

Recent progress on global and local polarization of hyperons in heavy-ion collisions

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Abstract. Since the observation of Λ global polarization at RHIC, indicating the most vortical fluid ever observed so far, many experimental and theoretical progresses have been made in understanding of vorticity and polarization phenomena in heavy-ion collisions. But there still exist open questions which are currently being studied. In these proceedings, recent experimental results on global and local polarization of hyperons in heavy-ion collisions are reviewed.

1 Introduction

A partial conversion of an orbital angular momentum carried by two colliding nuclei into spin angular momentum of produced particles is referred to as global polarization [1–3]. Observation of Λ global polarization by STAR experiment [4] revealed the creation of most vortical fluid ever observed. It will also help to constrain the lifetime of the initial magnetic field created in the collisions as the direction of the magnetic field coincides with the orbital angular momentum direction. While the experimental results of average global polarization are well reproduced by theoretical models, most of which are based on local thermal equilibrium, there are open questions and some of differential measurements including local polarization are not yet fully understood. Study of the polarization phenomena in heavy-ion collisions is relatively new but rapidly growing in this field, providing new information on the initial condition, medium properties, and the collision dynamics. In these proceedings, recent results of hyperon polarization in heavy-ion collisions are reviewed.

2 Global polarization

Global polarization P_H , the polarization component along the initial orbital angular momentum carried by two colliding nuclei in heavy-ion collisions, was first observed using Λ hyperons in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ -200 GeV by STAR experiment [4, 5] where the polarization signal decreases with increasing the energy. There was also an attempt to measure it at the LHC energy but the result is consistent with zero as the expected signal is at the level of current precision. Theoretical models predict that the polarization increases starting from $\sqrt{s_{NN}} \sim 2m_N$ and becomes a maximum around $\sqrt{s_{NN}} = 3$ GeV and the peak position could be different between Λ and $\bar{\Lambda}$ [6].

Recently, the measurement has been extended to lower energies by STAR fixed-target mode and HADES experiment [7, 8]. Figure 1(left) shows a compilation of Λ global polarization as a function of the collision energy. New results at 3 GeV from STAR and at 2.4

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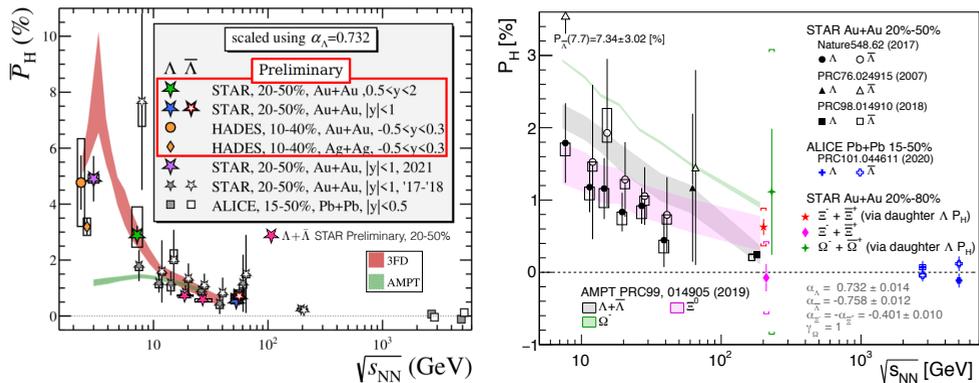


Figure 1. (Left) Global polarization of Λ and $\bar{\Lambda}$ hyperons as a function of the center-of-mass energy from STAR, ALICE, and HADES experiments [10]. (Right) global polarization of Ξ and Ω hyperons compared to that of Λ hyperons as a function of the collision energy [11].

and 2.55 GeV from HADES still show an increasing trend of the global polarization, consistent with the calculation from the hydrodynamic model based on three-fluid dynamics [9]. Note that the lower energy corresponds to the high baryon density region where the medium properties would be notably different. It should be also noted that the detector acceptance in rapidity and transverse momentum p_T affects the energy dependence since it covers only mid-rapidity at higher energies while it does a nearly whole distribution of produced particles at lower energies. Theoretical models predict the rapidity dependence of global polarization differently although the current measurements do not show any significant dependence [5, 7, 8]. Difference between Λ and $\bar{\Lambda}$, as a measure of the initial magnetic field, is not significant with large uncertainties which will be improved in the beam energy scan phase-II at RHIC-STAR.

