Recent Results on Hyperon Polarization & Vector Meson Spin Alignment at RHIC

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Produced-particle polarization

- Non-central nuclear collisions carry large angular momentum, \( \vec{J} = \vec{r} \times \vec{p} \)
- \( \vec{J} \) is manifested in the gradient (along \( \vec{x} \)) of the longitudinal momentum, \( p_z \)
- Simply through spin-orbit coupling, there can be non-zero polarization of produced particles aligned with \( \vec{J} \)

Produced-particle polarization

- Equilibrium hydrodynamics has proven as a successful description of the QGP
- Particle polarization should be able to be derived using this framework as well
- In this context, we think about thermal vorticity of QGP fluid cells that is transferred to hadron spin at freeze out

Measuring $\vec{P}$

"*" indicates Lambda’s frame

$\vec{P}_{\Lambda/\Lambda} = \frac{8}{\pi \alpha_{\Lambda/\Lambda}} \frac{1}{R^{(1)}_{\text{EP}}} \left\langle \sin \left( \Psi_1 - \varphi^*_p \right) \right\rangle$

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

Correlates angular momentum of QGP with Lambda’s spin

Lambdas don’t emit daughters exactly along spin

Measuring $\overline{P}$

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Initial measurements

- The STAR collaboration in 2007 measured $\overline{P}_{\Lambda/\bar{\Lambda}}$ at $\sqrt{s_{NN}} = 62.4$ and 200 GeV consistent with zero with an upper limit of 2%
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Initial measurements:

- The STAR collaboration in 2007 measured $P/Λ$ at 62.4 and 200 GeV, consistent with zero with an upper limit of 2%.

Later measurements at lower energies showed significant $P/Λ$ getting larger with decreasing $Λ$. 


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Later observation

- A more recent, high-statistics data set at $\sqrt{s_{NN}} = 200$ GeV taken by STAR shows significant $\overline{P}_{\Lambda/\bar{\Lambda}}$ of 0.25%.

- ALICE recently measured $\overline{P}_{\Lambda/\bar{\Lambda}}$ using Pb+Pb consistent with zero within uncertainties.

Energy-dependent model predictions

- Various model predictions show increasing $\overline{P}_{\Lambda/\bar{\Lambda}}$ as $\sqrt{s_{NN}}$ decreases
  - Viscous hydrodynamics
  - Partonic transport
  - Hadronic transport
  - Chiral-kinetic transport
Relation to vorticity

- Using $\bar{P}_{\Lambda/\bar{\Lambda}}$ to measure vorticity should be straightforward, but "feeddown" of Lambdas from parent particles complicates things.

\[
\begin{pmatrix}
\overline{\omega}_c \\
Bc/T
\end{pmatrix} = \left[ \frac{2}{3} \sum_R \left( f_{\Lambda R} C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R} C_{\Sigma^0 R} \right) S_R (S_R + 1) \right]^{-1} \begin{pmatrix}
\rho_{\text{meas}}^\Lambda \\
\rho_{\text{meas}}^\bar{\Lambda}
\end{pmatrix}
\]

Centrality dependence

- High-statistics data sets at $\sqrt{s_{NN}} = 27$ and 200 GeV allow for the study of centrality dependence

- $\overline{P}_{\Lambda/\overline{\Lambda}}$ becomes larger for more peripheral collisions; as expected from a $J$-driven effect!


$p_T$ dependence

• These data sets also allow for study of $p_T$ dependence

• Scattering at low $p_T$ or jet fragmentation at high $p_T$ may reduce $P_\Lambda/\bar{\Lambda}$

• With given uncertainties, we see no such dependence


η dependence

• The $\sqrt{s_{NN}}$ dependence could be dominated by an underlying $\eta$ dependence

• Not observed!


Low energy

• It is unlikely $P_{\Lambda/\bar{\Lambda}}$ ever starts to rise as $\sqrt{s_{NN}}$ increases.

• What happens as $\sqrt{s_{NN}}$ goes to zero?

• Various models predict sharp rise below STAR BES energies before falling, but models are being “pushed to the limits”
  • Three-fluid dynamics
  • UrQMD
Low energy

• It is unlikely $P_{\Lambda/\bar{\Lambda}}$ ever starts to rise as $\sqrt{s_{NN}}$ increases

• What happens as $\sqrt{s_{NN}}$ goes to zero?

• The STAR Collaboration recently took a high-statistics data set at $\sqrt{s_{NN}} = 3$ GeV, which will shed light on $P_{\Lambda/\bar{\Lambda}}$ at sub-QGP energies

• $\eta$ dependence at this energy will also answer questions
  • STAR will be able to accept even the most forward $\Lambda$s
Low energy

• It is unlikely $\bar{P}_{\Lambda/\bar{\Lambda}}$ ever starts to rise as $\sqrt{s_{NN}}$ increases.

