Global polarization in heavy-ion collisions based on axial vortical effect

Yu. B. Ivanov\textsuperscript{1,2,3,*}

\textsuperscript{1}Bogoliubov Laboratory for Theoretical Physics, Joint Institute for Nuclear Research, Dubna 141980, Russia
\textsuperscript{2}National Research Nuclear University "MEPhI", Moscow 115409, Russia
\textsuperscript{3}National Research Centre "Kurchatov Institute", Moscow 123182, Russia

Global polarization of $\Lambda$ and $\bar{\Lambda}$ is calculated based on the axial vortical effect (AVE). Simulations are performed within the model of the three-fluid dynamics. Equations of state with the deconfinement transition result in a good agreement with STAR data for both $\Lambda$ and $\bar{\Lambda}$ polarization, in particular, with the $\Lambda$-$\bar{\Lambda}$ splitting. Suppression of the gravitational-anomaly contribution required for the data reproduction is in agreement with predictions of the QCD lattice simulations. Predictions for the global polarization in forthcoming experiments at lower collision energies are made. These forthcoming data will provide a critical test for the AVE and thermodynamic mechanisms of the polarization.

PACS numbers: 25.75.-q, 25.75.Nq, 24.10.Nz
Keywords: relativistic heavy-ion collisions, hydrodynamics, polarization

I. INTRODUCTION

Experimental discovery of global and local polarization of hadrons in STAR experiments \cite{1-3} gave us evidence of existence of a new class of collective phenomena in heavy-ion collisions \cite{4}. The thermodynamic approach based on hadronic degrees of freedom \cite{5,7} well describes the global polarization of hyperons \cite{1,2} as it was demonstrated by its implementations within various hydrodynamical \cite{8,11} and transport \cite{12,16} models of heavy-ion collisions. However, this approach encounters problems.

The thermodynamic approach predicts wrong sign of the local longitudinal polarization as compared with that measured in the STAR experiment \cite{8}. This discrepancy is rather robust, it comes out in both hydrodynamical \cite{17,18} and transport \cite{15,19,20} calculations. The thermodynamic approach fails to explain preliminary results on alignment of of $\phi$ and $K^*$ mesons \cite{21} at energies of the Relativistic Heavy Ion Collider (RHIC).

The above problems indicate that the mechanism of particle polarization in heavy-ion collisions is not that clear so far. Therefore, alternative approaches should be considered. An alternative approach based on the axial vortical effect (AVE) \cite{22,24} assumes equilibrium but not for spin degrees of freedom. The first applications of this approach \cite{28,29} within the Quark-Gluon-String Model (QGSM) \cite{25,27} and a multiphase transport model \cite{30} demonstrated its ability to describe the data on the global polarization and to naturally explain the $\Lambda$-$\bar{\Lambda}$ splitting \cite{28}. The AVE approach also gives qualitatively correct local longitudinal polarization \cite{31}.

In this paper, we report calculation of the global polarization of $\Lambda$ and $\bar{\Lambda}$ based on the AVE approach. Simulations are performed within 3FD model \cite{32}. The 3FD model is based on minimal way to implement the early-stage nonequilibrium of the produced strongly-interacting matter at high collision energies. This early nonequilibrium stage is modeled by means of two counterstreaming baryon-rich fluids (p and t fluids). Newly produced particles, dominantly populating the midrapidity region, are associated with a fireball (f) fluid. These fluids are governed by conventional hydrodynamic equations coupled by friction terms in the right-hand sides of the Euler equations.

Calculations were carried out with two versions of equation of state (EoS) with the deconfinement transition \cite{33}, i.e. a first-order phase (1PT) transition and a crossover one. Results with hadronic EoS \cite{34} are also presented. The physical input of the present 3FD calculations is described in Ref. \cite{35}.

II. POLARIZATION BASED ON THE AVE

Presence of vorticity in a system

\begin{equation}
\omega_{\mu\nu} = \frac{1}{2} (\partial_\nu u_\mu - \partial_\mu u_\nu),
\end{equation}

where $u_\mu(x)$ is local 4-velocity of the medium, induces the axial current of chiral particles

\begin{equation}
J_5^\nu(x) = N_c \left( \frac{\mu^2}{2\pi^2} + \kappa \frac{T^2}{6} \right) \epsilon^{\nu\alpha\beta\gamma} u_\alpha \partial_\beta u_\gamma
\end{equation}

where $\mu$ is the chemical potential of these particles, $T$ is the temperature of the medium, and $\kappa$ is a parameter discussed below. Spins of these particles get aligned along the direction of the axial current. Thus, these particles become polarized. This is the essence of the axial vortical effect \cite{22,24}.

