MEASUREMENTS OF HYPERON POLARIZATION IN HEAVY-ION COLLISIONS AT $\sqrt{s_{NN}} = 3$–200 GeV WITH THE STAR DETECTOR*

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In heavy-ion collisions with energies ranging from $\sqrt{s_{NN}} = 7.7$ GeV to 5.02 TeV, the observation of the global hyperon polarization, P_H, has revealed the existence of large vorticities perpendicular to the reaction plane due to the system's orbital angular momentum. This discovery has posed new questions: does P_H grow at $\sqrt{s_{NN}} \lesssim 7.7$ GeV, indicating hydrodynamic behavior in the hadron gas? Can high-precision measurements of the suggested $P_{\bar{\Lambda}}$–P_{Λ} indicate a large late-stage magnetic field sustained by the QGP? Can further studies of vorticity driven by collective flow, leading to a longitudinal spin polarization, P_z, shed light on the discrepancies between measurements and model predictions? To answer these questions, and more, we present here recent results of integrated and differential measurements of P_H and P_z in recent high-statistics data sets acquired by the STAR Collaboration. We show the integrated and differential P_H in Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ and 27 GeV, as well as at the fixed-target collision energies of $\sqrt{s_{NN}} = 3$ and 7.2 GeV. Furthermore, Ru+Ru and Zr+Zr collisions allow for the study of the system-size dependence of P_H and P_z, as well as P_z relative to the higher-order event-plane angles.

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1. Introduction

The discovery of substantial fluid vorticity supported by the Quark–Gluon Plasma (QGP) in heavy-ion collisions through the use of Λ-hyperon spin polarization [1] has proven substantial, providing a new confirmation of the hydrodynamic paradigm of the QGP and prompting numerous questions and studies, both experimental and theoretical. A high-statistics data set at $\sqrt{s_{NN}} = 200$ GeV by STAR was able to study the dependence of P_H on collision centrality, transverse momentum, p_{T}, and rapidity, y [2]. The

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polarization itself was of smaller magnitude than the previous study, and P_H measurements by ALICE at much higher $\sqrt{s_{NN}}$ [3] showed consistency with zero; these results across $\sqrt{s_{NN}}$ painted a clear picture of decreasing P_H with $\sqrt{s_{NN}}$. P_H clearly rises with collision centrality, which agrees with what one might expect from an angular-momentum-driven phenomenon. There may be a slight suppression of P_H at higher p_{T} due in part to jets [4]; however, this has not yet been observed. Numerous model calculations predict a substantial dependence of P_H on y [5–9]; however, this has not been observed either.

A notable effect in previous measurements of P_H across $\sqrt{s_{NN}}$ is an enhancement of $P_{\bar{\Lambda}}$ over P_{Λ}. Although this "polarization splitting" is not statistically significant, it is in fact consistent with a large late-stage magnetic field supported by the QGP's finite conductivity [10]. The full picture is quite a bit more complicated, with necessary considerations of differences between the freeze-out times of Λ and $\bar{\Lambda}$ hyperons, their phase-space distributions, *etc.* [11]. Nevertheless, high-statistics studies at lower $\sqrt{s_{NN}}$, where the splitting may be larger, is necessary to form a more complete understanding of the QGP's ability to support a magnetic field.

Yet another avenue of study is that of longitudinal hadron polarization along the beam direction, P_z. In this case, the spin polarization is driven by collective flow in the transverse plane [12]. P_z is measured, then, as a function of the difference between the azimuthal angle, ϕ, of the hadron and the event-plane angle, Ψ_n, describing the orientation of the collision. The second-order P_z had been studied by STAR at $\sqrt{s_{NN}} = 200$ GeV in Au+Au collisions, where sinusoidal behavior consistent with expectations was observed [13]; however, various model calculations which agreed fairly well with P_H measurements disagreed about the sign of P_z [14–17]. This puzzle has proved to be of concern within the community, and is likely alleviated by the recent attempts to include shear terms in the calculations [18, 19].

2. Method

Spin polarization, either P_H or P_z, is studied through correlations with hadron spin. Λ and $\bar{\Lambda}$ hyperons are the hadrons of choice because their parity-violating decays reveal the direction of spin through the preferential emission of daughters along the direction of spin. Two subsystems within the STAR detector serve to reconstruct Λ hyperons from the collision products: the Time Projection Chamber (TPC) and the Time of Flight detector (TOF).

