Lambda Polarization in Heavy-Ion Collisions

RHIC & AGS Users’ Meeting
Beam Energy Scan Workshop
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A measurement of polarization by STAR

- 2017 STAR publication confirming $\bar{P}_{\Lambda/\bar{\Lambda}} > 0$ made cover of Nature magazine
  - What motivated this measurement?
  - What are the implications?

Background

- Lambda polarization has been measured in p+p and p+A collisions for decades now\(^1,2\).

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Spin polarization of hadrons

Hydrodynamics/Partonic interactions

System angular momentum

\[ \langle \vec{\omega}_{QGP} \rangle \parallel \vec{L}_{QGP} \]

Local angular momentum conservation

\[ \langle \vec{S}_{\omega, \text{hadrons}} \rangle \parallel \vec{L}_{QGP} \]
Spin polarization of Lambdas

- Lambdas preferentially emit positively charged daughters along the direction of their spin

\[ \frac{dN}{d\theta^*} = 1 + \alpha_\Lambda P_\Lambda \cos \theta^* \]

("*" indicates the Lambda rest frame)

\( \alpha_\Lambda \approx 0.642 \pm 0.013 \)
Corrects for known effects that dampen the signal

\[
\bar{P}_{\Lambda/\bar{\Lambda}} = \frac{1}{\Pi \pi \alpha} \frac{8}{R^{(1)}_{EP}} \left( \sin \left( \Psi_1 - \varphi^*/\pi^+ \right) \right)
\]

Correlates angular momentum of the system (\(\hat{J}_{sys}\)) with the orientation of the Lambda’s spin
Measuring $\hat{L}_{\text{QGP}}$

$$\bar{P}_\Lambda/\bar{\Lambda} = \frac{1}{\Pi} \frac{8}{\pi \alpha} \frac{1}{R_{\text{EP}}^{(1)}} \left( \sin \left( \Psi_1 - \phi_{p^+}^*/\pi^+ \right) \right)$$

Correlates angular momentum of the system ($\hat{j}_{\text{sys}}$) with the orientation of the Lambda’s spin.

Not all reconstructed Lambdas are actually Lambdas.

The measured $\Psi_1$ differs from $\Psi_{\text{RP}}$.

Lambdas do not emit their positive daughters exactly along the direction of their spins.
Measuring $\hat{L}_{QGP}$

- Lambdas’ daughter momenta need to be correlated with $\hat{L}_{QGP}$
- Approximate $\hat{L}_{QGP}$ using the first-order event plane angle $\Psi_1$
- $R_{EP}^1$ quantifies how good this approximation is
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Finding Lambdas

- Lambdas by reconstructed with protons and pions found with TPC and TOF.

- Requirements for a pair being identified as Lambda depend on the type of information available for the daughters.
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Measuring polarization

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- A new door opened for plenty of physics:
  - Energy dependence
  - Longitudinal polarization
  - Spin-spin correlations
  - QGP vorticity
  - Late-stage magnetic field
  - And more!

Quantification of polarization

Angular momentum of the system is straightforward to calculate, and simulations aim to estimate expected polarization by answering:

- How much angular momentum is transferred to the QGP?
- How much of the angular momentum in the QGP is transferred to the quarks?
- How much of the quark polarization is transferred to the final-state hadrons?

Collision-energy dependence

- Higher energies have longer-lived systems, but lower energies have more angular momentum transferred to the system
  - The collision-energy dependence is not immediately obvious

- Simulations show inverse relationship using UrQMD+vHLLE, PICR, and AMPT\textsuperscript{1-4}.


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Collision-energy dependence

- Will we see a drop-off at the critical point?
  - Not necessarily – hadron interactions within a system of large angular momentum can still yield spin polarization... *but...* interesting to look anyways
Collision-energy dependence

- Need to study these effects at fixed-target energies
  - Anti-lambda yield very low, so stick with Lambdas
  - $\sqrt{s_{NN}} = 3, 4.5$ GeV Au+Au collisions at STAR
    - Analysis by Joseph Adams
      - Analysis is ready; waiting for production of data
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  - $\sqrt{s_{\text{NN}}} = 2.4$ GeV Au+Au collisions at HADES
    - Analysis by Frederic Kornas
    - Preliminary results show drop-off!

