Observation of Global Hyperon Polarization in Ultrarelativistic Heavy Ion Collisions

Isaac Upsal for the STAR Collaboration
The Ohio State University: 191 W Woodruff Ave. Columbus, Ohio, USA
E-mail: upsal.1@osu.edu

Abstract. Non-central heavy-ion collisions provide a system with non-zero total angular momentum which can be transferred, in part, to the fireball via baryon stopping. It has been predicted that a net spin of emitted particles aligned with the system angular momentum may emerge through coupling with the bulk material. Due to its parity violating decay the $\Lambda$ baryon is self-analyzing, which allows us to associate the daughter proton decay direction with $\Lambda$ particle spin. Ultimately this allows us to use them as a probe of net-particle spin. In preliminary STAR measurements of the net $\Lambda$ baryon polarization from Au+Au collisions at 7.7, 11.5, 14.5, 19.6, 27, and 39 GeV we find that both $\Lambda$ and $\bar{\Lambda}$ particles are polarized in the direction of the system angular momentum. Including previously published STAR results we see a polarization of about 2% for mid-central collisions when $\sqrt{s_{NN}} < 100$ GeV.

Collisions of nuclei at ultra-relativistic energies create a system of deconfined colored quarks and gluons, called the Quark-Gluon Plasma (QGP)[1, 2, 3, 4]. The large angular momentum ($\sim 10^{4-5}\hbar$) present in non-central collisions may produce a “polarized QGP,” in which quarks are polarized through spin-orbit coupling in QCD [7, 8, 9]. The polarization would be transmitted to hadrons in the final state and could be detectable through global hyperon polarization.

“Global” polarization refers to the phenomenon in which the spin of baryons emitted from the mid-rapidity fireball are correlated with the net angular momentum of the system. This is distinct from production plane polarization, an effect seen in $p+p$ and $p+A$ collisions, in which $\Lambda$ baryons are polarized relative to the plane spanned by $\vec{p}_{\text{beam}} \times \vec{p}_\Lambda$ [10, 11]. Production plane polarization is found in the beam fragmentation region (i.e. at forward rapidity) and vanishes by symmetry when averaged over rapidity or azimuthal angle.

Global polarization has been predicted in hydrodynamic calculations of non-central collisions [14, 15, 44, 17, 18]. In three-dimensional hydrodynamic calculations, the initial shear structure of the flow field results in a vortical structure. This vorticity is sensitive to the initial conditions [14, 15, 18], as well as the viscosity [14, 33, 18] and temperature [17] of the fluid as it evolves. Vortical structure of the velocity field has also been recently reported in microscopic transport simulations of heavy ion collisions at RHIC [19]. Global polarization arising from QCD spin-orbit coupling is expected to give a signal of similar size and magnitude for $\Lambda$ and $\bar{\Lambda}$ baryons.

A global polarization signal may also arise due to a coupling of the hadronic magnetic dipole moment $\vec{\mu}_H$ to the magnetic field $\vec{B}$ produced by the charged spectators in a non-central heavy ion collision. A purely magnetic polarization would give signals of similar magnitude but opposite sign for $\Lambda$ and $\bar{\Lambda}$ baryons.

In this preliminary STAR analysis the first observation of global hyperon polarization in heavy ion collisions is seen. The measurements were performed by the STAR experiment at RHIC, in Au+Au
collisions at center-of-mass energies of $\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, \text{ and } 39 \text{ GeV}$. In this report, we focus on mid-central collisions, 20-50% of the total inelastic cross-section as estimated from the charged-particle yield at midrapidity [22] measured in the STAR TPC [21].

The reaction plane of an event is estimated by reconstructing the first-order event plane, $\Psi_{EP}^{(1)}$, in two Beam-Beam Counters (BBCs) [23, 24] covering pseudorapidity range $3.3 < |\eta| < 5.0$, as described previously [25, 26]. Taking into account that the spectators “bounce-off” outward from the center of the system [34] the reaction plane estimate allows the determination of the angular momentum direction. The event plane resolution, $R_{EP}^{(1)} = \langle \cos(\Psi_{EP}^{(1)} - \Psi_{RP}) \rangle$, is about 0.65 for midcentral events at $\sqrt{s_{NN}} = 7.7 \text{ GeV}$ and decreases with energy to about 0.2 at $\sqrt{s_{NN}} = 39 \text{ GeV}$.

