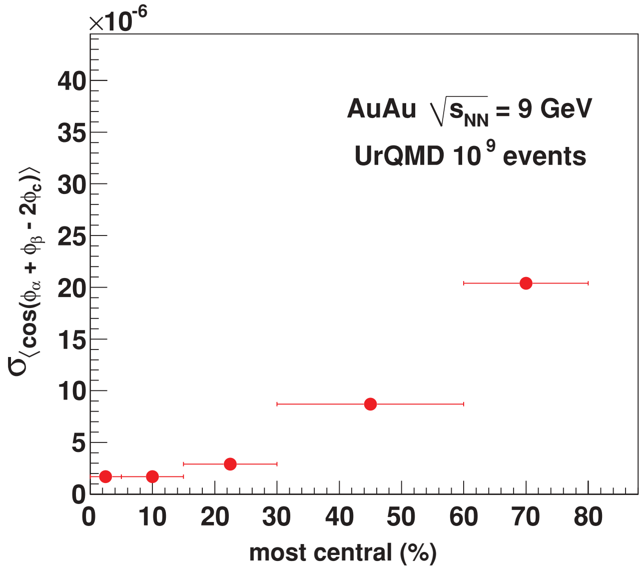

FIG. 3. (Color online) Estimation of statistical errors.

IV. CONCLUSIONS AND OUTLOOK

We have discussed new tests of P-odd effects in heavy-ion collisions owing to vorticity under the specific conditions of the MPD at the NICA. Special attention was paid to generalization of the CVE to the case of separation of the baryonic charge and its manifestation in neutron asymmetries.

We proposed to study two- and three-particle correlations similar to those used in studies of the CME. We compared the required accuracies and found that the CVE could be studied with the data collected in a few months of NICA running.

As for the outlook, let us first mention that nonperturbative (in particular, lattice QCD [19]) studies of vorticity effects are very important. Let us also note that a high chemical potential might result in meson decays forbidden in vacuum, like C-violating $\rho \to 2\gamma$ [20,21] or the recently considered CP-violating $\eta \to 3\pi$ [22].

Vorticity is related to lobal rotation of hadronic matter, an interesting observable in itself. Its calculation in the framework of various models is very desirable, as well as studies of its possible relations to other collective effects owing to noncentrality of heavy-ion collisions, such as directed (v_1) and elliptic (v_2) flows.

Another interesting problem is the possible manifestation of vorticity in the polarization of Λ particles, as suggested some time ago in Ref. [23], although experimental tests at the RHIC [14] did not show any significant effect. One might think that such a polarization could emerge owing to the anomalous coupling of vorticity to a (strange) quark axial current via the respective chemical potential, which is very low at RHIC but substantial at FAIR and NICA energies. In that case, Λ polarization at the NICA [17] owing to a triangle anomaly can be considered together with other probes of vorticity [24] and recently suggested signals [25] of a hydrodynamical anomaly.

One would expect that polarization is proportional to the anomalously induced axial current [7]

$$j_A^\mu \sim \mu^2 \left(1 - \frac{2\mu n}{3(\epsilon + P)}\right) \epsilon^{\mu\nu\lambda\rho} V_\nu \partial_\lambda V_\rho, \tag{6}$$

where n and ϵ are the corresponding charge and energy densities and P is the pressure. Therefore, the μ dependence of polarization must be stronger than that of the CVE, leading to the effect's increasing rapidly with decreasing energy.

This option may be explored in the framework of the program of polarization studies at the NICA [17] performed at collision points as well as within the low-energy scan program at the RHIC.

To collect polarization data from different events, one needs to supplement the production plane with some sort of orientation. For this purpose one might use the left-right asymmetry of *forward* neutrons as done at the RHIC [14,15] or another observable, interesting in itself. The latter comment regards handedness [26], namely, the P-odd multiparticle momentum correlation. Its exploration in heavy-ion collisions provides a way of orienting the event plane and collecting data for Λ polarization and other P-odd observables.

Finally, let us mention the possibility [17] of studying P-even angular distributions of dileptons [27], which might be used as probes of quadratic effects of the CME [28] and, quite probably, the CVE.

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