Global polarization of hyperons measured by STAR

Mike Lisa, Ohio State University
for the STAR Collaboration
Outline

• Motivation
  – angular momentum and vorticity in heavy ion collisions
  – self-analyzing nature of Lambda decay

• Current analysis: STAR @ BES energies – preliminary results
  • Analysis details: acceptance, resolution correction
  • positive signals for Lambdas and AntiLambdas
  • consistency with previous STAR results

• Summary & Outlook
\[ |L| \sim 10^5 \hbar \text{ in non-central collisions} \]

- Does angular momentum get distributed thermally?
- Does it generate a “spinning QGP?”
  - consequences?
- How does that affect fluid/transport?
  - Vorticity: \( \vec{\omega} = \vec{V} \times \vec{v} \)
- How would it manifest itself in data?
Rotational & Irrotational Vortices

Simplest vorticity: $\vec{\omega} = \vec{\nabla} \times \vec{v}$

Rigid-body-like vortex

$\nu \propto r$

Irrotational vortex

$\nu \propto 1/r$

Like the moon, always the same side toward Earth

Notice the rotation, or lack thereof, in the fluid elements
Localized vortex generation via baryon stopping

Viscosity dissipates vorticity to fluid at larger scale

Vorticity – fundamental sub-femtoscopic structure of the “perfect fluid” and its generation

Calculations behind the “perfect fluid” story neglect angular momentum & vorticity altogether. Problem?
Connection to experiment

• Fluid vorticity may generate global polarization (alignment of spin with collision system angular momentum) of emitted particles
  – Betz, Gyulassy, Torrieri PRC76 044901 (2007)
  – Becattini et al., PRC88 034905 (2013)
  – Csernai et al., JPhys 012054-5 (2014) (SQM2013)
  – Becattini et al. arxiv:1501.04468

• Similar conclusions based on QCD spin-orbit coupling (non-hydro picture)
  – Voloshin arxiv:nucl-th/0410089
  – Liang and Wang, PRL94 102301 (2005); PRL96 039901(E) (2006)
  – Liang and Wang, PLB629 20 (2005)
Analysis approach

- Study Au+Au collision in the BES:
  - 7.7, 11.5, 19.6, 27, 39 GeV

- Tracking is performed by the **TPC**
- PID is done using the **TPC + TOF**

- **BBC** detects participants to determine first order event plane
  \[ \hat{L} \]

\[ \hat{L} \times \text{estimate of direction of angular momentum} \]

\( \hat{L} \)
Lambdas are “self-analyzing”

- reveal polarization by preferentially emitting daughter proton in spin direction
- more on this in a few slides

E. Cummins, Weak Interactions (McGraw-Hill, 1973)

**Basic Track Cuts**
- If proton has ToF: $0.5 \left( \frac{\text{GeV/c}^2}{c} \right)^2 < m^2 < 1.5 \left( \frac{\text{GeV/c}^2}{c} \right)^2$ (TPC $|n_\sigma| < 3$)
- If pion has ToF: $(0.017 - 0.013 \cdot \frac{p}{\text{GeV/c}})^2 < m^2 < 0.04 \left( \frac{\text{GeV/c}^2}{c} \right)^2$ (TPC $|n_\sigma| < 3$)

**Lambda Topological cuts**
- Daughter DCA < 1 cm, $1.108 \frac{\text{GeV}}{c^2} < m < 1.122 \frac{\text{GeV}}{c^2}$

<table>
<thead>
<tr>
<th>lengths in cm</th>
<th>Both have ToF</th>
<th>Proton has ToF</th>
<th>Pion has ToF</th>
<th>Neither has ToF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton DCA</td>
<td>0.1</td>
<td>0.15</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Pion DCA</td>
<td>0.7</td>
<td>0.8</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>Lambda DCA</td>
<td>1.3</td>
<td>1.2</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Lambda Decay Length</td>
<td>2</td>
<td>2.5</td>
<td>3.5</td>
<td>4</td>
</tr>
</tbody>
</table>

Topological cuts optimized to maximize yield significance

$\vec{S}_\Lambda \theta \vec{p}_p$
• Vortical or QCD spin-orbit: Lambda and AntiLambda spins aligned with L
  • Sigma feed-down tends to dampen the effect
**Contributors to Global Polarization**

