Rapid Communications

Hyperon polarization in heavy-ion collisions and holographic gravitational anomaly

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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 the kinetic quark-gluon-string model with the anomalous mechanism related to the axial vortical effect. We pay special attention to the temperature-dependent contribution related to the holographic gravitational anomaly and find that the preliminary data from the BNL Relativistic Heavy Ion Collider are compatible with its suppression discovered earlier in lattice calculations.

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Introduction. The experimental evidence for polarization of hyperons in heavy-ion collisions found by the STAR Collaboration [1] recently attracted much attention [2–6]. The studies of polarization are often performed [7] in the framework of an approach exploring local equilibrium thermodynamics [8] and hydrodynamical calculations of vorticity [9–11]. Another (although related [12]) approach to polarization was first proposed in [13] and independently in [14]. The so-called axial vortical effect (see, e.g., [15] and references therein) is the macroscopic manifestation of an axial anomaly [16] that leads to induced axial current of strange quarks which may be converted to polarization of Λ hyperons [13,14].

The effect is proportional to vorticity and helicity of the strong interacting medium, and, in particular, to the helicity separation effect discovered [17] in the kinetic quark-gluon-string model (QGSM) [18–20] and confirmed [21] in the Hadron String Dynamics [22] model. This helicity separation effect receives [17,21] a significant contribution $\sim\vec{v}_y\vec{\omega}_y$ from the transverse components of velocity and vorticity. It is easily explained [17] by the same signs of transverse vorticities in the "upper" and "lower" (with respect to the reaction plane) half spaces, combined with the opposite signs of the velocities. At the same time, even larger contributions [17,21] of the longitudinal components of velocity and vorticity $\sim\vec{v}_z\vec{\omega}_z$ imply 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" (with respect to the vertical plane $x = 0$ normal to the reaction one and containing the beam direction) require exactly the quadrupole structure of longitudinal vorticities in the quarter spaces formed by the intersection of reaction and vertical planes:

$$h = h_x + h_y + h_z \sim \text{sign}(y), \tag{1}$$

$$v_z \sim \text{sign}(x), \tag{2}$$

$$\omega_z \sim \text{sign}(x)\text{sign}(y), \tag{3}$$

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 Eq. (2) applicable and observe the quadrupole picture one needs to average the longitudinal velocity and vorticity over the cylinder symmetric with respect to 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 Fig. 1.

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 the anomalous approach to polarization.

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 charge-parity(CP)-violating (electro)magnetic field emerging in heavy ion collisions in order to probe the CP-odd effects in QCD matter.

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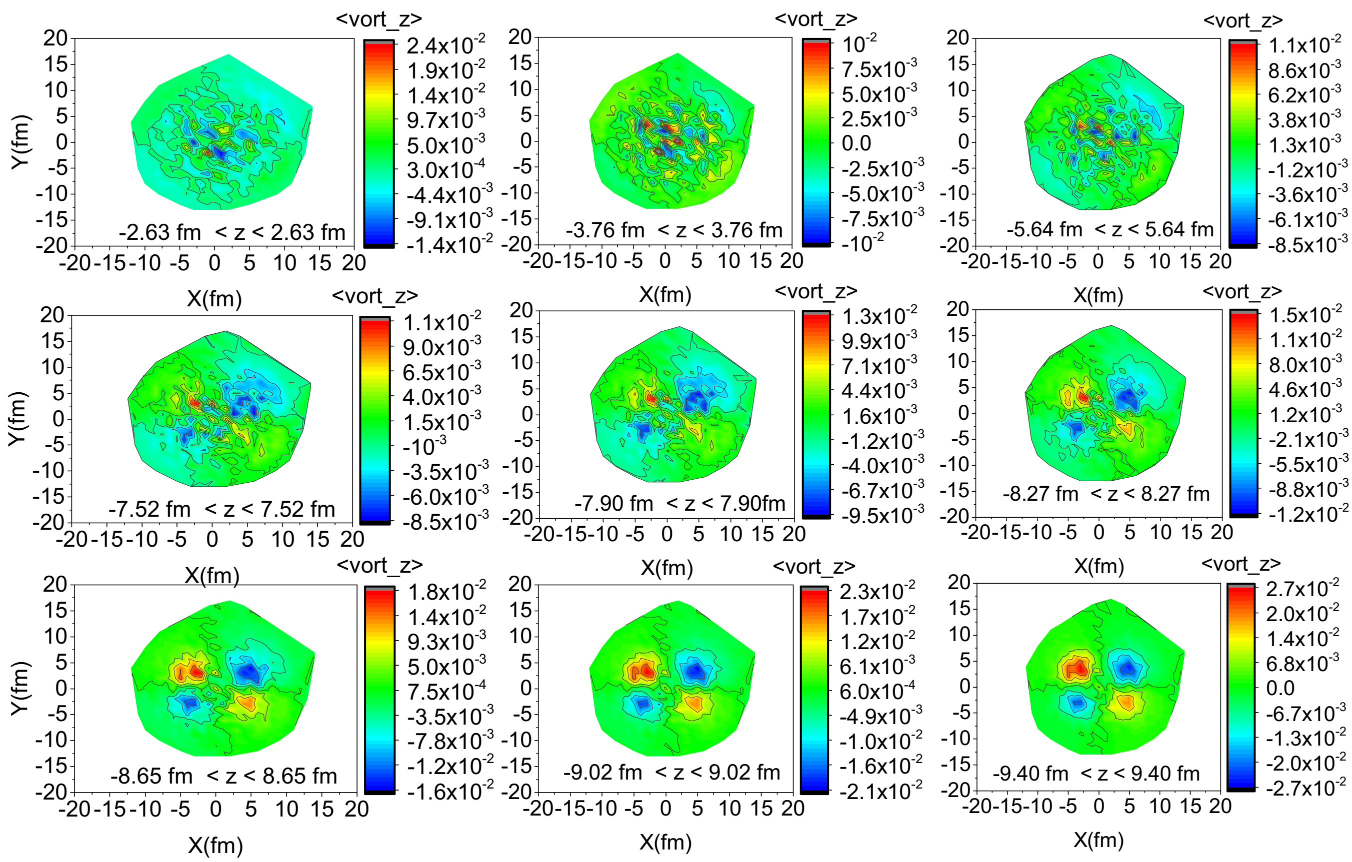