Hyperons were reconstructed in the TPC via the decay channel $\Lambda \rightarrow p + \pi^- \ (\bar{\Lambda} \rightarrow \bar{p} + \pi^+)$. The charged daughters were identified through their specific energy loss in the gas of the TPC for $|p| \lesssim 0.6 \text{ GeV/c}$, and with the Time of Flight (TOF) detector for momenta up to 2.5 GeV/c. Hyperon candidates were identified according to topological properties of the decay vertex – projected distance of closest approach of the daughters to the primary vertex, of the parent hyperon to the primary vertex, and of the daughters to each other as well as apparent decay length. Our analysis is restricted to midrapidity hyperons, $|y_H| < 1$.

We focus on $\Lambda$ and $\bar{\Lambda}$ hyperons because their decay topology reveals their polarization. In particular, in the $\Lambda$ ($\bar{\Lambda}$) particle’s frame, the daughter proton (antiproton) tends to be emitted along (opposite) the parent’s polarization direction. If $\theta^*$ is the angle between the daughter proton (antiproton) momentum and the hyperon polarization vector $\vec{P}_H$, then

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2} \left( 1 + \alpha_H |\vec{P}_H| \cos\theta^* \right),$$

(1)

where $\alpha_{\Lambda} = 0.642$ and $\alpha_{\bar{\Lambda}} = -0.642$.

Symmetry demands that, averaged over all phasespace, $\vec{P}$ is parallel to $\vec{J}_{sys}$, the unit vector in the

Figure 1. A sketch of the collision from several perspectives, illustrating the vectors and angles discussed in this study. Panel (a): The direction of the system angular momentum, $\vec{J}_{sys}$ is estimated by measuring the azimuthal angle of projectile fragments in forward detectors; the vorticity of the hot system at midrapidity and resulting polarized hyperons are schematically illustrated. Panel (b): At the energies under study, spectators “bounce off” [34]. The impact parameter vector $\vec{b}$ points from the center of the ion traveling in the $-\hat{z}$ direction, to the ion traveling in the $+\hat{z}$ direction; thus, $\vec{J}_{sys} = \vec{b} \times \hat{z}$. Panel (c): The angles used in equation 2 are shown; here, $\vec{p}_p^*$ is the component of the daughter proton’s momentum transverse to the beam, in the $\Lambda$ particle’s frame.
Figure 2. (Color online) The average polarization of $\Lambda$ and $\bar{\Lambda}$ baryons from 20-50% central Au+Au collisions is plotted as a function of collision energy. The results of the present study ($\sqrt{s_{NN}} < 40$ GeV) are shown together with those reported earlier [6] for 62.4 and 200 GeV collisions. The results are corrected for feed-down coming only from $\Sigma^0$ decays. Only statistical errors are plotted.

direction of the angular momentum of the system. Both the magnitude ($0 \leq |\vec{P}| \leq 1$) and direction of $\vec{P}$ may depend strongly on transverse momentum, azimuthal angle, and rapidity. In this preliminary study the limited statistics of the datasets prohibits extensive exploration of these dependencies, and we extract only the average projection of the polarization on $\hat{J}_{\text{sys}}$. It may be shown [6] that

$$\overline{P}_H \equiv \langle \vec{P}_H \cdot \vec{J}_{\text{sys}} \rangle = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_{\text{EP}}^{(1)} - \phi_p^*) \rangle}{R_{\text{EP}}^{(1)}},$$

(2)

where $\Psi_{\text{EP}}^{(1)}$ is the angle of the first-order event plane, $\phi_p^*$ is the azimuthal angle of the daughter proton (antiproton) in the Lambda’s rest frame, and $\langle \cdots \rangle$ indicates an average over the azimuthal angle of the hyperon momentum. Since $R_{\text{EP}}^{(1)}$ depends on collision centrality, in the present analysis we calculate $\overline{P}_H$ separately for events of centrality 20-30%, 30-40%, and 40-50%, and report the weighted (with particle yield) average.