- **Vortical or QCD spin-orbit:**
  - Lambda and AntiLambda spins aligned with $L$
  - Sigma feed-down tends to dampen the effect
- **(electro)magnetic coupling:**
  - Lamdas $anti$-aligned, and AntiLambdas aligned
  - Sigma feed-down goes in same direction as the effect on primaries
Contributors to Global Polarization

Known effect in p+p collisions [e.g. Bunce et al, PRL 36 1113 (1976)]
- Lambda polarization at forward rapidity relative to production plane

- Vortical or QCD spin-orbit: Lambda and AntiLambda spins aligned with L
  - Sigma feed-down tends to dampen the effect

- (electro)magnetic coupling: Lamdas anti-aligned, and AntiLambdas aligned
  - Sigma feed-down goes in same direction as the effect on primaries

- Polarization w/ production plane: No integrated effect at midrapidity for Lambda
  - measured to have no effect at all for AntiLambdas (reason unknown)
  - also, would polarize perpendicular to L for out-of-plane particles – tested (big errors)
How to quantify the effect?

For an ensemble of $\Lambda$s with polarization $\vec{P}$:

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

$\alpha = 0.642$ [measured]

$\hat{p}_p^*$ is daughter proton momentum direction in $\Lambda$ frame

$0 < |\vec{P}| < 1$: \[ \vec{P} = \frac{3}{\alpha} \hat{p}_p^* \]
How to quantify the effect?

For an ensemble of $\Lambda$s with polarization $\tilde{P}$:

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

$\alpha = 0.642$ [measured]

$\hat{p}_p^*$ is daughter proton momentum direction \textit{in $\Lambda$ frame}

$0 < |\tilde{P}| < 1 : \quad \tilde{P} = \frac{3}{\alpha} \tilde{p}_p^*$

Dynamic heavy ion collision may produce several "ensembles" $\rightarrow \tilde{P}$ may depend on $\tilde{\beta}_\Lambda$

Models [Beccatini, Csernai, Liang, Wang, others] predict various dependence on $p_T$, $\phi$
How to quantify the effect?

For an ensemble of $\Lambda$s with polarization $\vec{P}$:

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

$\alpha = 0.642$ [measured]

$\hat{p}_p^*$ is daughter proton momentum direction $in \Lambda$ frame

$0 < |\vec{P}| < 1$: $\vec{P} = \frac{3}{\alpha} \hat{p}_p^*$

Dynamic heavy ion collision may produce several "ensembles" $\rightarrow \vec{P}$ may depend on $\vec{\beta}_\Lambda$

Models [Beccatini, Csernai, Liang, Wang, others] predict various dependence on $p_T$, $\phi$

Symmetry: $|y| < 1$, $0 < \phi < 2\pi$ $\rightarrow \vec{P}_{ave} \parallel \hat{L}$

Statistics-limited experiment: we report acceptance-integrated polarization, $P_{ave} = \int d\vec{\beta}_\Lambda \frac{dN}{d\vec{\beta}_\Lambda} \vec{P}(\vec{\beta}_\Lambda) \cdot \hat{L}$

$$P_{ave} = \frac{8}{\pi \alpha} \frac{\langle \sin(\phi_p^* - \Psi_{EP}^{(1)}) \rangle}{R_{EP}^{(1)}}$$ where the average is performed over events and $\Lambda$s

$\Psi_{EP}^{(1)}$ is the first-order event plane (found with BBCs)

$R_{EP}^{(1)}$ is the first-order event plane resolution (same as $v_1$ analysis)

STAR, PRC76 024915 (2007)
Correcting for reaction-plane resolution

$$R^{(1)}_{EP} = \langle \cos \Delta \psi \rangle = \langle \cos(\Psi_{RP} - \Psi_{EP}^{(1)}) \rangle$$

$$P_{ave} = \frac{8}{\pi \alpha} \frac{\langle \sin(\phi^*_p - \Psi_{EP}^{(1)}) \rangle}{R^{(1)}_{EP}}$$
Topologically-dependent efficiency

Spin-orientation-dependent efficiency (!)

Daughter proton & pion have equal-magnitude momentum in Lambda frame, but not in STAR frame

\[
\frac{R_\pi}{R_p} = \left| \frac{\vec{p}_{T,\pi}}{\vec{p}_{T,p}} \right| \approx \frac{m_\pi}{m_p} \approx \frac{1}{7} \rightarrow \pi \text{ tracking drives } \Lambda \text{ efficiency}
\]

pion emitted backward in Lambda c.m., \( \rightarrow \) tight curl, large DCA (distance to collision vertex)
\( \rightarrow \) much-reduced efficiency
\( \rightarrow \) higher efficiency to find negative-helicity Lambdas
Topologically-dependent efficiency

Spin-orientation-dependent efficiency (!)