FIG. 1. Quadrupole structure of average longitudinal vorticity for different heights of the cylinders in the z direction (see text).

The polarization, in turn, is similar to chiral vortical effect (CVE) [26] caused by coupling to P-odd medium vorticity leading to the induced electromagnetic and all conserved-charge currents [13], in particular the baryonic one.

Recently the pioneering preliminary results on global polarization of Λ and $\bar{\Lambda}$ hyperons in Au-Au collisions in the beam energy scan at the BNL Relativistic Heavy Ion Collider (RHIC) were released [1] and the qualitative tendency of polarization to decrease with energy in agreement with the prediction [13] was revealed. The recent theoretical analysis [27] suggested that the decrease of polarization with energy is related to the suppression of the axial magnetic effect contribution in the 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 a temperature-dependent term related to the holographic gravitational anomaly [28], which is the holographic implementation of the mixed gauge-gravitational anomaly in four-dimensional field theories with chiral fermions. Naively it can be quite substantial and increase with energy. However, lattice simulations [29] lead to a zero result in the confined phase and to the suppression by one order of magnitude at high temperatures. Neglecting the axial chemical potential, the coefficient c_V 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 in a large lattice volume at fixed temperature the standart term corresponding to $k = 1$ is recovered [30]. It was suggested [27] that the accurate measurements of polarization energy dependence may serve as a sensitive probe of strongly correlated QCD matter. In the current paper we perform numerical simulations to implement this suggestion.

Polarization is related to the strange axial charge

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

in the following way [27] acquiring also for kinematical boost:

$$\langle \Pi_y^\Lambda \rangle = \left\langle \frac{m_\Lambda}{N_\Lambda\, p_y} \right\rangle \frac{N_c}{2\pi^2} \int d^3x\, \mu_s^2(x) \gamma^2 \epsilon^{ijk} v_i \partial_j v_k. \tag{7}$$

It is important that the sign of the transverse component of momentum p_y is different for hyperons above and below the reaction plane, compensating for the different signs of helicity [Eq. (1)], so that the signs of polarization of hyperons with different directions of transverse momentum are the same. This corresponds to the transverse component of polarization,

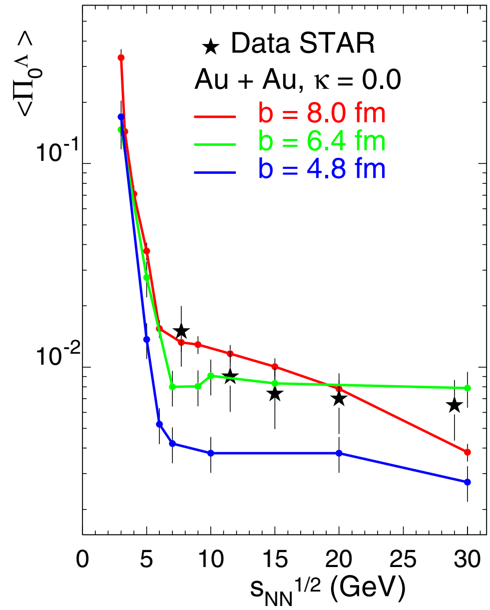

FIG. 2. Energy dependence of polarization for different values of impact parameter.