The results are shown in Fig. 2. At collision energies below 39 GeV, a significant polarization is observed for both $\Lambda$ and $\bar{\Lambda}$ baryons, at the level of 1.5-3.5 times statistical uncertainty. While including a broader centrality range into the analysis increases the hyperon statistics, the significantly poorer event plane resolution for more central or more peripheral collisions reduces the significance of the signal.

The results in Fig. 2 have been corrected to account for the combinatoric background of $p + \pi$ pairs that pass our topological criteria and fall within the selected invariant mass window. This corresponds to a $\sim 55\%$ ($\sim 35\%$) correction for $\Lambda$ ($\bar{\Lambda}$) baryon polarization for most data points. For the $\sqrt{s_{NN}} = 14.5$ GeV data, the correction is larger ($90\%$ and $70\%$, respectively) due to the presence of additional material for runs at this energy. A very small residual signal, at the level of the statistical uncertainty, is observed in the combinatoric background for $p - \pi$ pairs with invariant mass slightly different from the $m_\Lambda$. This residual effect may be due to daughter protons of a real $\Lambda$ particles which are paired with background pions to make a candidate $\Lambda$ particle. Since the protons carry most of the momentum this may lead to a small polarization from such particles. This residual correlation is included in the combinatoric background correction. Not including it would lead to an upward shift on the order of 0.2% for most data points.

A significant number of $\Lambda$ particles come from decays of others baryons. Since the $\Sigma^0$ baryon has a very short lifetime compared to the $\Lambda$ baryon, a $\Lambda$ baryon coming from a primary $\Sigma^0$ will look just like primary $\Lambda$ so it is not possible to distinguish the two. It is clear from figure 2 that the vortical or
spin-orbit contribution to the polarization is dominant since the polarization results for \( \Lambda \) and \( \bar{\Lambda} \) baryons are the same sign and similar magnitude. If we assume that the polarization from this effect is the same for \( \Sigma^0 \) particles as it is for \( \Lambda \) particles then we can correct for the feed-down. It is known that the daughter \( \Lambda \) particle will carry, on average, \(-\frac{1}{2}\) of the polarization of the \( \Sigma^0 \) particle. The contribution due to feed-down from multi-strange hadrons is not included. The number of \( \Sigma^0 \) baryons is estimated from a simple thermal scaling based on the mass difference of the particles \( -N_{\Sigma^0}/N_{\Lambda} = e^{-\Delta m/T} \), where \( T = 150\text{MeV} \). The results in figure 2 are corrected for \( \Sigma^0 \) feed-down.

Figure 2 also includes the polarization measurements STAR has published previously [6], for \( \text{Au+Au} \) collisions at \( \sqrt{s_{\text{NN}}} = 62.4 \text{ GeV} \) and 200 GeV. In order to account for a sign error in the direction of \( \hat{J}_{\text{sys}} \) in reference [6], the sign on these data have been flipped here.

Both \( \Lambda \) and \( \bar{\Lambda} \) baryons exhibit a similar and positive polarization, consistent with a common spin-orbit or vortical origin. While the difference is of the order of the uncertainties, \( \hat{P}_{\Lambda} \) is slightly larger than \( \hat{P}_{\bar{\Lambda}} \) at all collision energies, suggesting the possibility of an additional magnetic contribution. This difference could also arise due to finite baryonic chemical potential [44, 42].

Early spin-orbit-based calculations [7] predicted quark polarization \( P_q \sim 10 - 30\% \), though a more complete calculation [9] suggested \( P_q \lesssim 0.4\% \) for collisions at \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \). Hyperon polarizations were expected to be of the same order. While some hydrodynamic models predict a vanishing hyperon polarization [12, 13] in \( \text{Au+Au} \) collisions at RHIC, others [15] predict an average value of \( P_V \sim 1 - 2\% \) for collisions at \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \), due to plasma vorticity. Spin-orbit-based calculations [9] suggest larger polarizations at LHC energies than at RHIC. Hydrodynamical calculations [17, 41, 14] suggest that \( P_V \) will decrease with increasing collision energy as thermal fluctuations overcome vortical effects. Microscopic transport calculations [37, 19] find that 10-20\% of the total angular momentum of the colliding system is retained by the plasma at midrapidity. Although this angular momentum increases with \( \sqrt{s_{\text{NN}}} \), Jiang, et al. [19] report that the velocity-field vorticity decreases significantly with energy in the range \( 30-200 \text{ GeV} \). Meanwhile, Baznat, et al. [37] predict \( P_V \) of several percent at forward rapidity for much lower-energy collisions (\( \sqrt{s_{\text{NN}}} = 5 \text{ GeV} \)), but \( \sim 10^{-4} \) at midrapidity.