To confirm the vorticity and global polarization picture, it is important to have the measurements for different particle species, preferably with different spins, which provides new insights into the polarization mechanism in heavy-ion collisions. Recently, the measurements with multistrangeness, i.e. Ξ (spin-1/2) and Ω (spin-3/2), have been performed by STAR experiment [11]. Unlike for Λ hyperons ($\alpha_\Lambda = 0.732$), the magnitude of decay parameter is small for Ξ ($\alpha_\Xi = -0.401$) and is close to zero for Ω ($\alpha_\Omega = 0.0157$) which makes the polarization measurement difficult. One can use the measurement of daughter Λ polarization to know its parent particle's polarization: $P_\Lambda^* = C_{X\Lambda} P_X^*$ where P_X^* and P_Λ^* are polarizations of parent particle X and its daughter Λ in parent rest frame, and $C_{X\Lambda}$ denotes polarization transfer factor. The factor $C_{X\Lambda}$ is +0.944 for the decay of $\Xi^- \rightarrow \Lambda\pi^-$ and could be either +1 or -0.6 for the decay of $\Omega^- \rightarrow \Lambda K^-$ due to the uncertainty of decay parameter $\gamma_\Omega (\approx \pm 1)$. Based on the vorticity picture, the sign of γ_Ω can be determined by the measurement of Ω global polarization.

Figure 1(right) shows global polarization of Ξ and Ω hyperons comparing to Λ global polarization as well as transport model calculations. The global polarization averaged over transverse momentum and rapidity for 20-80% Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is measured to be $\langle P_\Lambda \rangle = 0.24 \pm 0.03(\text{stat}) \pm 0.03(\text{stat})\%$, $\langle P_\Xi \rangle = 0.47 \pm 0.10(\text{stat}) \pm 0.23(\text{stat})\%$, and $\langle P_\Omega \rangle = 1.11 \pm 0.87(\text{stat}) \pm 1.97(\text{stat})\%$. Based on thermal model in the nonrelativistic limit [12], the polarization can be given by

$$P = \langle s \rangle / s \approx (s + 1)\omega / (3T), \quad (1)$$

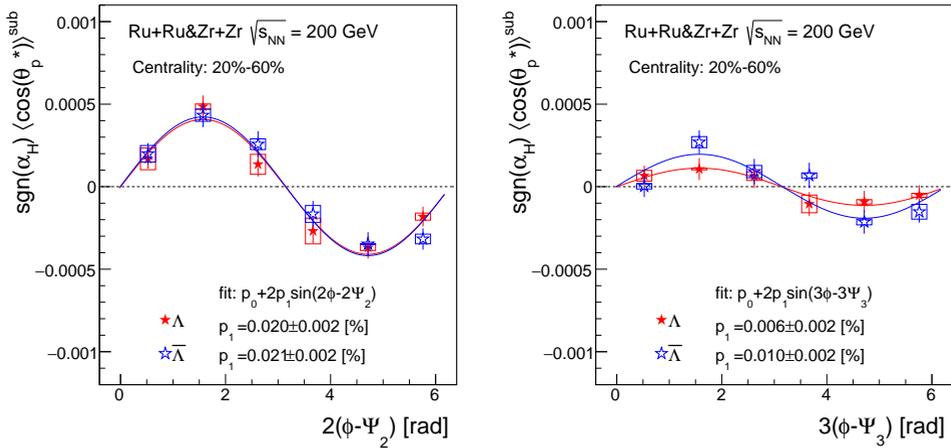


Figure 2. Longitudinal polarization of Λ and $\bar{\Lambda}$ hyperons, $\langle \cos \theta_p^* \rangle \approx P_z \alpha_H / 3$, as a function of azimuthal angle with respect to the second-order event plane Ψ_2 (left) and to the third order event plane Ψ_3 (right) in 20-60% isobar (Ru+Ru and Zr+Zr) collisions at $\sqrt{s_{NN}} = 200$ GeV [22]. The solid lines are fit functions as indicated in the figures.

where s is the spin of the particle, ω is the local vorticity of the fluid, and T is the temperature. There seems to be a hierarchy in the measured $\langle P_H \rangle$ as expected from Eq. (1) although the uncertainty is still large to make definitive conclusion. The current measurement seems to favor the decay parameter γ_Ω to be +1. More precise measurements in the future runs at RHIC and the LHC will help to shed light on the uncertainty of γ_Ω as well as for better understanding of the polarization dependence on particle species.

3 Local polarization

In general, local velocity would depend on many other things, such as density fluctuations, the effect of jets passing through the medium, and collective flow. Thus vorticity could be created locally in heavy-ion collisions [13–15]. Vorticity along the beam direction, therefore the polarization, is expected to be induced by elliptic flow, i.e. stronger expansion (more particle emission) in the reaction plane direction than in the out-of-plane direction [16, 17]. Such a longitudinal polarization was first observed in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by STAR experiment [18], and later in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV by ALICE experiment [19]. There have been extensive theoretical studies to understand the data since the hydrodynamic and transport models fail to explain the sign of the observed signal, although they reasonably describe the data of the global polarization. New term of shear tensor proposed in Refs. [20, 21] seems to be necessary to explain the data but further experimental inputs are needed for better understanding.

