Chiral vortaic effect and neutron asymmetries at NICA

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Abstract

We study the possibility of testing experimentally signatures of P-odd effects related with 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 effect should manifest itself in neutron asymmetries at the NICA accelerator complex measured by the MPD detector. 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.

We dedicate this paper to the memory of Academician Alexei Norairovich Sissakian

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I. INTRODUCTION

The local violation of discrete symmetries in strongly interacting QCD matter is now under intensive theoretical and experimental investigations. The renowned Chiral Magnetic Effect (CME) uses the (C)P-violating (electro)magnetic field emerging in heavy ion collisions in order to probe the (C)P-odd effects in QCD matter.

There is an interesting counterpart of this effect, Chiral Vortaic Effect (CVE) due to coupling to P-odd medium vorticity. In its original form this effect leads to the appearance of the same electromagnetic current as CME. Here we suggest a straightforward generalization of 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 CME), which can be measured by the MultiPurpose Detector (MPD) at the Nuclotron-based Ion Collider fAcility (NICA) at the Joint Institute for Nuclear Research (JINR).

II. CHIRAL MAGNETIC AND VORTAIC EFFECTS

The basic point in the emergence of CME is the coupling of the topological QCD field $\theta$ to the electromagnetic field $A_\alpha$ controlled by the triangle axial-anomaly diagram. Similar interaction of $\theta$ with the velocity field $V_\alpha$ exists in relativistic hydrodynamics due to the new coupling

$$e_j A_\alpha J^\alpha \Rightarrow \mu_j V_\alpha J^\alpha$$

involving the chemical potentials $\mu_j$ (for various flavours $j$) and the current $J^\alpha$. It provides also the complementary description of the recently found contribution of fluid vorticity to the anomalous non-conserved current. Note that the similarity between the effects of the magnetic field and the rotation mentioned in is very natural as the rotation is related by the Equivalence Principle to the so called gravitomagnetic field (see e.g. and references therein).

1 Its effect is potentially much larger than the effects of CP-violation responsible e.g. for neutron EDM.
CVE leads to similar (to CME) contribution to the electromagnetic current:
\[
J_e^\nu = \frac{N_c}{4\pi^2 N_f} \varepsilon^{\gamma\beta\alpha} \partial_\alpha V_\rho \partial_\beta (\theta \sum_j e_j \mu_j)
\]  
(2)

where \(N_c\) and \(N_f\) are the numbers of colours and flavours, respectively. If variation of the chemical potential is neglected, the charge induced by CVE for a given flavour can be obtained from that due to CME by substitution of the magnetic field with the curl of the velocity: \(e_j \vec{H} \rightarrow \mu_j \vec{\nabla} \times \vec{V}\).

In order to estimate the vorticity one may appeal [2] to the Larmor theorem relating the magnetic field to the angular velocity of the 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 CVE should be the same as that of CME.

On one hand, CVE provides another source for the observed consequences of CME, relating with both light and strange [9] quarks (regarded as the heavy ones [10]). On the other hand (this is the basis of our following discussion), 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 flavours \(j\) carry various charges \(g_{i(j)}\) (see Fig.1). The calculation may also be performed following [2] by variation of 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):
\[
J_i^\nu = \frac{\sum_j g_{i(j)} \mu_j}{\sum_j e_j \mu_j} J_e^\nu.
\]  
(3)

In another extreme case of dominance of chemical potential gradients (assumed to be collinear) one gets the relation
\[
|J_i^0| = \frac{\left|\vec{\nabla} \sum_j g_{i(j)} \mu_j\right|}{\left|\vec{\nabla} \sum_j e_j \mu_j\right|} |J_e^0|
\]  
(4)

which might be useful e.g. for the mixed phase [17] description.
In particular, the large baryonic chemical potential (actually the largest one which is achievable in accelerator experiments [11]), appearing in the collisions at comparatively low energies at the FAIR and NICA (and possibly SPS and RHIC at 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 CME and, from the experimental side, there is a unique opportunity to study neutron production and asymmetries by MPD at NICA. Besides that, the noticeable strange chemical potential at the NICA energy range (see e.g. [12] and references therein) might result in the strangeness separation.

