Global polarization of Lambda hyperons in Au+Au Collisions at RHIC BES

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For the STAR collaboration
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• $|L| \sim 10^3 \hbar$ in non-central collisions
• How much is transferred to particles at mid-rapidity?
• Does angular momentum get distributed thermally?
• Does it generate a “spinning QGP?”
  • consequences?
• How does that affect fluid/transport?
  • Vorticity: $\vec{\omega} = \frac{1}{2} \vec{\nabla} \times \vec{v}$
• How would it manifest itself in data?
Vorticity $\rightarrow$ Global Polarization

- **Vortical or QCD spin-orbit:** Lambda and Anti-Lambda spins aligned with $L$
Magnetic field → **Global** Polarization

- **Vortical or QCD spin-orbit:** Lambda and Anti-Lambda spins aligned with $L$
- **(electro)magnetic coupling:** Lambdas *anti*-aligned, and Anti-Lambdas aligned

Both may contribute
Barnett effect

• Nice correspondence in **Barnett effect**

• **BE**: uncharged object rotating with angular velocity $\omega$ magnetizes

$$M = \chi \omega / \gamma$$

• $\gamma$ = gyromagnetic ratio,

$\chi$ = magnetic susceptibility

Barnett Science 42, 163, 459 (1915); Barnett Phys. Rev. 6, 239–270 (1915)
How to quantify the effect (I)

- Lambdas are “self-analyzing”
- Reveal polarization by preferentially emitting daughter proton in spin direction

Λ's with Polarization $\vec{P}$ follow the distribution:

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi} \left( 1 + \alpha \vec{P} \cdot \vec{p}_p^* \right) = \frac{1}{4\pi} \left( 1 + \alpha P \cos \theta^* \right)$$

$\alpha = 0.642 \pm 0.013$ [measured]

$\hat{p}_p^*$ is the daughter proton momentum direction in the $\Lambda$ frame (note that this is opposite for $\bar{\Lambda}$)

$0 < |\vec{P}| < 1$:

$$\vec{P} = \frac{3}{\alpha} \hat{p}_p^*$$
How to quantify the effect (II)

Symmetry: $|\eta| < 1, \ 0 < \varphi < 2\pi \rightarrow ||\hat{L}||$

Statistics-limited experiment: we report acceptance-integrated polarization, $P_{\text{ave}} \equiv \int d\hat{\beta}_\Lambda \frac{dN}{d\hat{\beta}_\Lambda} \hat{P} \langle \hat{\beta}_\Lambda \rangle \cdot \hat{L}$

$$P_{\text{AVE}} = \frac{8}{\pi \alpha} \left\langle \sin \left( \varphi_b - \varphi_p^* \right) \right\rangle$$

where the average is performed over events and $\Lambda$'s

$R_{EP}^{(1)}$ is the first-order event plane resolution and $\varphi_b$ is the impact parameter angle

** if $v \cdot y > 0$ in BBCs $\varphi_b = \Psi_{EP}$, if $v \cdot y < 0$ in BBCs $\varphi_b = \Psi_{EP} + \pi$
• Measured Lambda and Anti-Lambda polarization

• Includes results from previous STAR null result (2007)

• $P_H(\Lambda)$ and $P_H(\bar{\Lambda}) > 0$ implies positive vorticity

• $P_H(\bar{\Lambda}) > P_H(\Lambda)$ would imply magnetic coupling
Global polarization measure

- Measured Lambda and Anti-Lambda polarization
- Includes results from previous STAR null result (2007)

We can study more fundamental properties of the system

\[ \overline{P}_H(\Lambda) \text{ and } \overline{P}_H(\bar{\Lambda}) > 0 \]
implies positive vorticity

\[ \overline{P}_H(\bar{\Lambda}) \geq \overline{P}_H(\Lambda) \]
would imply magnetic coupling

[Graph showing data points and lines with annotations]

arXiv:1701.06657
Vortical and Magnetic Contributions

- Magneto-hydro equilibrium interpretation

\[ P \sim \exp \left( -\frac{E}{T} + \mu_B B/T + \vec{\omega} \cdot \vec{S}/T + \vec{u} \cdot \vec{B}/T \right) \]