Recent high statistics data in isobar collisions at $\sqrt{s_{NN}} = 200$ GeV taken by STAR allow to study the polarization even with higher harmonic flow plane. Figure 2 shows raw signal of the longitudinal polarization as a function of hyperon’s azimuthal angle relative to the second-order (left) and third-order (right) event planes [22]. Results with the second-order event plane show a clear sine modulation as seen in Au+Au collisions. Results with the third-order event plane also exhibit a similar sinusoidal pattern relative to the azimuthal angle, indicating that vorticity along the beam direction is induced by triangular flow as well as elliptic flow. Hydrodynamic model with the shear term [23] qualitatively explain the data

for both the second and third-orders in central-midcentral collisions (but not in peripheral collisions), showing sensitivity of the measurement to specific shear viscosity of quark-gluon plasma formed in the collisions.

4 Summary

In these proceedings, recent progress on the polarization measurements has been reviewed. Thanks to new experimental data at lower energies, energy dependence of global polarization has been studied in detail. Interestingly, the global polarization smoothly increases in lowering collision energy, with a possible maximum around $\sqrt{s_{NN}} = 3$ GeV, despite the change from partonic matter to hadronic matter in studied energy range. The uncertainty is still large but it can be improved in future analyses or experiments. Measurements with multistrangeness are of great interest and future improvements will provide critical information on spin dynamics in the collisions. New measurement on local polarization with the third-order event plane in isobar collisions indicates the creation of triangular-flow-driven vorticity along the beam direction, which shed light on the sign problem of the local polarization.

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References

- [1] Z.T. Liang, X.N. Wang, Phys. Rev. Lett. **94**, 102301 (2005), [Erratum: Phys.Rev.Lett. 96, 039901 (2006)]
- [2] S.A. Voloshin (2004), [nucl-th/0410089](#)
- [3] F. Becattini, F. Piccinini, J. Rizzo, Phys. Rev. C **77**, 024906 (2008)
- [4] L. Adamczyk et al. (STAR), Nature **548**, 62 (2017)
- [5] J. Adam et al. (STAR), Phys. Rev. C **98**, 014910 (2018)
- [6] A. Ayala, I. Domínguez, I. Maldonado, M.E. Tejeda-Yeomans, Phys. Rev. C **105**, 034907 (2022)
- [7] M.S. Abdallah et al. (STAR), Phys. Rev. C **104**, L061901 (2021)
- [8] R. A. Yassine et al. (HADES) (2022), [2207.05160](#)
- [9] Y.B. Ivanov, Phys. Rev. C **103**, L031903 (2021)
- [10] J. Adams (STAR), Quark Matter 2022
- [11] J. Adam et al. (STAR), Phys. Rev. Lett. **126**, 162301 (2021)
- [12] F. Becattini, I. Karpenko, M. Lisa, I. Upsal, S. Voloshin, Phys. Rev. C **95**, 054902 (2017)
- [13] L.G. Pang, H. Petersen, Q. Wang, X.N. Wang, Phys. Rev. Lett. **117**, 192301 (2016)
- [14] B. Betz, M. Gyulassy, G. Torrieri, Phys. Rev. C **76**, 044901 (2007)
- [15] X.L. Xia, H. Li, Z.B. Tang, Q. Wang, Phys. Rev. C **98**, 024905 (2018)
- [16] S.A. Voloshin, EPJ Web Conf. **171**, 07002 (2018)
- [17] F. Becattini, I. Karpenko, Phys. Rev. Lett. **120**, 012302 (2018)
- [18] J. Adam et al. (STAR), Phys. Rev. Lett. **123**, 132301 (2019)
- [19] S. Acharya et al. (ALICE), Phys. Rev. Lett. **128**, 172005 (2022)
- [20] F. Becattini, M. Buzzegoli, G. Inghirami, I. Karpenko, A. Palermo, Phys. Rev. Lett. **127**, 272302 (2021)
- [21] B. Fu, S.Y.F. Liu, L. Pang, H. Song, Y. Yin, Phys. Rev. Lett. **127**, 142301 (2021)
- [22] T. Niida (STAR), Quark Matter 2022
- [23] S. Alzhrani, S. Ryu, C. Shen, Phys. Rev. C **106**, 014905 (2022)