While the first term $\sim \mu^2$ in the braces of Eq. \cite{2} is topologically protected, i.e. it is related to topological invariant in the momentum space, the term $\sim T^2$ related to gravitational anomaly \cite{30} is not. Therefore, similarly to Ref. \cite{28} a parameter $\kappa$ is introduced into Eq. \cite{2} which scales this gravitational term. Lattice simulations

*e-mail: yivanov@theor.jinr.ru
of Ref. \cite{37} result in zero \( \kappa \) in the confined phase and predict suppression of the gravitational term by one order of magnitude, i.e. \( \kappa \approx 0.1 \), at very high temperatures \( T > 400 \) MeV.

We are interested in \( \Lambda \) and \( \bar{\Lambda} \) hyperons. Their polarization is related to the axial current of (anti)strange quark \( J_{3s}^A \), which differs from \cite{2} by replacement of the chemical potential \( \mu \) by the chemical potential of (anti)strange quark \( \mu_s = -\mu_{\bar{s}} = \mu_B/3 - \mu_S \), where \( \mu_B \) is the baryon chemical potential and \( \mu_S \) is the strange one. Following Refs. \cite{23} \cite{28}, the global polarization of \( \Lambda \) and \( \bar{\Lambda} \) is related to \( J_{3s}^A \) as

\[
P_{\Lambda} = \int d^3x \frac{(J_{3s}^A / u_y) / (N_\Lambda + N_{K^*})}{\langle \omega_{xz} \rangle}, \tag{3}
\]

\[
P_{\bar{\Lambda}} = \int d^3x \frac{(J_{3s}^A / u_y) / (N_{\bar{\Lambda}} + N_{\bar{K}^*})}{\langle \omega_{xz} \rangle}, \tag{4}
\]

where \( u_y \) is \( y \)-component of the 4-velocity, \( N_\Lambda \) and \( N_{\bar{\Lambda}} \) are numbers of produced \( \Lambda \)'s and \( \bar{\Lambda} \)'s, respectively, and \( N_{K^*} \) and \( N_{\bar{K}^*} \) are numbers of produced \( K^* \) and \( \bar{K}^* \) mesons, respectively. Here \( N_\Lambda \) and \( N_{\bar{\Lambda}} \) count the number of strange quarks which carry the polarization, similarly for anti-strange quarks. This is because only strange particles with nonzero spin carry the \( s \)-quark polarization. The \( 1/u_y \) factor results from boost to the rest frame of the fluid element.

Expressions \cite{2} and \cite{4} are just estimates of the polarization rather than rigorously derived formulas. In the original papers \cite{23} \cite{28} the boost was made to the rest frame of the produced hyperon, where the polarization is measured. A shortcoming of that recipe is that the result of averaging over momenta of produced hyperons diverges. Indeed, only the \( 1/p_y \) factor, resulted from that boost, depends on the momentum in Eqs. \cite{3} and \cite{4}, which results in divergence at low \( p_y \). In addition, the boost to the fluid local rest frame is more natural because this approach deals only with properties of the medium rather than with separate particles. The \( u_y \) component of the 4-velocity in Eq. \cite{2} cancel the \( 1/u_y \) factor thus eliminating the divergence.

Thus, collecting all together, we arrive at the expression in terms quantities averaged over the medium \( \langle (... \rangle \) \n
\[
P_{\Lambda} = \frac{N_c}{(n_\Lambda + n_{\bar{K}^*})} \left\langle \frac{\mu_s^2}{2\pi^2} + \frac{\kappa}{3} \frac{T^2}{6} \right\rangle \langle \omega_{xz} \rangle \tag{5}
\]

where \( n_\Lambda \) and \( n_{\bar{K}^*} \) are densities of \( \Lambda \)'s and \( \bar{K}^* \) mesons, respectively. Similar result holds for \( P_{\bar{\Lambda}} \). Here we decoupled averaging of the vorticity and the prefactor.

### III. GLOBAL POLARIZATION

The above approach is very suitable for the calculation of the global vorticity within the method suggested in Refs. \cite{10} \cite{11}. This method consists in calculation of average polarization in the central region of colliding nuclei, the right and left borders of which are chosen from the condition \( |y| \leq 0.5 \). The rapidity \( y \) is calculated based on hydrodynamical velocities. The experimental acceptance \( |\eta| < 1 \), where \( \eta \) is pseudorapidity, better comply with the condition \( |y| \leq 0.7 \) in terms of the true \( y \) rapidity \cite{11}. However, hydrodynamical rapidity does not well coincide with the true one at low collision energies. Taking also into account that the condition \( |y| \leq 0.5 \) results in better reproduction of the data at low collision energies while only slightly differing from the \( |y| \leq 0.7 \) results at high energies \cite{11}, we took the condition \( |y| \leq 0.5 \) for the theoretical acceptance. Details of the polarization calculation in the central region are described in Ref. \cite{11}. The calculation of the AVE polarization is very similar to the thermodynamical one in Ref. \cite{11}. 3FD simulations of Au+Au collisions were performed at fixed impact parameter \( b = 8 \) fm. This impact parameter was taken to roughly comply with the STAR centrality selection of 20-50\% \cite{1}. Glauber simulations of Ref. \cite{38} were used to relate the experimental centrality and the mean impact parameter.