• What happens as $\sqrt{s_{NN}}$ goes to zero?

• If we find non-zero $\bar{P}_{\Lambda}$ at $\sqrt{s_{NN}} = 3$ GeV...
  • Are we forming QGP droplets?
  • How viscous is the overlap region?
  • What is the spin equilibration timescale?
Global $\overline{P}_\Lambda/\overline{P}_\Lambda$ as a tool

- Vorticity gives positive contribution to $P_\Lambda$ and $P_{\overline{\Lambda}}$
- $|\vec{B}|$ enhances $P_{\overline{\Lambda}}$ and suppresses $P_\Lambda$
  - $\vec{\mu}_B$, $\Lambda = -\vec{\mu}_B$, $\overline{\Lambda}$
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  - We measure $|\vec{B}|$ via $P_\Lambda$, $P_{\overline{\Lambda}}$ splitting

\[ \hat{L}_{\text{system}} \parallel \hat{B}_{\text{system}} \]

STAR, Nature 548 (2017) 62548

\[ \sqrt{s_{\text{NN}}} \text{ (GeV)} \]

\[ P_H \text{ [%]} \]

\[ \bar{P}_H \text{ [%]} \]
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- Potentially measure magnetic susceptibility of the QGP, $\sigma_{LQCD}$!

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- We need to be careful with this interpretation! Such splitting can have other explanations
  - Spin-meson field interaction
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  - Spin-meson field interaction
  - Core-corona
Global $\overline{P}_{\Lambda/\overline{\Lambda}}$ as a tool

- $\overline{P}$ is affected by:
  - $\langle \omega_{QGP} \rangle$
  - $|\overline{B}|$
  - Production time
  - Production location
  - etc.

- To establish the global nature of $\overline{P}$, it is necessary to study other particles
  - Parity-violating hyperons are the most straightforward way to do this
Global $\overline{P}_\Xi$, $\overline{P}_\Omega$

- As before (with $\Lambda$s), we know how $\Xi \to \Lambda + \pi^-$ and $\Omega \to \Lambda + K$ decay with respect to their spin:

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi} \left( 1 + \alpha_H P_H \cdot \hat{P}_B^* \right)$$

- $\alpha_\Lambda = 0.750 \pm 0.009$
- $\alpha_\Xi = -0.401 \pm 0.01$
- $\alpha_\Omega = 0.0157 \pm 0.0021$

- $\alpha_\Omega$ being small makes the measurement of $\overline{P}_\Omega$ in this case difficult. Instead, $\overline{P}_\Lambda^* = C_{\Omega-\Lambda} \overline{P}_\Omega^*$ is used, with $C_{\Omega-\Lambda} = -0.6$
Recent Measurements of $\overline{P}_H$ at $\sqrt{s_{NN}} = 27$ GeV by STAR agree with previous $\overline{P}_\Lambda/\overline{\Lambda}$ measurements

More statistics are obviously needed

These polarizations are being actively studied at other energies by STAR

Recent detector upgrades (esp. iTPC) will be very useful in this search
Further polarization studies

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• Just as global $\mathbf{P}_{\Lambda/\bar{\Lambda}}$ comes from collision-driven shear in the QGP in the $\hat{x} - \hat{z}$ plane, we can expect $\mathbf{P}_{\Lambda/\bar{\Lambda}}$ along $\hat{z}$ coming from flow-driven shear in the $\hat{x} - \hat{y}$ plane
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• Measure with $\langle \cos (\theta_p^*) \rangle$ as a function of $\phi_{\Lambda/\bar{\Lambda}} - \Psi_2$, as opposed to $\langle \sin (\Psi_1 - \phi_p^*) \rangle$ from before.
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  • Measure with $\langle \cos (\theta^*_p) \rangle$ as a function of $\varphi_{\Lambda/\bar{\Lambda}} - \Psi_2$, as opposed to $\langle \sin (\Psi_1 - \varphi^*_p) \rangle$ from before.

• Naïvely expect $\langle \cos (\theta^*_p) \rangle \propto \sin (\varphi_{\Lambda/\bar{\Lambda}} - \Psi_2)$.
Further polarization studies

- Just as global $\overline{P}_{\Lambda/\bar{\Lambda}}$ comes from collision-driven shear in the QGP in the $\hat{x} - \hat{z}$ plane, we can expect $\overline{P}_{\Lambda/\bar{\Lambda}}$ along $\hat{z}$ coming from flow-driven shear in the $\hat{x} - \hat{y}$ plane.
  - Measure with $\langle \cos (\theta_p^*) \rangle$ as a function of $\varphi_{\Lambda/\bar{\Lambda}} - \Psi_2$, as opposed to $\langle \sin (\Psi_1 - \varphi_p^*) \rangle$ from before.
  - Naïvely expect $\langle \cos (\theta_p^*) \rangle \propto \sin (\varphi_{\Lambda/\bar{\Lambda}} - \Psi_2)$.
  - This is what we measure!