Systematic, quantitative theoretical predictions for global polarization due to vorticity in collisions with \( \sqrt{s_{\text{NN}}} < 200 \text{ GeV} \) would be valuable, to compare with these first measurements and explore the physical mechanisms driving the polarization. Similarly, a study of polarization due to magnetic coupling may shed light on the dynamics of the magnetic field generated in these collisions. The primary theoretical uncertainty in our understanding of \( B \)-field effects [29, 27, 28, 38, 39] concerns its time evolution, which depends strongly on the electric conductivity of the plasma. Calculations with different conductivities differ by a few orders of magnitude [36]; the calculations with conductivity determined in the lattice QCD, yields fields (at the time of a few fm/c) \( eB \sim (a \text{ few}) \times 10^{-2} m_e^2 \).

We have reported a preliminary first observation of global \( \Lambda \) and \( \bar{\Lambda} \) baryon polarization in heavy ion collisions. The signal is on the order of a few percent and falls with increasing collision energy, though the \( \sqrt{s_{\text{NN}}}-\)dependence is small compared to experimental uncertainty. Theoretical calculations [9, 15, 17] for collisions at \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \) predict a polarization \( \approx 0.5 - 2\% \), and others suggest [14, 19] that the signal may be larger at lower \( \sqrt{s_{\text{NN}}} \). Quantitative predictions of the energy dependence may provide important constraints on the vortical structure of the quark-gluon plasma.

Specific theoretical predictions have been made on the dependence of \( \hat{P}_{\Lambda} \) on \( p_T \), rapidity, and azimuthal emission angle of the hyperon, as well as on the impact parameter. To test these predictions, and to quantify the level of magnetically-induced splitting, statistical uncertainties, depending on both event statistics and event plane resolution, should be reduced by at least a factor of 5. The second beam energy scan (BES-II) program at RHIC ¹, planned for the end of the decade, will improve both statistics (through accelerator upgrades and increased beam time) and event plane resolution (through detector upgrades to the STAR experiment) and provide the opportunity to explore the systematics of global hyperon polarization more extensively.

¹ STAR Collaboration, STAR Note 0598, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598
The discovery of global hyperon polarization in heavy ion collisions may represent the first experimental access to the vortical structure of the quark gluon plasma, as well as providing constraints on magnetic effects in noncentral collisions. Further research on both the experimental and theoretical fronts is clearly required to understand this substructure fully.