When correlating hadron spin with the collision orientation, we measure so-called event-plane angles, Ψ_n [12]. The STAR Event Plane Detector (EPD) is a recent upgrade of the previously used Beam Beam Counter

(BBC), and offers nearly double the resolution on Ψ_n. The EPD sits at forward rapidity, accepting forward-going collision fragments as well as collision spectators. The azimuthal distribution of charged particles yields Ψ_n [12].

When operating RHIC in collider mode, global hadron polarization is measured through the traditional invariant-mass method [13]. In order to reach the lowest collision energies available at RHIC, STAR was retrofitted with an Au fixed target sitting at $(x, y) = (0, -2)$ cm within the beam pipe. The beam is then steered downwards leading to fixed-target collisions. In order to compensate for broken symmetries when operating in this mode, the generalized invariant-mass method is applied to measure P_H [20]. When measuring longitudinal polarization, we correlate the polar angle of the daughter spin with the beam direction. This is performed by measuring $\langle\cos(\theta_p^*)\rangle$ with respect to $\phi - \Psi_n$.

3. Results

At $\sqrt{s_{NN}} = 7.2$ GeV, operating STAR in fixed-target mode, we see results consistent both with previous results in collider mode at $\sqrt{s_{NN}} = 7.7$ GeV [1] and with predictions made by the 3-Fluid Dynamics model (3FD) [6]; however, this measurement is at forward rapidity $(0.5 < y < 2)$ and is not necessarily a fair comparison between these measurements and predictions. At $\sqrt{s_{NN}} = 3$ GeV, we see a significant P_H of about 5%, with nearly 6σ of statistical significance. This is evidence that even the hadron gas supports enormous fluid vorticity, and the consistency with the 3FD model over AMPT suggests that the hadron gas evolves hydrodynamically. These new results, plotted alongside previous measurements and model predictions, are shown in Fig. 1 (upper plot). In both of these studies, we see P_H increase monotonically with collision centrality and no dependence of P_H on p_{T} or y. The data set at $\sqrt{s_{NN}} = 3$ GeV provides a unique environment for the study of the rapidity dependence of P_H. Here, the detector coverage is such that we are able to reconstruct even the most forward-rapidity Λ hyperons, whereas previous studies have been limited to a fraction of hyperon production in y. These results are shown in Fig. 1 (lower plot). Numerous model calculations predict significant dependence of P_H on y which becomes more dramatic at lower $\sqrt{s_{NN}}$ [5–9], so the lack of observation in this data set is striking. Still, uncertainties grow at forward rapidity as hyperon yield falls off, so further experimental study and theoretical understanding are required.

P_H can also be used as a tool to study other phenomena, such as the magnetic field sustained by the QGP measured by $P_{\bar{\Lambda}}$–P_{Λ}. This field could be measured in the recent high-statistics data sets of Ru+Ru and Zr+Zr, where the system sizes are the same but the number of protons differs; however, no significant difference is observed. STAR measurements at $\sqrt{s_{NN}} = 54.4$ and 200 GeV show no significant $P_{\bar{\Lambda}}$–P_{Λ}, but recent high-statistics data sets