- for small polarization:

\[
P_{\Lambda} \approx \frac{1}{2} \frac{\omega}{T} + \frac{\mu_{\Lambda} B}{T} \quad \quad P_{\bar{\Lambda}} \approx \frac{1}{2} \frac{\omega}{T} + \frac{\mu_{\Lambda} B}{T}
\]

- vorticity from addition:

\[
\frac{\omega}{T} = P_{\bar{\Lambda}} + P_{\Lambda}
\]

- B from the difference:

\[
\frac{B}{T} = \frac{1}{2\mu_{\Lambda}} (P_{\bar{\Lambda}} - P_{\Lambda})
\]

** \( \hbar = k_B = 1 \)

But even with topological cuts, significant feeddown from \( \Sigma^0, \Xi^{0/-}, \Sigma^{*+/0} \)...

... which themselves will be polarized...
Accounting for polarized feeddown

\[
\begin{pmatrix} \frac{\omega}{T} \\ \frac{B}{T} \end{pmatrix} = \left[ \frac{2}{3} \sum_R \left( f_{\Lambda R} C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R} C_{\Sigma^0 R} \right) S_R (S_R + 1) \right] \left[ \frac{2}{3} \sum_R \left( f_{\Xi R} C_{\Xi R} \right) S_R (S_R + 1) \right] \left[ \frac{2}{3} \sum_R \left( f_{\Sigma R} C_{\Sigma R} \right) S_R (S_R + 1) \right] \left[ \frac{2}{3} \sum_R \left( f_{\Omega R} C_{\Omega R} \right) S_R (S_R + 1) \right]^{-1} \begin{pmatrix} P_{\Lambda \text{ meas}} \\ P_{\Xi \text{ meas}} \end{pmatrix}
\]

- \( f_{\Lambda R} \) = fraction of \( \Lambda \)s that originate from parent \( R \rightarrow \Lambda \)
- \( C_{\Lambda R} \) = coefficient of spin transfer from parent \( R \) to daughter \( \Lambda \)
- \( S_R \) = parent particle spin
- \( \mu_R \) is the magnetic moment of particle \( R \)
- overlines denote antiparticles

\[
\begin{array}{|c|c|}
\hline
\text{Decay} & C \\
\hline
\text{parity-conserving: } & \frac{1}{2}^+ \rightarrow \frac{1}{2}^+ 0^- & -\frac{1}{3} \\
\hline
\text{parity-conserving: } & \frac{1}{2}^- \rightarrow \frac{1}{2}^+ 0^- & 1 \\
\hline
\text{parity-conserving: } & \frac{3}{2}^+ \rightarrow \frac{1}{2}^+ 0^- & \frac{1}{3} \\
\hline
\text{parity-conserving: } & \frac{3}{2}^- \rightarrow \frac{1}{2}^+ 0^- & -\frac{1}{15} \\
\hline
\Xi^0 \rightarrow \Lambda + \pi^0 & +0.900 \\
\Xi^- \rightarrow \Lambda + \pi^- & +0.927 \\
\Sigma^0 \rightarrow \Lambda + \gamma & -1/3 \\
\hline
\end{array}
\]

** \( \hbar = k_B = 1 \)

\[\text{TABLE I. Polarization transfer factors } C \text{ (see eq. (31)) for Becattini, Karpenko, Lisa, Upsal, Voloshin arxiv:1610.02506}\]
Extracted Physical Parameters

- Significant vorticity signal
  - Hints at falling with energy, despite increasing $J_{\text{collision}}$
  - $6\sigma$ average for 7.7-39GeV
  - $P_{\Lambda_{\text{primary}}} = \frac{\omega}{2T} \sim 5\%$

- Magnetic field
  - $\mu_N = \text{nuclear magneton}$
  - Positive value, $2\sigma$ average for 7.7-39GeV
Vorticity ~ theory expectation