[Graph showing the relationship between $\cos(\theta_p^*)$ and $\varphi_{\Lambda/\bar{\Lambda}} - \Psi_2$]
Further polarization studies

- This agrees with *some* model descriptions
  - (3+1)D PICR hydro
    - Y. Xie, D. Wang, and L. P. Csernai, EPJ C 80, 39 (2020)
  - Chiral kinetic
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  - (3+1)D PICR hydro
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  - Chiral kinetic

- It disagrees with others
  - UrQMD initial cond. + hydro
    - F. Becattini and I. Karpenko, PRL.120.012302 (2018)
  - AMPT
Global spin polarization of vector mesons

- Vector mesons produced by quark combination $q\bar{q} \rightarrow V$ have equal probabilities of occupying the three spin states, given no global polarization:
  - $|1\ 1\rangle = |\uparrow\uparrow\rangle$
  - $|1\ 0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$
  - $|1\ -1\rangle = |\downarrow\downarrow\rangle$

- The angular distribution of decay products can be written with the spin density matrix $\rho_{NN}$; the relevant observable is $\rho_{00} = \frac{1}{3} - \frac{8}{3} \langle \cos [2(\varphi_p^* - \Psi_{RP})] \rangle$
  - Deviation of $\rho_{00}$ from $1/3$ indicates global polarization
  - $\rho_{00} < 1/3 \leftrightarrow \omega$
Global spin polarization of vector mesons

• STAR measurements of $\rho_{00}$ at $\sqrt{s_{NN}} = 54.4$, 200 GeV for $K^{*0}$, $\phi$ mesons show deviation from $1/3$
  • Below $1/3$ for $K^{*0}$ and above for $\phi$
Global spin polarization of vector mesons

- STAR measurements of $\rho_{00}$ at $\sqrt{s_{NN}} = 54.4, 200$ GeV for $K^{*0}, \phi$ mesons show deviation from $\frac{1}{3}$
  - Below $\frac{1}{3}$ for $K^{*0}$ and above for $\phi$
- ALICE measurements agree qualitatively for $K^{*0}$, but are below $\frac{1}{3}$ for $\phi$
  - What is driving this? $\bar{\omega}$ domination at lower energy and fragmentation/$|\vec{B}|$ domination at higher energy?
Future measurements

- Additionally, $\rho_{00}$ falls below $1/3$ much further than expected based on $\overline{P}_\Lambda/\overline{\Lambda}$-driven vorticity measurements.

- **Future high-statistics data sets complemented by detector upgrades hold important information!**
Future measurements

• To establish the global nature of $\overline{P}$, it is necessary to study how $\overline{P}$ depends on spatial/temporal particle formation
  • Study $\overline{P}_{\Lambda/\overline{\Lambda}}$ w.r.t. rapidity
  • Study $\overline{P}_\Xi$, $\overline{P}_\Omega$ alongside $\overline{P}_{\Lambda/\overline{\Lambda}}$

• Future high-statistics data sets complemented by detector upgrades hold important information!
Summary

• Significant $\bar{P}_{\Lambda/\bar{\Lambda}}$ at RHIC energies
• Will soon measure $\bar{P}_{\Lambda}$ at $\sqrt{s_{NN}} = 3$ GeV including $y$ dependence *with most forward $\Lambda$s being measured!*
• Possible $|\vec{B}|$ measurement via $P_{\Lambda}, P_{\bar{\Lambda}}$
• $P_{\Xi}, P_{\Omega}$ help establish global nature of $\bar{P}$
• Important questions still remain!
  • Will we find non-zero $\bar{P}_{\Lambda/\bar{\Lambda}}$ in collisions with insufficient energy to form QGP?
  • Is $\bar{P}_{\Lambda/\bar{\Lambda}}$ migrating to forward rapidity at higher energies?
  • How do we reconcile measured longitudinal $\bar{P}_{\Lambda/\bar{\Lambda}}$ with models that predict the opposite behavior?
  • Why the $\rho_{00}, \varphi$ discrepancy between STAR and ALICE?
  • Why the $\langle \omega_{QGP} \rangle$ discrepancy between $\rho_{00}$ and $\bar{P}_{\Lambda/\bar{\Lambda}}$ derivations?
  • And more!!!

• High-statistics data sets by STAR along with numerous detector upgrades now in place will be crucial to answering these!

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