III. EXPERIMENTS AT NICA AND NEUTRON ASYMMETRIES

The numerical smallness of such expected vortaic effect makes it highly improbable to search it on an event-by-event basis. 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 [13–16] by consideration of the angular asymmetries of pairs of particles with the same and opposite charges with

\[ \theta \]

\[ g_i \mu_j \]

\[ v_\beta \]

\[ g_i j_\alpha \]

\[ \mu_j \]

\[ \theta \]

Figure 1: The generation of the current of the conserved charge \( g_i \) by the chemical potential \( \mu_j \).

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

We suggest to use the 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 produced antibaryons, in particular, antineutrons. Nevertheless, the two-particle correlation for neutrons still might be used as one of the probes of 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 the comparison of above-mentioned correlations for various particles could be very useful. Namely, the direct effect of CVE is negligible for pions, due to the rather small chemical potential, so that only CME contributes. On the other hand, for neutrons the correlations are entirely due to CVE, while for protons one should have both such effects. In case the correlations emerged due to other reasons than CVE and CME to quadratic order, then their simultaneous observation would be an important test of their actual existence.

For the studies of CVE we suggest the collider NICA which is expected to operate with average luminosity \( L \sim 10^{27} \text{cm}^{-2}\text{s}^{-1} \) for \( Au + Au \) collisions in the energy range \( \sqrt{s_{NN}} = 4 \div 11 \text{ GeV/n} \) (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. The number of registered neutrons in each event depends on the event centrality and varies on the range 10 \( \div \) 150 with a reasonable efficiency \( \sim 60\% \) for neutron detection. 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

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

Note that the opposite sign charge correlations for CME are also very small.

The value of CME at NICA is under intensive discussion.
which was used for the detection of CME [13–16].

![Graph](image.png)

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

Fig. 2 shows the distribution of correlators (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 ($\alpha$ and $\beta$ in eq. (5)) from the mid-rapidity range ($|\eta| < 3$) and a third one ($c$ in eq. (5)) was taken from the large rapidity range ($|\eta| > 3$). The correlators mean value is equal to zero due to an absence of the neutron asymmetry in the model simulation as it is shown on the Fig. 2.

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 [16], we need to have a much larger number of events. For the rough estimation, while $\sim 15M$ of events were sufficient at RHIC for targeted precision in the CME case, at NICA we need $\sim 1000M$ 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 Fig. 3.

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

IV. CONCLUSIONS AND OUTLOOK

We discussed the new tests of P-odd effects in heavy ions collisions due to vorticity in
the specific conditions of the MPD detector at NICA. Special attention was paid to the
generalization of the Chiral Vortaic Effect to the case of separation of the baryonic charge
and its manifestation in neutron asymmetries.

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

As an outlook, let us first mention that the non-perturbative (in particular, lattice QCD
studies of vorticity effects are very important. Let us also note that 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 is 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 $\Lambda$ particles was suggested some time ago in [23] although the experimental tests at RHIC [14] 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 $\Lambda$ polarization at NICA [17] due to triangle anomaly can be considered together with other probes of vorticity [24] and recently suggested signals [25] of hydrodynamical anomaly.

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

$$j^\mu_A \sim \mu^2 \left(1 - \frac{2 \mu n}{3 (\epsilon + P)}\right) \epsilon^{\mu \nu \lambda \rho} V_\nu \partial_\lambda V_\rho$$  \hspace{1cm} (6)

where $n$ and $\epsilon$ are the corresponding charge and energy densities and $P$ is the pressure. Therefore, the $\mu$-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 [17] performed in the both collision points as well as at the low-energy scan program at RHIC.

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

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