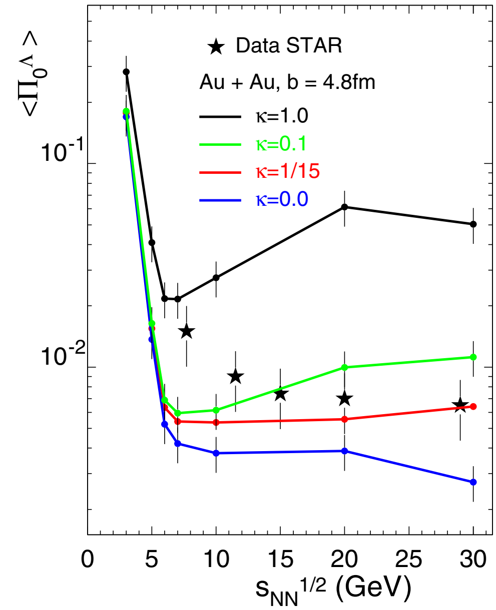

FIG. 3. Energy dependence of polarization for different values of holographic gravitational anomaly contribution.

while the consideration of its longitudinal components requires special investigation.

Note that the quark and hadronic observables appear to be related, manifesting a sort of duality that is of special importance in the confined phase. Another approach to the confined phase is provided by consideration [31] of the vortices in pionic superfluid, whose cores are associated with polarized baryons.

Numerical simulations of axial anomaly contributions to (anti)hyperon polarization. We performed the numerical simulations in the QGSM model [18–20]. We decomposed the space-time to the cells, allowing us to define velocity and vorticity in the kinetic model, as described in detail in [17]. To define the strange chemical potential (assuming that Λ polarization is carried by a 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. Such coarse-graining procedure allows one to study 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 in Fig. 2. The curves (top to bottom) correspond to $b = 8.0$, 6.4, and 4.8 fm.

We continue by the inclusion of the contribution related to gravitational anomaly, which is the central issue of this paper. The results are presented in Fig. 3. We consider as a starting point the original value of the anomaly coefficient [28] $T^2/6$ which is reproduced for a large lattice volume at fixed temperature [30]. We present the curves following from the coefficients suppressed by factor k [Eq. (5)] resulting from the lattice calculations [29]. We compare the values of $k = 1$ with $k = 0$, 1/15, and 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 the $k = 0$ curve to the experimental points may be related to the contribution of the 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, because the axial current

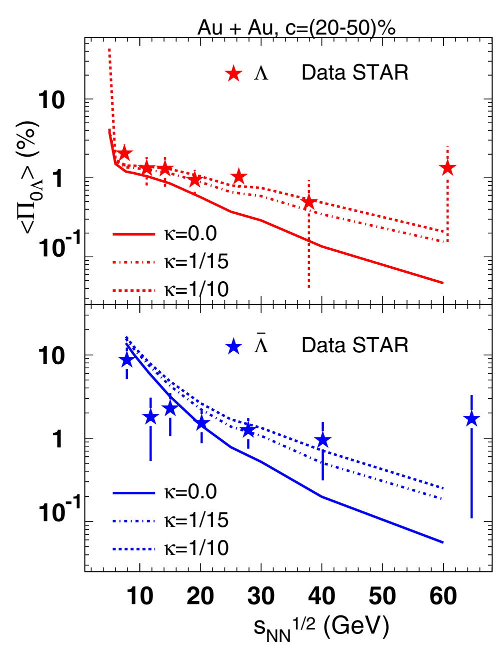

FIG. 4. Comparison of Λ and $\bar{\Lambda}$ polarizations for different values of gravitational anomaly contribution.

and charge are C-even operators. The magnitude of the $\bar{\Lambda}$ is larger because 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 Λ 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.

Note that this excess is larger for smaller energies, where suppression of $\bar{\Lambda}$ is larger. This differs from the (C-odd) effect of the 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 in Fig. 4. The result is in reasonable agreement with STAR data, although further analysis is required.

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 the 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 the 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 Λ and is growing at smaller energies. Further more accurate measurements of Λ polarization should provide the additional check of gravitational anomaly related contribution.

