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$\Lambda(\overline{\Lambda})$ polarization in Au+Au collisions at RHIC

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Abstract. Initial large global angular momentum in non-central relativistic heavy-ion collisions can produce strong vorticity, and through the spin-orbit couping, causes the spin of particles to align with the system's global angular momentum. We present the azimuthal angle dependent (relative to the first-order plane) global polarization for Λ hyperons in midcentral Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. We also present the polarization of Λ hyperons along the beam direction as a function of Λ hyperons' emission angle relative to the second-order event plane at $\sqrt{s_{NN}}$ = 200 GeV. This longitudinal polarization is found to increase in more peripheral collision. The implications of the results are discussed.

1 Introduction

It is believed that a strongly interacting, hot and dense medium known as Quark Gluon Plasma (QGP) [1] has been created in high-energy heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC). In non-central collisions, the initial angular momentum associated with the receding spectators is large ($\sim 1000\hbar$), and can be transferred to quarks through the spin-orbit coupling [2, 3]. Such effect can manifest itself via final-state hadrons and is detectable through the $\Lambda(\overline{\Lambda})$ polarization. Therefore, measurements of the polarization of the particles produced in heavy-ion collisions can provide new insights into the initial conditions and evolution of the QGP [4, 5].

The STAR experiment at RHIC has observed for the first time a significant alignment between the angular momentum of the medium produced in non-central collisions and the spin of $\Lambda(\overline{\Lambda})$ hyperons (J=1/2), revealing that the matter produced in heavy-ion collisions is by far the most vortical system ever observed [6]. Such vorticity is expected to depend on hyperon's azimuthal angle, however, so far the theoretical guidances on the azimuthal angle dependence of global polarization are not consistent [7–11], due to various treatments on how spin is transported in the fluid. Thus the experimental study of the azimuthal angle dependence of hyperon polarization can help us in understanding transport properties of the system and shed light on dynamics in a highly vortical, low viscous environment.

The averaged vorticity of the system is generated by the initial orbital angular momentum of the medium, and therefore hyperons are globally polarized. The vorticity can also be locally non-zero in general. Because of the presence of elliptic flow in non-central heavy-ion collisions, particles flying in the reaction plane tend to have larger velocity than those flying

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out of the plane. Such a gradient in particle flow velocity may create a local vorticity along the beam direction [12–14]. This can lead to $\Lambda(\overline{\Lambda})$ polarization along the beam direction. The study of longitudinal polarization can help us to understand when and how the vorticity and polarization are coupled with other dynamics of the system evolution.

2 Observable

The global polarization of Λ hyperons can be determined from the angular distribution of hyperon decay products relative to the system's orbital momentum **L** [15]:

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1 + \alpha_H P_H \cos\theta^*), \tag{1}$$

where P_H is the hyperon global polarization, α_H is the hyperon decay parameter (α_Λ = -$\alpha_{\overline{\Lambda}}$ = 0.642), and θ^* is the angle in the Λ rest frame between the system orbital angular momentum (**L**) and the three-momentum of the daughter proton from the hyperon decay. Here, the orbital angular momentum of the system points to the direction perpendicular to the reaction plane. By averaging over all phase space, we extract the average projection of the polarization on **L** [16]:

$$\overline{P}_H = -\frac{8}{\pi\alpha_H}\frac{< \sin(\phi^* - \Psi_{EP}) >}{R_{EP}}, \tag{2}$$

where Ψ_{EP} is the angle of the first-order event plane that is an estimation of the true, reaction plane angle Ψ_{RP}, ϕ^* is the azimuthal angle of the daughter proton (antiproton) in the $\Lambda(\overline{\Lambda})$ frame, $R_{EP} = < \cos(\Psi_{RP} - \Psi_{EP}) >$ is the event plane resolution.

Similar to the global polarization, the longitudinal polarization can be measured by projecting onto the beam direction, P_z, and can be expressed as:

$$P_z = \frac{\langle \cos\theta_p^\star \rangle}{\alpha_H \langle (\cos\theta_p^\star)^2 \rangle} = \frac{3\langle \cos\theta_p^\star \rangle}{\alpha_H}, \tag{3}$$

where $\cos\theta_p^\star$ is the angle in the hyperon rest frame between beam direction and the three-momentum of the daughter proton from the hyperon decay. The term $\langle (\cos\theta_p^\star)^2 \rangle$ accounts for non-uniformity of detector in pseudorapidity and was found to be close to 1/3 on average in all centralities.