References

[1] J. Adams et al. [STAR Collaboration], Nucl. Phys. A 757 (2005) 102 doi:10.1016/j.nuclphysa.2005.03.085 [nucl-ex/0501009].
[2] K. Adcox et al. [PHENIX Collaboration], Nucl. Phys. A 757 (2005) 184 doi:10.1016/j.nuclphysa.2005.03.086 [nucl-ex/0410003].
[3] B. B. Back et al., Nucl. Phys. A 757 (2005) 28 doi:10.1016/j.nuclphysa.2005.03.084 [nucl-ex/0410022].
[4] I. Arsene et al. [BRAHMS Collaboration], Nucl. Phys. A 757 (2005) 1 doi:10.1016/j.nuclphysa.2005.02.130 [nucl-ex/0410020].
[5] U. Heinz and R. Snellings, Ann. Rev. Nucl. Part. Sci. 63 (2013) 123 doi:10.1146/annurev-nucl-102212-170540 [arXiv:1301.2826 [nucl-th]].
[6] B. I. Abelev et al. [STAR Collaboration], Phys. Rev. C 76 (2007) 024915 doi:10.1103/PhysRevC.76.024915 [arXiv:0705.1691 [nucl-ex]].
[7] Z. T. Liang and X. N. Wang, Phys. Rev. Lett. 94 (2005) 102301 Eratum: [Phys. Rev. Lett. 96 (2006) 039901] doi:10.1103/PhysRevLett.94.102301, 10.1103/PhysRevLett.96.039901 [nucl-th/0410079].
[8] S. A. Voloshin, nucl-th/0410089.
[9] J. H. Gao, S. W. Chen, W. t. Deng, Z. T. Liang, Q. Wang and X. N. Wang, Phys. Rev. C 77 (2008) 044902 doi:10.1103/PhysRevC.77.044902 [arXiv:0710.2943 [nucl-th]].
[10] G. Bunce et al., Phys. Rev. Lett. 36 (1976) 1113. doi:10.1103/PhysRevLett.36.1113.
[11] K. J. Heller et al., Phys. Rev. Lett. 51 (1983) 2025. doi:10.1103/PhysRevLett.51.2025.
[12] C. D. C. Barros, Jr. and Y. Hama, Phys. Lett. B 699 (2011) 74 doi:10.1016/j.physletb.2011.03.052 [arXiv:0712.3447 [hep-ph]].
[13] C. C. Barros, Jr., J. Phys. Conf. Ser. 509 (2014) 012056. doi:10.1088/1742-6596/509/1/012056.
[14] B. Betz, M. Gyulassy and G. Torrieri, Phys. Rev. C 76 (2007) 044901doi:10.1103/PhysRevC.76.044901 [arXiv:0708.0035 [nucl-th]].
[15] F. Becattini, L. Csernai and D. J. Wang, Phys. Rev. C 88 (2013) no.3, 034905 Eratum: [Phys. Rev. C 93 (2016) no.6, 069901] doi:10.1103/PhysRevC.93.069901, 10.1103/PhysRevC.88.034905 [arXiv:1304.4427 [nucl-th]].
[16] F. Becattini, V. Chandra, L. Del Zanna and E. Grossi, J. Phys. Conf. Ser. 509 (2014) 012055. doi:10.1088/1742-6596/509/1/012055.
[17] L. P. Csernai, F. Becattini and D. J. Wang, J. Phys. Conf. Ser. 509 (2014) 021054. doi:10.1088/1742-6596/509/1/021054.
[18] F. Becattini et al., Eur. Phys. J. C 75 (2015) no.9, 406 doi:10.1140/epjc/s10052-015-3624-1 [arXiv:1501.04468 [nucl-th]].
[19] Y. Jiang, Z. W. Lin and J. Liao, arXiv:1602.06580 [hep-ph].
[20] S. A. Voloshin, A. M. Poskanzer and R. Snellings, arXiv:0809.2949 [nucl-ex].
[21] M. Anderson et al., Nucl. Instrum. Meth. A 499 (2003) 659 doi:10.1016/S0168-9002(02)01964-2 [nucl-ex/0301015].
[22] L. Adamczyk et al. [STAR Collaboration], Phys. Rev. C 88 (2013) 014902 doi:10.1103/PhysRevC.88.014902 [arXiv:1301.2348 [nucl-ex]].
[23] C. A. Whitten [STAR Collaboration], AIP Conf. Proc. 980 (2008) 390. doi:10.1063/1.2888113.
[24] F. S. Bieser et al., Nucl. Instrum. Meth. A 499 (2003) 766. doi:10.1016/S0168-9002(02)01974-5.