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[1] L. Adamczyk *et al.* (STAR Collaboration), Nature **548**, 62 (2017).
[2] F. Becattini, I. Karpenko, M. A. Lisa, I. Upsal, and S. A. Voloshin, Phys. Rev. C **95**, 054902 (2017).
[3] I. Karpenko and F. Becattini, Eur. Phys. J. C **77**, 213 (2017).
[4] I. Karpenko and F. Becattini, J. Phys. Conf. Ser. **779**, 012068 (2017).
[5] Y. Xie, R. C. Glastad, and L. P. Csernai, Phys. Rev. C **92**, 064901 (2015).
[6] R. h. Fang, J. y. Pang, Q. Wang, and X. n. Wang, Phys. Rev. D **95**, 014032 (2017).
[7] F. Becattini, L. P. Csernai, and D. J. Wang, Phys. Rev. C **88**, 034905 (2013).
[8] F. Becattini, L. Bucciantini, E. Grossi, and L. Tinti, Eur. Phys. J. C **75**, 191 (2015).
[9] B. Betz, M. Gyulassy, and G. Torrieri, Phys. Rev. C **76**, 044901 (2007).
[10] L. P. Csernai, V. K. Magas, and D. J. Wang, Phys. Rev. C **87**, 034906 (2013).
[11] L. P. Csernai, D. J. Wang, and T. Csorgo, Phys. Rev. C **90**, 024901 (2014).
[12] G. Prokhorov and O. Teryaev, Phys. Rev. D (to be published), arXiv:1707.02491.
[13] O. V. Rogachevsky, A. S. Sorin, and O. V. Teryaev, Phys. Rev. C **82**, 054910 (2010).
[14] J.-H. Gao, Z.-T. Liang, S. Pu, Q. Wang, and X.-N. Wang, Phys. Rev. Lett. **109**, 232301 (2012).
[15] T. Kalaydzhyan, Phys. Rev. D **89**, 105012 (2014).
[16] D. T. Son and P. Surowka, Phys. Rev. Lett. **103**, 191601 (2009).
[17] M. Baznat, K. Gudima, A. Sorin, and O. Teryaev, Phys. Rev. C **88**, 061901 (2013).
[18] V. D. Toneev and K. K. Gudima, Nucl. Phys. A **400**, 173c (1983).
[19] V. D. Toneev, N. S. Amelin, K. K. Gudima, S. Yu. Sivoklokov, Nucl. Phys. A **519**, 463c (1990).
[20] N. S. Amelin, E. F. Staubo, L. P. Csernai, V. D. Toneev, and K. K. Gudima, Phys. Rev. C **44**, 1541 (1991).
[21] O. Teryaev and R. Usubov, Phys. Rev. C **92**, 014906 (2015).
[22] W. Cassing and E. L. Bratkovskaya, Phys. Rep. **308**, 65 (1999).
[23] Plenary talks of F. Becattini, and S. Voloshin at SQM-2017, Utrecht, July 11-15; Plenary talks of F. Becattini and I. Karpenko, Phys. Rev. Lett. **120**, 012302 (2018).
[24] M. I. Baznat, K. K. Gudima, A. S. Sorin, and O. V. Teryaev, Phys. Rev. C **93**, 031902 (2016).
[25] K. Fukushima, D. E. Kharzeev, and H. J. Warringa, Phys. Rev. D **78**, 074033 (2008).
[26] D. Kharzeev and A. Zhitnitsky, Nucl. Phys. A **797**, 67 (2007).
[27] A. Sorin and O. Teryaev, Phys. Rev. C **95**, 011902 (2017).
[28] K. Landsteiner, E. Megias, L. Melgar, and F. Pena-Benitez, J. High Energy Phys. **1109**, 121 (2011).
[29] V. Braguta, M. N. Chernodub, K. Landsteiner, M. I. Polikarpov, M. V. Ulybyshev, Phys. Rev. D **88**, 071501 (2013); V. Braguta, M. N. Chernodub, V. A. Goy, K. Landsteiner, A. V. Molochkov, and M. I. Polikarpov, *ibid.* **89**, 074510 (2014); V. Braguta, M. N. Chernodub, V. A. Goy, K. Landsteiner, A. V. Molochkov, and M. Ulybyshev, AIP Conf. Proc. **1701**, 030002 (2016); V. Goy, Investigation of SU(2) gluodynamics in the framework of the lattice approach, Ph.D. thesis (in Russian), Far Eastern Federal University, Vladivostok, 2015.
[30] P. V. Buividovich, J. Phys. Conf. Ser. **607**, 012018 (2015).
[31] O. V. Teryaev and V. I. Zakharov, Phys. Rev. D **96**, 096023 (2017).