In this analysis we use charged particles reconstructed by the Time Projection Chamber (TPC) and matched to the Time Of Flight (TOF) detector near midrapidity ($|\eta| < 1.0$). We reconstruct $\Lambda(\overline{\Lambda})$ invariant masses through its decay channel: Λ $(\overline{\Lambda}) \rightarrow p + \pi^-$ $(\overline{p} + \pi^+)$. Topological and kinematic cuts are applied to reduce the combinatorial background. The direction of **L** is determined by the first-order event plane reconstructed using the information from the Shower Maximum Detectors in Zero Degree Calorimeters. The direction of the second-order event plane is reconstructed with the TPC tracks. For $\Lambda(\overline{\Lambda})$ analysis, the results are based on 440 M and 1000 M minimum bias events taken in years 2011 and 2014.

3 Results

3.1 Azimuthal angle dependence of $\Lambda(\overline{\Lambda})$ polarization

In Fig. 1, the resolution-corrected P_H, for Λ and $\bar{\Lambda}$ combined, is presented as as a function of $\phi_\Lambda - \Psi_1$ at midrapidity in 20-50% central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Here, the P_H between Λ and $\overline{\Lambda}$ were combined to increase the statistical significance. When the P_H is

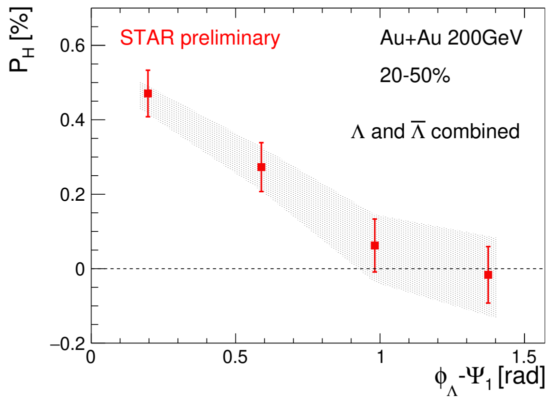

Figure 1: Global polarization of Λ+$\overline{\Lambda}$ as a function of azimuthal angle ϕ relative to the first-order event plane for 20-50% central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The shaded band shows systematic uncertainty.

presented as a function of $\phi_\Lambda - \Psi_1$, the measured event plane is different from reaction plane, so both the P_H and $\phi_\Lambda - \Psi_1$ are affected. The smearing of reaction plane not only reduces the observed averaged polarization, but also makes the observed azimuthal dependence weaker. We followed the procedure in [17] to correct for the event plane resolution. The finite P_H, averaged over four $\phi_\Lambda - \Psi_1$ is ∼ 0.2% which is consistent with STAR's previous published result [18]. We see that the P_H is positive for in-plane going $\Lambda(\bar{\Lambda})$ and decreases with increasing $(\phi_\Lambda - \Psi_1)$, and P_H for out-of-plane going $\Lambda(\bar{\Lambda})$ is consistent with zero. The larger in-plane than out-of-plane polarization is consistent with the picture of maximum vorticity in the equator and low viscosity of the system. This pattern so far is not present in model calculations [7–11], reflecting that our understanding of the vorticity field and its evolution is not yet complete.

3.2 Longitudinal $\Lambda(\overline{\Lambda})$ polarization

The left panel of Fig. 2 shows $\langle \cos\theta_p^\star \rangle$ as a function of azimuthal angle relative to the second-order event plane. The solid lines are fitting functions with $p_0(1 + 2p_1 \sin(2(\phi_\Lambda - \Psi_2)))$. Here, Ψ_2 is the second order event plane reconstructed by TPC tracks. The smearing correction of $\phi - \Psi_2$ bins is not applied yet. The data points clearly show a *sine* structure for both Λ and $\overline{\Lambda}$, indicating the existence of local vorticity field. This longitudinal polarization is larger than zero in the first quadrant, but smaller than zero in the second quadrant. The sign of this quadrupole structure is consistent with a naive picture of local vorticity generated by elliptic flow [12], but not consistent with the theoretical calculations [13, 14].

In the right panel of Fig. 2, the second-order Fourier *sine* coefficient of P_z, $\langle P_z \sin(2(\phi_\Lambda - \Psi_2))\rangle$, is presented as a function of centrality. It increases from most central to midcentral collisions for both Λ and $\overline{\Lambda}$ which is similar to the centrality dependence of the elliptic flow. But in peripheral collisions it is not clear whether the signal would drop off or keep increasing due to the large uncertainties.