F. Kornas for the HADES Collaboration, $\Lambda$ polarization in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 2.4$ GeV Measured with HADES. Hirschegg 2019.
Longitudinal polarization

- Spin alignment perpendicular to the reaction plane implies vorticity in the reaction plane
  - Due to angular momentum of the system
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- Spin alignment perpendicular to the transverse plane (longitudinal) implies vorticities in the transverse plane
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Longitudinal polarization

- Measure with $\langle \cos(\theta_p^*) \rangle$ as a function of $\varphi_{\Lambda/\bar{\Lambda}} - \Psi_2$
  - As opposed to $\langle \sin(\psi_1 - \varphi_{p^+/\pi^+}^*) \rangle$ from before
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- Measurements agree qualitatively with expectations
  - Analysis by Takafumi Niida

J. Adam, et. al. Polarization of $\Lambda (\Lambda^-)$ hyperons along the beam direction in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. arXiv:1905.11917 [nucl-ex]
QGP vorticity

- The averaged $\bar{P}_\Lambda$ and $\bar{P}_\bar{\Lambda}$ allows us to measure the vorticity of the system.
- Magnitude and energy dependence match observation

$$\bar{P}_{\Lambda/\bar{\Lambda}} = \bar{P}_{\Lambda/\bar{\Lambda}, \bar{\omega}} + \bar{P}_{\Lambda/\bar{\Lambda}, \vec{B}}$$

$$\bar{P}_{\Lambda, \bar{\omega}} = \bar{P}_{\bar{\Lambda}, \bar{\omega}}$$

$$\bar{P}_{\Lambda, \vec{B}} = -\bar{P}_{\bar{\Lambda}, \vec{B}}$$

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*Assuming no feeddown*
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$$
\begin{pmatrix}
\omega_c \\
B_c/T
\end{pmatrix} = 
\left[
\begin{array}{c}
\frac{2}{3} \sum_R \left( f_{\Lambda R} C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R} C_{\Sigma^0 R} \right) S_R(S_R + 1) \\
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- Identical-particle momentum correlations yield *sub-QGP* momentum information
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- Global polarization tells us there is large vorticity
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Late-stage magnetic field

\[ \mu_B \langle \vec{S}_{\vec{B}, \text{hadrons}} \rangle \parallel \vec{B}_{\text{QGP}} \]

\[ \vec{B}_{\text{System}} \propto \mu_B \langle \vec{S}_{\vec{B}} \rangle \]
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\begin{align*}
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  - Dileptons are tools with which to probe the early-stage field strength
- Late-stage magnetic field measurement is a gauge for the electrical conductivity, $\sigma_{\text{QGP}}$
  - Lambdas are tools with which to probe the late-stage field strength

Search for the magnetic field

From the recent *Nature* paper:

Relativistic heavy ion collisions are expected to produce intense magnetic fields parallel to $\hat{f}_{sys}$. Coupling between the field and the intrinsic magnetic moments of emitted particles may induce a larger polarization for $\bar{\Lambda}$ hyperons than for $\Lambda$ hyperons. This is not inconsistent with our observations, but probing the [magnetic] field will require more data to reduce statistical uncertainties as well as potential effects related to differences in the measured momenta of $\Lambda$ and $\bar{\Lambda}$ hyperons.

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*We’ve got more data!*

The STAR Collaboration, *Global Lambda hyperon polarization in nuclear collisions: evidence for the most vortical fluid.* Nature **548** (2017) 62

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Measuring $\hat{L}_{\text{QGP}}$

- Significant increase in event-plane resolution from the newly installed Event Plane Detector
Measuring $\hat{L}_{\text{QGP}}$

- The EPD has far more coverage than the BBC

East EPD hits rotated by $\Psi_{1,\text{EPD West}}$

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East EPD hits rotated by $\Psi_{\text{EPD West}}$

- Negative flow barely visible over many tiles
- Positive flow obvious over few tiles
Increase in statistics

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QA study by Prithwish Tribedy
Increase in statistics

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  • An unfortunate TPC space charge issue caused by the beam abort gap is making TPC calibration more challenging
• Data was recently re-produced following the realization of a bug in the tracking software
  • Analysis is ongoing
Summary

- A long-awaited confirmation of $\bar{P}_{\Lambda/\bar{\Lambda}} > 0$ was provided by the STAR collaboration.
- Many new avenues of polarization study now available.
- Ongoing study could yield potentially very exciting results!
  - Low-energy polarization drop-off?
  - Significant splitting between $\bar{P}_\Lambda$ and $\bar{P}_{\bar{\Lambda}}$?