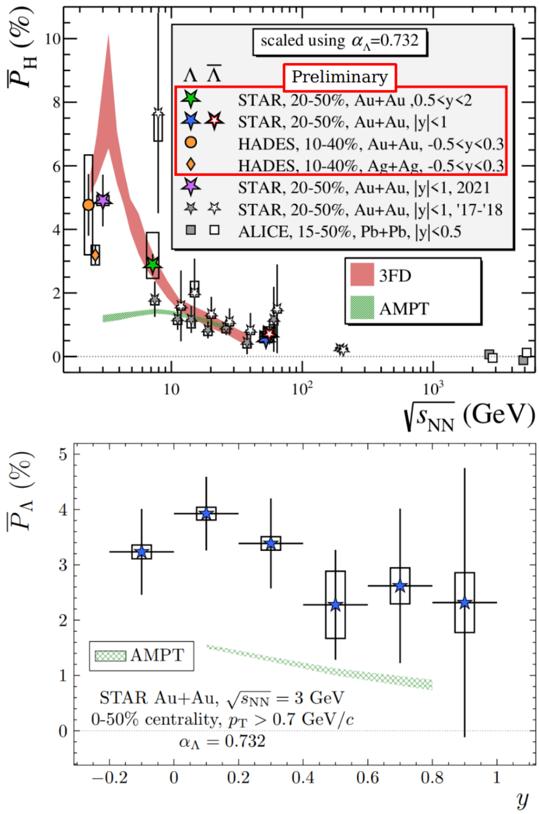

Fig. 1. Hyperon polarization at low $\sqrt{s_{NN}}$ in recent studies presented here, alongside model predictions. Upper: Hyperon polarization in previous experimental studies, compared to recent preliminary results and model predictions. We see here the agreement between the trend in the data at small $\sqrt{s_{NN}}$ and the 3FD hydrodynamic model. Lower: Λ hyperon polarization at $\sqrt{s_{NN}} = 3$ GeV with respect to Λ rapidity. At this energy, the range in Λ-hyperon production is entirely within $|y| < 1$, and so the STAR detector has full rapidity coverage.

of Au+Au collisions collected by the STAR detector at $\sqrt{s_{NN}} = 19.6$ and 27 GeV allow for more precise measurements where the splitting may be larger. Using P_H averaged for Λ and $\bar{\Lambda}$ hyperons at these collision energies, we achieve a factor of ~ 10 reduction in uncertainties, which will allow STAR to make a high-precision measurement on the late-stage magnetic field sustained by the QGP. This averaged P_H at $\sqrt{s_{NN}} = 19.6$ and 27 GeV with respect to collision centrality displays the familiar monotonic increase, consistent with a phenomenon driven by angular momentum. Similarly, we see no trend within uncertainties for the p_T and y dependence of P_H at these energies.

The STAR measurements of P_z in the recent high-statistics data sets of Ru+Ru and Zr+Zr collisions agree very well with previous measurements and provide dramatically improved precision. Interestingly, we can study this P_z relative to Ψ_3, which is related to triangular flow. STAR measured this, again in the Ru+Ru and Zr+Zr data sets, and find the qualitative behavior consistent with expectations; however, detailed studies on this third-order longitudinal polarization using models have yet to be conducted and will provide valuable insight. Both $P_{z,n=2,3}$ increase with centrality and have comparable magnitude; however, $P_{z,n=3}$, is systematically smaller than $P_{z,n=2}$ at centralities above 30%. Comparing our results here to those obtained by the ALICE Collaboration [3], we can test for a dependence on $\sqrt{s_{NN}}$; however, this is not observed within uncertainties. We can also test for a system-size dependence by comparing these results to STAR's previous results in the larger Au+Au system [13]. We do not observe any such dependence within uncertainties.

4. Summary

Recent measurements of substantial P_H at $\sqrt{s_{NN}} = 3$ and 7.2 GeV demonstrate that the system evolves hydrodynamically even at very low collision energies. Here, measurements of P_H with respect to collision centrality, p_{T}, and y agree with observations at two orders of magnitude larger $\sqrt{s_{NN}}$. The lack of observation of a dependence on y is striking, considering that the acceptance allowed for full coverage of the Λ rapidity distribution. While further study is necessary, this calls for a better theoretical understanding of the rapidity distribution of vorticity. At $\sqrt{s_{NN}} = 19.6$ and 27 GeV, STAR shows an order of magnitude reduction in uncertainties relative to past measurements, which will allow for a precision measurement of the late-stage magnetic field through $P_{\bar{\Lambda}}$–P_{Λ}. The differential measurements there also exhibit the familiar differential dependencies: no observed dependence of P_H on p_{T} or y, within uncertainties, and a monotonic increase of P_H with collision centrality. The P_H difference between Zr+Zr and Ru+Ru collisions, which may also signal a late-stage magnetic field, is not measured by STAR to be significant. Transverse-flow-driven P_z is measured in these collisions, however, with drastically improved precision. Also studied in these systems is P_z relative to Ψ_3, and STAR reports here vorticity measurements driven by the triangular flow. The behavior of the second- and third-order P_z is consistent with predictions which now agree due to the inclusion of shear terms. Measurements of hyperon polarization have opened the door for a variety of important studies shedding light on the nature of vorticity formation within the medium formed in heavy-ion collisions, and call for further experimental and theoretical studies.

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