Measurements of hyperon polarization in heavy-ion collisions at $\sqrt{s_{\mathrm{NN}}} = 3 - 200$ GeV with the STAR detector *

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In heavy-ion collisions, the observation of the global hyperon polarization, P_{H}, ranging from $\sqrt{s_{\mathrm{NN}}} = 7.7$ GeV to 5.02 TeV has revealed the existence of large vorticities perpendicular to the reaction plane due to system's orbital angular momentum. This discovery has posed new questions: does P_{H} grow at $\sqrt{s_{\mathrm{NN}}} \lesssim 7.7$ GeV, indicating hydrodynamic behavior in the hadron gas? Can high-precision measurements of the suggested $P_{\bar{\Lambda}} - P_{\Lambda}$ 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 integrated and differential P_{H} in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 19.6$ and 27 GeV, as well as at the fixed-target collision energies of $\sqrt{s_{\mathrm{NN}}} = 3$ 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 higher-order event-plane angles.

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 [5] 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 $\sqrt{s_{\mathrm{NN}}} = 200$ GeV by STAR was able to study the dependence of P_{H} on collision centrality, transverse momentum, p_{T}, and rapidity, y [3]. The polarization itself was of smaller magnitude than the previous study, and

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$P_{\rm H}$ measurements by ALICE at much higher $\sqrt{s_{\rm NN}}$ [2] showed consistency with zero; these results across $\sqrt{s_{\rm NN}}$ painted a clear picture of decreasing $P_{\rm H}$ with $\sqrt{s_{\rm NN}}$. $P_{\rm H}$ 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 $P_{\rm H}$ at higher $p_{\rm T}$ due in part by jets [7]; however, this has not yet been observed. Numerous model calculations predict a substantial dependence of $P_{\rm H}$ on y [18, 12, 10, 14, 13]; however, this has not been observed either. While these differential measurements at $\sqrt{s_{\rm NN}} = 200$ GeV were useful, they certainly call for further high-statistics studies at lower $\sqrt{s_{\rm NN}}$ where $P_{\rm H}$ is larger. Furthermore, model calculations extended to $\sqrt{s_{\rm NN}} \lesssim 7.7$ GeV diverge, suggesting that the polarization is sensitive to the state of the system. High-statistics measurements which yield statistically significant $P_{\rm H}$ integrated and differential measurements will shed light on these open questions.

A notable effect in previous measurements of $P_{\rm H}$ across $\sqrt{s_{\rm NN}}$ 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 [15]. 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 [9]. Nevertheless, high-statistics studies at lower $\sqrt{s_{\rm NN}}$, 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 [17]. P_z is measured, then, as a function of the difference between the aziumthal 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 $\sqrt{s_{\rm NN}} = 200$ GeV in Au+Au collisions, where sinusoidal behavior consistent with expectations was observed [4]; however, various model calculations which agreed fairly well with $P_{\rm H}$ measurements disagreed about the sign of P_z [20, 16, 8, 19]. This "spin 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 [11, 6]. Further study using higher statistics and measuring P_z driven by higher-order transverse flow will provide valuable insight.

2. Method

Spin polarization, either $P_{\rm H}$ 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 Λ and $\bar{\Lambda}$ hyperons decay, their charged daughters bend in STAR's magnetic field and their helical paths are reconstructed. Using energy-loss information from the TPC and particle mass-square information from the TOF, protons and pions are identified. Each proton-pion pair is checked against a series of conditions to determine if they are likely products of a $\Lambda, \bar{\Lambda}$ decay. These include, for example, the Distance at Closest Approach (DCA) between the proton's and pion's helical tracks. See Ref. [1] for more details. The set of hyperon candidates have a signal-to-background ratio of $> 95\%$, but nevertheless have contamination from the combinatoric background.

When correlating hadron spin with the collision orientation, we measure so-called event-plane angles, Ψ_n [17]. The STAR Event Plane Detector (EPD) is a recent upgrade to 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 [17].

When operating RHIC in collider mode, global hadron polarization is measured through the traditional invariant-mass method [4]. In order to reach the lowest collision energies available at RHIC, STAR was retrofitted with a 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} [1].

$$\frac{8}{\pi \alpha_\Lambda} \frac{1}{R_{\mathrm{EP}}^{(1)}} \left\langle \sin\left(\Psi_1 - \phi_p^*\right)\right\rangle^{\mathrm{sig}} = P_{\Lambda,\hat{j}} + c \sin(\phi_\Lambda - \phi_p^*). \tag{1}$$

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 $\sqrt{s_{\mathrm{NN}}} = 7.2$ GeV, operating STAR in fixed-target mode, we see results consistent both with previous results in collider mode at $\sqrt{s_{\mathrm{NN}}} = 7.7$ GeV [5] and with predictions made by the 3-Fluid Dynamics model (3FD) [12]; however, this measurement is at forward rapidity ($0.5 < y < 2$) and is not necessarily a fair comparison between these measurements and predictions. At $\sqrt{s_{\mathrm{NN}}} = 3$ 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. 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 $\sqrt{s_{\mathrm{NN}}} = 3$ 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. Numerous model calculations predict significant dependence of P_{H} on y which becomes more dramatic at lower $\sqrt{s_{\mathrm{NN}}}$ [18, 12, 10, 14, 13], 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 $P_{\bar{\Lambda}} - P_{\Lambda}$. 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 $\sqrt{s_{\mathrm{NN}}} = 54.4$ and 200 GeV show no significant $P_{\bar{\Lambda}} - P_{\Lambda}$, but recent high-statistics data sets collected by the STAR detector at $\sqrt{s_{\mathrm{NN}}} = 19.6$ 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 $\sqrt{s_{\mathrm{NN}}} = 19.6$ 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.

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 $P_{\mathrm{Z,n=2,3}}$ increase with centrality and have comparable magnitude; however, $P_{\mathrm{Z,n=3}}$, is systematically smaller than $P_{\mathrm{Z,n=2}}$ at centralities above 30%. Comparing our results here to those obtained by the ALICE collaboration [2], we can test for a dependence on $\sqrt{s_{\mathrm{NN}}}$; 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 [4]; however, this is not observed either.

4. Summary

Recent measurements of substantial P_{H} at $\sqrt{s_{\mathrm{NN}}} = 3$ 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 $\sqrt{s_{\mathrm{NN}}}$. 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 $\sqrt{s_{\mathrm{NN}}} = 19.6$ 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 $P_{\bar{\Lambda}} - P_{\Lambda}$. 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 triangular flow. The behavior of 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 voriticity formation within the medium formed in heavy-ion collisions, and call for further experimental and theoretical studies.

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