Hyperon polarization in Heavy-Ion Collisions and gravity-related anomaly

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Abstract

We study the energy dependence of global polarization of Λ hyperons in peripheral Au – Au collisions. We combine the calculation of vorticity and strange chemical potential in the framework of kinetic Quark-Gluon String Model with the anomalous mechanism related to axial vortical effect. We pay special attention to the temperature dependent contribution related to gravitational anomaly and found that the preliminary RHIC data are compatible with its suppression discovered earlier in lattice calculations.

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I. INTRODUCTION

The experimental evidences for polarization of hyperons in heavy-ion collisions found by STAR collaboration \[1\] attracted recently much attention \[2\–6\].

The studies of polarization are often performed \[7\] in the framework of approach exploring local equilibrium thermodynamics \[8\] and hydrodynamical calculations of vorticity \[9\–11\].

There is another (although related \[12\]) approach to polarization first proposed in \[13\] and independently in \[14\]. The so-called axial vortical effect (see e.g. \[15\] and references therein) being the macroscopic manifestation of axial anomaly \[16\] leads to induced axial current of strange quarks which may be converted to polarization of \(\Lambda\)-hyperons \[13\, 14\].

The effect is proportional to vorticity and helicity of the strong interacting medium, and, in particular, to helicity separation effect discovered \[17\] in the kinetic Quark-Gluon-String Model(QGSM) \[18\–20\] and confirmed \[21\] in HSD \[22\] model. This helicity separation effect receives \[17\, 21\] the significant contribution \(\sim \vec{v}_y \vec{\omega}_y\) from the transverse component of velocity and vorticity. It is easily explained \[17\] by the same signs of transverse vorticities in the "upper" and "lower" (w.r.t. reaction plane) half-spaces, combined with the opposite signs of velocities. At the same time, even larger contribution \[17\, 21\] of longitudinal components of velocity and vorticity \(\sim \vec{v}_z \vec{\omega}_z\) implies the appearance of the "quadrupole" structure of longitudinal vorticity, recently found \[23\] in the hydrodynamical approach.

Indeed, the opposite values of longitudinal velocities in the "left" and "right" (w.r.t. to "vertical" plane \(x = 0\) normal to reaction one and containing the beams direction) require exactly the quadrupole structure of longitudinal vorticities in the quater-spaces formed by the intersection of reaction and vertical planes:

\[
h = h_x + h_y + h_z \sim \text{sign}(y); \quad (1)
\]

\[
v_z \sim \text{sign}(x); \quad (2)
\]

\[
\omega_z \sim \text{sign}(x) \text{sign}(y), \quad (3)
\]

where \(h_i = v_i \omega_i\) is the contribution of the respective component of velocity and vorticity to the helicity density. It is this quadrupole structure of vorticity that leads to the up-down mirror structure of helicity after multiplication by the left-right mirror structure of velocity:

\[
h_z = \omega_z v_z \sim (\text{sign}(x))^2 \text{sign}(y) = \text{sign}(y).
\]
To make (2) applicable and observe the quadrupole picture one needs to average the longitudinal velocity and vorticity over the cylinder symmetric w.r.t. the plane $z = 0$. Otherwise, taking the different slices $z = \text{const}$, longitudinal velocity is not, generally speaking, changing sign with $x$. The dependence of the quadrupole picture over the height of this cylinder is represented at Figure 1.

Figure 1: Quadrupole structure of average longitudinal vorticity for different heights of the cylinders in $z$ direction (see text).

Later more detailed calculations were performed [24], including the structure of emergent vortex sheets, as well as spatial and temporal dependence of strange chemical potential which is also the ingredient of anomalous approach to polarization.

II. ANOMALOUS MECHANISM OF HYPERON POLARIZATION

Anomalous mechanism of polarization makes this effect qualitatively similar to the local violation [25] of discrete symmetries in strongly interacting QCD matter. The most
well known here is the Chiral Magnetic Effect (CME) which 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.

The polarization, in turn, is similar to Chiral Vortical Effect (CVE) due to coupling to P-odd medium vorticity leading to the induced electromagnetic and all conserved-charge currents, in particular the baryonic one.

Recently the pioneering preliminary results on global polarization of Λ and ¯Λ hyperons in Au − Au collisions in Beam Energy Scan at RHIC were released and the qualitative tendency of polarization decrease with energy in agreement with the prediction was revealed. The recent theoretical analysis suggested that decrease of polarization with energy is related to the suppression of Axial Magnetic effect contribution in strongly correlated QCD matter found in lattice simulations.