- Thermal vorticity:
  \[ \frac{\omega}{T} \approx 2 - 10 \% \]
  \[ \omega \approx 0.02 - 0.09 \text{ fm}^{-1} \quad (T_{\text{assumed}} = 160 \text{ MeV}) \]

- Magnitude, \( \sqrt{s} \)-dep. in range of transport & 3D viscous hydro calculations with rotation

\[
\omega \left( \sqrt{s_{\text{NN}}} \right) \quad \text{GeV}^{1/2}
\]

Jiang et al, PRC 94 044910 (2016)

Csernai et al, PRC 90 021904(R) (2014)

**TABLE I.** Time dependence of average vorticity projected to the reaction plane for heavy-ion reactions at the NICA energy of \( \sqrt{s_{\text{NN}}} = 4.65 + 4.65 \text{ GeV} \).

<table>
<thead>
<tr>
<th>( t ) (fm/c)</th>
<th>Vorticity (classical) ( (c/\text{fm}) )</th>
<th>Thermal vorticity (relativistic) (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17</td>
<td>0.1345</td>
<td>0.0847</td>
</tr>
<tr>
<td>1.02</td>
<td>0.1238</td>
<td>0.0975</td>
</tr>
<tr>
<td>1.86</td>
<td>0.1079</td>
<td>0.0846</td>
</tr>
<tr>
<td>2.71</td>
<td>0.0924</td>
<td>0.0886</td>
</tr>
<tr>
<td>3.56</td>
<td>0.0773</td>
<td>0.0739</td>
</tr>
</tbody>
</table>
Vorticity comparison

- Solar subsurface flow: $\omega \sim 10^{-6}$ s$^{-1}$
- Ocean flows: $\omega \sim 10^{-5}$ s$^{-1}$
- Terrestrial atmosphere: $\omega \sim 10^{-4}$ s$^{-1}$
- “Collar” of Jupiter’s Great Red Spot: $\omega \sim 10^{-4}$ s$^{-1}$
- Core of supercell tornado: $\omega \sim 10^{-1}$ s$^{-1}$

- Max vorticity in bulk superfluid He-II: $\omega \sim 150$ s$^{-1}$
- Max vorticity in nanodroplets of superfluid He-II: $10^6$ s$^{-1}$
  - Shomroni et al, Science 345 (2014) 903

RHIC produces the least viscous fluid.
RHIC produces the most vortical fluid!
Magnetic field:

- Expected sign

\[ B \sim 10^{14} \text{ Tesla} \]

\[ eB \sim 1 m_{\pi}^{2} \sim 0.5 \text{ fm}^{-2} \]

- Magnitude at high end of theory expectation (expectations vary by orders of magnitude)

- But... consistent with zero
  - A definitive statement requires more statistics/better EP determination

Gursoy, Kharzeev & Rajagopal
PRC 89 054905 (2014)

Effect of QGP electrical conductivity
Non-central heavy ion collisions create QGP with high vorticity
- generated by early shear viscosity (closely related to initial conditions), persists through low viscosity
- fundamental feature of any fluid, unmeasured until now
  - an incomplete characterization of QGP
  - relevance for other hydro-based conclusions?

Huge and rapidly-changing B-field in non-central collisions
- not directly measured
- theoretical predictions vary by orders of magnitude
- sensitive to electrical conductivity, early dynamics

Both of these extreme conditions must be established & understood to put recent claims of chiral effects on firm ground
Summary II

• **Global hyperon polarization:** unique probe of vorticity & B-field
  – non-exotic, non-chiral
  – quantitative input to calibrate chiral phenomena

• STAR has made the **first observation** of global Λ polarization
  – statistics- & resolution-limited: 1-5σ effect for any given √s_{NN}
    • ~6σ effect on average

• **Interpretation** in magnetic-vortical model:
  – clear vortical component of right sign, magnitude for √s_{NN} < 30 GeV
  – magnetic component of right sign, magnitude *hinted at*, but consistent with zero at each √s_{NN}

• **BES-II: Statistics & upgrades** [Chi Yang 02/07 18:10] will allow characterization & model discrimination