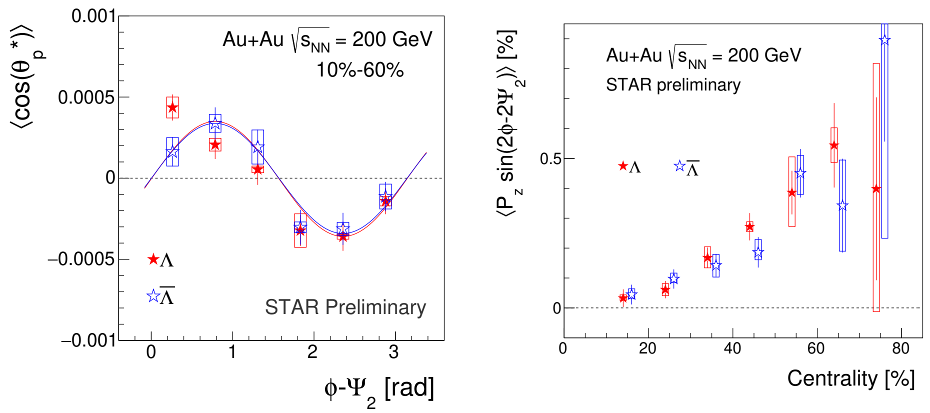

Figure 2: Left panel: $\cos(\theta_p^\star)$ and as a function of $\Lambda(\overline{\Lambda})$ hyperons's azimuthal angle ϕ relative to the second-order event plane for 10-60% centrality bin in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Open boxes show the systematic uncertainties. Note that the resolution on Ψ_2 is not corrected here. Right panel: Sine modulation of polarization along the beam direction relative to the second-order event plane as a function of centrality in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Open boxes show the systematic uncertainties.

4 Summary

The measurements of the Λ and $\overline{\Lambda}$ polarization as a function of azimuthal angle relative to the first-order event plane in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV is presented. Larger polarization is observed in in-plane direction than in out-of-plane direction. This trend is consistent with the naive picture of a low viscosity system with maximum vorticity at the equator, however, so far it is not seen in model calculations. We have also presented the results of longitudinal component of the polarization for Λ and $\overline{\Lambda}$ hyperons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. A *sine* structure is observed for both Λ and $\overline{\Lambda}$ when presented as a funtion of azimuthal angle relative to the second-order event plane. The second-order *sine* coefficient in Fourier series increases from most central to middle central collisions, but the trend is not clear in peripheral collisions due to the large uncertainties. These results are qualitatively consistent with the expectation from the existence of a local vorticity, generated by the elliptic flow, along the beam direction.

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References

[1] I. Arsene *et al.* (BRAHMS Collaboration), Nucl. Phys. A **757**, 1 (2005); B.B. Back *et al.* (PHOBOS Collaboration), Nucl. Phys. A **757**, 28 (2005); J. Adams *et al.* (STAR Collab-

oration), Nuclear Physics A **757**, 102 (2005); K. Adcox *et al*. (PHENIX Collaboration), Nucl. Phys. A **757**, 184 (2005)

[2] Z. T. Liang and X. N. Wang, Phys. Rev. Lett. **94**, 102301 (2005) Erratum: [Phys. Rev. Lett. **96**, 039901 (2006)]

[3] S. A. Voloshin, nucl-th/0410089.

[4] B. Betz, M. Gyulassy and G. Torrieri, Phys. Rev. C **76**, 044901 (2007)

[5] F. Becattini, F. Piccinini and J. Rizzo, Phys. Rev. C **77**, 024906 (2008)

[6] L. Adamczyk *et al.* [STAR Collaboration], Nature **548**, 62 (2017)

[7] F. Becattini, L. Csernai and D. J. Wang, Phys. Rev. C **88**, no. 3, 034905 (2013) Erratum: [Phys. Rev. C **93**, no. 6, 069901 (2016)]

[8] W. T. Deng and X. G. Huang, Phys. Rev. C **93**, no. 6, 064907 (2016)

[9] I. Karpenko and F. Becattini, Eur. Phys. J. C **77**, no. 4, 213 (2017)

[10] H. Li, H. Petersen, L. G. Pang, Q. Wang, X. L. Xia and X. N. Wang, Nucl. Phys. A **967**, 772 (2017)

[11] D. X. Wei, W. T. Deng and X. G. Huang, arXiv:1810.00151 [nucl-th].

[12] S. A. Voloshin, EPJ Web Conf. **17**, 10700 (2018)

[13] F. Becattini and I. Karpenko, Phys. Rev. Lett. **120**, 012302 (2018)

[14] X. L. Xia, H. Li, Z. B. Tang and Q. Wang, Phys. Rev. C **98**, 024905 (2018)

[15] G. Bunce *et al.*, Phys. Rev. Lett. **36**, 1113 (1976).

[16] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. C **76**, 024915 (2007) Erratum: [Phys. Rev. C **95**, 039906 (2017)]

[17] A. H. Tang, B. Tu and C. S. Zhou, Phys. Rev. C **98** (2018) , 044907

[18] J. Adam *et al.* [STAR Collaboration], Phys. Rev. C **98**, 014910 (2018)