Indeed, the chiral vorticity coefficient describing the axial vortical effect

\[ c_V = \frac{\mu_s^2 + \mu_A^2}{2\pi^2} + \frac{T^2}{6}, \tag{4} \]

contains temperature dependent term related to gravitational anomaly, and naively it can be quite substantial and increase with energy. However, lattice simulations lead to the zero result in the confined phase and to the suppression by one order of magnitude at high temperatures. Neglecting axial chemical potential, the coefficient takes the form

\[ c_V = \frac{\mu_s^2}{2\pi^2} + k \frac{T^2}{6}, \tag{5} \]

As soon as for free fermion gas the \( T^2/6 \) term is recovered for large lattice volume at fixed temperature, the above-mentioned suppression should be attributed to the correlation effects. It was suggested, that the accurate measurements of polarization energy dependence may serve a sensitive probe of strongly correlated QCD matter. In the current paper we perform numerical simulations to implement this suggestion.

The polarization is related to the strange axial charge

\[ Q_5^s = N_c \int d^3x c_V \gamma^2 \epsilon^{ijk} v_i \partial_j v_k, \tag{6} \]

and as a result the quark and hadronic observables are related, that is of special importance in the confined phase. Another approach to confined phase is provided by consideration of the vortices in pionic superfluid, whose cores are associated with polarized baryons.
III. NUMERICAL SIMULATIONS OF AXIAL ANOMALY CONTRIBUTIONS TO (ANTI)HYPERON POLARIZATION

We performed the numerical simulations in QGSM model [18–20]. We decomposed the space-time to the cells, allowing to define velocity and vorticity in the kinetic model, as described in detail in [17]. To define the strange chemical potential (assuming that \( \Lambda \) polarization is carried by strange quark) we used the matching procedure [24] of distribution functions to its (local) equilibrium values. In this paper, we also determine in this way the values of temperature. In general, let us stress that we realized in our particular case the relation between kinetics, hydrodynamics and thermodynamics.

We first neglect the gravitational anomaly contribution and start by considering the energy dependence of polarization (described in detail in [27]) for three values of impact parameter. The results are presented at Figure 2. The curves correspond to \( b = 8.0 fm, 6.4 fm, 4.8 fm \).

We continue by the inclusion of contribution related to gravitational anomaly, which is the central issue of this paper. The results are presented at Figure 3. We consider as a starting point the original value of anomaly coefficient [28] \( T^2/6 \) which is reproduced for large lattice volume at fixed temperature [30]. We present the curves following from the coefficients suppressed by factor \( k(5) \) resulting from the lattice calculations [29]. We compare values of \( k = 1 \) with \( k = 0, 1/15, 1/10 \). As one can see, the lattice-supported value 1/15 is most close to the behavior of preliminary data which may be considered as a signal of strongly correlated matter formation. The closeness of \( k = 0 \) curve to the experimental points may be related to the contribution of confinement phase, where lattice calculations [29] lead to zero temperature-dependent effect. At the same time, already \( k = 1/10 \) leads to the curve growing with energy, while \( k = 1 \) leads to extremely strong growth.

The \( \bar{\Lambda} \) polarization is emerging due to the polarization of \( \bar{s} \)–quarks, which has the same sign, as the axial current and charge are C-even operators. The magnitude of the \( \bar{\Lambda} \) is larger as the same axial charge is distributed between the polarizations of the smaller number of particles [27]. It is mandatory to take into account the contribution of \( K^* \) mesons. In the case of \( \Lambda \) the \( K^{*-}, \bar{K}^0 \) mesons contain two sea(anti)quarks and does not change the polarization significantly. At the same time, for \( \bar{\Lambda} \) the relevant \( K^{**}, K^0 \) mesons are more numerous and make the excess of \( \bar{\Lambda} \) polarization less pronounced.
Figure 2: Energy dependence of polarization for different values of impact parameter.

Note that this excess is larger for smaller energies, where suppression of $\bar{\Lambda}$ is larger. This differs from the (C-odd) effect of magnetic field, which is increasing with energy, although more detailed studies taking into account the finite time of magnetic field existence are required.

The quantitative analysis of these effects, taking into account the gravitational anomaly contribution, is presented at Figure 4. The result is in reasonable agreement with STAR data, although further analysis is required.
Figure 3: Energy dependence of polarization for different values of gravitational anomaly contribution.

IV. CONCLUSIONS AND OUTLOOK

We numerically studied the generation of polarization by the anomalous mechanism (Axial Vortical Effect) and compared it with the observed data.

First we neglected the gravitational anomaly related temperature dependent contribution when the decrease of chemical potential with energy leads, in turn, to the decrease of
polarization. We considered this effect for three impact parameters.

We also included the contribution related to gravitational anomaly proportional to \( T^2 \) and studied its possible suppression in strongly correlated matter. We found that the preliminary data are in accordance with suppression effect found on the lattice.

We also considered the polarization of \( \bar{\Lambda} \) hyperons, taking into account the contribution of \( K^* \) mesons. We found that the \( \bar{\Lambda} \) polarization is larger than that of \( \Lambda \) and is growing at
smaller energies.

The further more accurate measurements of Λ polarization should provide the additional check of gravitational anomaly related contribution.

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