![Fig. 1: Global polarization of \( \Lambda \) hyperons in Au+Au collisions at \( b = 8 \) fm as function of collision energy \( \sqrt{s_{NN}} \). Upper borders of the bands correspond to parameters \( \kappa \) [see Eq. (3)] displayed in the legend, while the lower borders -- to \( \kappa = 0 \). STAR data on global \( \Lambda \) and \( \bar{\Lambda} \) polarization \cite{11} are also displayed.](image1.png)

![Fig. 2: The same as in Fig. 1 but for the \( \bar{\Lambda} \) hyperons.](image2.png)
we present results without this term, i.e. $\kappa = 0$, see Eq. (2), and with this term fitted to reproduce data on the global polarization at high collision energies. The results of these fitted values of $\kappa$ are displayed in Figs. 1 and 2. Though being EoS dependent, the matched values of $\kappa$ are the same for $\Lambda$'s and $\bar{\Lambda}$'s, as it should be. Moreover, at lowest considered collision energy, $\sqrt{s_{NN}} = 7.7$ GeV, the data better agree with results without the gravitational term, i.e. $\kappa = 0$, while at higher energies - with those, where this term is suppressed by more than one order of magnitude. All this agrees with predictions of lattice simulations of Ref. [11]. Suppression by more than one order of magnitude at higher energies also matches with the lattice results [37].

IV. CONCLUSIONS

Calculation of the global polarization of $\Lambda$ and $\bar{\Lambda}$ are made based on the AVE approach. Simulations are performed within 3FD model [32]. EoS’s with the deconfinement transition result in a good agreement with STAR data [1] for both $\Lambda$ and $\bar{\Lambda}$ polarization, in particular, with the $\Lambda$-$\bar{\Lambda}$ splitting. Suppression of the gravitational-anomaly contribution required for the data reproduction is in agreement with predictions of the QCD lattice simulations [37]. At the lowest considered collision energy, $\sqrt{s_{NN}} = 7.7$ GeV, the data better comply with results without the gravitational term, while at higher energies - with results, where this term is suppressed by more than one order of magnitude. At the same time, the hadronic EoS fails to reproduce the data on the global polarization.

The AVE global polarization rises with the collision-energy decrease faster than the thermodynamic polarization does [11], as the 3FD simulations beyond the RHIC range indicate. Therefore, the forthcoming data from the Facility for Antiproton and Ion Research (FAIR) and Nuclotron-based Ion Collider Facility (NICA) will provide a critical test for the AVE and thermodynamic approaches.

Acknowledgments

Fruitful discussions with O. V. Teryaev are gratefully acknowledged. This work was carried out using computing resources of the federal collective usage center “Complex for simulation and data processing for mega-science facilities” at NRC "Kurchatov Institute", http://ckp.nrcki.ru/. This work was partially supported by the Russian Foundation for Basic Research, Grants No. 18-02-40084 and No. 18-02-40085, and by the Ministry of Education and Science of the Russian Federation within the Academic Excellence Project of the NRNU MEPhI under contract No. 02.A03.21.0005.

[1] L. Adamczyk et al. [STAR Collaboration], Nature 548, 62 (2017) [arXiv:1701.06657 [nucl-ex]].
[2] J. Adam et al. [STAR Collaboration], Phys. Rev. C 98, 014910 (2018) [arXiv:1805.04400 [nucl-ex]].
[3] J. Adam et al. [STAR], Phys. Rev. Lett. 123, no.13, 132301 (2019) [arXiv:1905.11917 [nucl-ex]].
[4] F. Becattini and M. Lisa, arXiv:2003.03640 [nucl-ex].
[5] F. Becattini, V. Chandra, L. Del Zanna and E. Grossi, Annals Phys. 338, 32 (2013) [arXiv:1303.3431 [nucl-th]].
[6] R. h. Fang, L. g. Pang, Q. Wang and X. n. Wang, Phys. Rev. C 94, no. 2, 024904 (2016) [arXiv:1604.04036 [nucl-th]].
[7] F. Becattini, I. Karpenko, M. Lisa, I. Upsal and S. Voloshin, Phys. Rev. C 95, no. 5, 054902 (2017) [arXiv:1610.02506 [nucl-th]].
[8] I. Karpenko and F. Becattini, Eur. Phys. J. C 77, no. 4,