[25] G. Agakishiev et al. [STAR Collaboration], Phys. Rev. C 85 (2012) 014901 doi:10.1103/PhysRevC.85.014901 [arXiv:1109.5446 [nucl-ex]].
[26] L. Adamczyk et al. [STAR Collaboration], Phys. Rev. Lett. 112 (2014) no.16, 162301 doi:10.1103/PhysRevLett.112.162301(2014), 10.1103/PhysRevLett.112.162301 [arXiv:1401.3043 [nucl-ex]].
[27] V. Sokov, A. Y. Ilarionov and V. Toneyev, Int. J. Mod. Phys. A 24 (2009) 5925 doi:10.1142/S0217751X09047570 [arXiv:0907.1396 [nucl-th]].
[28] V. Voronyuk, V. D. Toneev, W. Cassing, E. L. Bratkovskaya, V. P. Konchakovski and S. A. Voloshin, Phys. Rev. C 83 (2011) 054911 doi:10.1103/PhysRevC.83.054911 [arXiv:1103.4239 [nucl-th]].
[29] D. E. Karzeev, L. D. McLerran and H. J. Warringa, Nucl. Phys. A 803 (2008) 227 doi:10.1016/j.nuclphysa.2008.02.298 [arXiv:0711.0950 [hep-ph]].
[30] R. Armenteros et al., Nucl. Phys. B 21 (1970) 15. doi:10.1016/0550-3213(70)90461-X.
[31] S. A. Bass et al., Prog. Part. Nucl. Phys. 41 (1998) 255 [Prog. Part. Nucl. Phys. 41 (1998) 225] doi:10.1016/S0146-6410(98)00058-1 [nucl-th/9803035].
[32] G. Van Buren [STAR Collaboration], J. Phys. G 31 (2005) S1127 doi:10.1088/0954-3899/31/6/072 [nucl-ex/0412034].
[33] L. P. Csernai, D. D. Strottman and C. Anderlik, Phys. Rev. C 85 (2012) 054901 doi:10.1103/PhysRevC.85.054901 [arXiv:1112.4287 [nucl-th]].
[34] S. A. Voloshin and T. Niida, arXiv:1604.04597 [nucl-th].
[35] D. E. Kharzeev, J. Liao, S. A. Voloshin and G. Wang, Prog. Part. Nucl. Phys. 88 (2016) 1 doi:10.1016/j.ppnp.2016.01.001 [arXiv:1511.04050 [hep-ph]].
[36] L. McLerran and V. Skokov, Nucl. Phys. A 929 (2014) 184 doi:10.1016/j.nuclphysa.2014.05.008 [arXiv:1305.0774 [hep-ph]].
[37] M. I. Baznat, K. K. Gudima, A. S. Sorin and O. V. Teryaev, Phys. Rev. C 93 (2016) no.3, 031902 doi:10.1103/PhysRevC.93.031902 [arXiv:1507.04652 [nucl-th]].
[38] U. Gursoy, D. Kharzeev and K. Rajagopal, Phys. Rev. C 89 (2014) no.5, 054905 doi:10.1103/PhysRevC.89.054905 [arXiv:1401.3805 [hep-ph]].
[39] K. Tuchin, Int. J. Mod. Phys. E 23 (2014) 1430001. doi:10.1142/S021830131430001X
[40] A. Vilenkin, Phys. Rev. D 21 (1980) 2260. doi:10.1103/PhysRevD.21.2260
[41] L. P. Csernai, D. J. Wang, M. Bleicher and H. Sticker, Phys. Rev. C 90 (2014) no.2, 021904. doi:10.1103/PhysRevC.90.021904
[42] R. h. Fang, L. g. Pang, Q. Wang and X. n. Wang, arXiv:1604.04036 [nucl-th].
[43] F. Becattini and F. Piccinini, Annals Phys. 323 (2008) 2452 doi:10.1016/j.aop.2008.01.001 [arXiv:0710.5694 [nucl-th]].
[44] F. Becattini, V. Chandra, L. Del Zanna and E. Grossi, Annals Phys. 338 (2013) 32 doi:10.1016/j.aop.2013.07.004 [arXiv:1303.3431 [nucl-th]].
[45] M. Huang et al. [HyperCP Collaboration], Phys. Rev. Lett. 93 (2004) 011802. doi:10.1103/PhysRevLett.93.011802
[46] S. Wheaton and M. Hauer, Phys. Part. Nucl. Lett. 8 (2011) 869. doi:10.1134/S1547477111080152
[47] S. Wheaton and J. Cleymans, Comput. Phys. Commun. 180 (2009) 84 doi:10.1016/j.cpc.2008.08.001 [hep-ph/0407174].