- Same effect seen in embedding/GEANT simulations
- $p_T$-dependent
- not correlated with RP
- explicitly cancels when summing regions separated by 180 degrees

**effect does not affect $P_{\text{ave}}$**
• First clear positive signal of global polarization in heavy ion collisions!

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>7.7</th>
<th>11.5</th>
<th>14.5</th>
<th>19.6</th>
<th>27</th>
<th>39</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$</td>
<td>3.6σ</td>
<td>3.6σ</td>
<td>2.4σ</td>
<td>3.1σ</td>
<td>3.5σ</td>
<td>1.1σ</td>
</tr>
<tr>
<td>anti-$\Lambda$</td>
<td>-</td>
<td>2.1σ</td>
<td>1.1σ</td>
<td>2.4σ</td>
<td>2.9σ</td>
<td>1.6σ</td>
</tr>
</tbody>
</table>

Marginal significance for one energy. Ensemble & trend adds confidence.

• Both Lambdas and AntiLambdas show positive polarization $\rightarrow$ vorticity and/or spin-orbit
  • increased AntiLambdas polarization could arise from (electro)magnetic contribution, but errorbars...

• Signal falls with energy – physics or simply loss of resolution?
First clear positive signal of global polarization in heavy ion collisions!

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>7.7</th>
<th>11.5</th>
<th>14.5</th>
<th>19.6</th>
<th>27</th>
<th>39</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$</td>
<td>3.6σ</td>
<td>3.6σ</td>
<td>2.4σ</td>
<td>3.1σ</td>
<td>3.5σ</td>
<td>1.1σ</td>
</tr>
<tr>
<td>anti-$\Lambda$</td>
<td>-</td>
<td>2.1σ</td>
<td>1.1σ</td>
<td>2.4σ</td>
<td>2.9σ</td>
<td>1.6σ</td>
</tr>
</tbody>
</table>

Marginal significance for one energy. Ensemble & trend adds confidence.

Both $\Lambda$s and Anti-$\Lambda$s show positive polarization $\Rightarrow$ vorticity and/or spin-orbit
  - increased Anti-$\Lambda$s polarization could arise from (electro)magnetic contribution, but errorbars...

Resolution corrected in centrality bins
Corrected RP resolution & combinatoric background

- Subtracting residual effect from combinatoric background below mass peak

![Graph showing resolution and combinatoric-corrected data for Lambda and Antilambda in Au+Au 20-50% collisions with statistical errors only.](image-url)
• Subtracting residual effect from combinatoric background below mass peak
• Correcting for feed-down from Sigma0

\[ \Sigma^0 \rightarrow \Lambda + \gamma \]

- A significant fraction (~30%) of our Lambdas are actually feed-down from Sigma0
- The daughter Lambda tends to have spin direction opposite that of the parent Sigma

(p-wave decay)
• Subtracting residual effect from combinatoric background below mass peak
• Correcting for feed-down from Sigma0

\[ \Sigma^0 \rightarrow \Lambda + \gamma \]

- A significant fraction (~30%) of our Lambdas are actually feed-down from Sigma0
- The daughter Lambda tends to have spin direction opposite that of the parent Sigma

(p-wave decay)

• previous STAR results (corrected for sign) continue systematics
Summary

• Large angular momentum in noncentral heavy ion collisions may be partially transferred to the hot fireball at midrapidity
  – thermalization: if angular momentum is distributed thermally, spin states will be preferentially occupied
  – In a hydro scenario, achieved through vorticity generated by shear viscosity
  – At a microscopic level, may be due to QCD spin-orbit coupling

• Global hyperon polarization probes this (largely unexplored) physics

• STAR has seen the first positive signal of global hyperon polarization
  – 2.5σ to 3.5σ signal for Λ’s at each energy below 39 GeV
  – previous STAR “null result” appears to fall in line with systematics!
  – falls with energy – driving physics?
  – hint of larger signal for antibaryons – additional magnetic effect?

• higher statistics & resolution in BES-II will allow important differential studies
  – centrality, $p_T$, phi, directional mapping
### BES-II: 2019-2020

- **Collider (e-cooling) & detector upgrades**
- **Finer-grained measurements**
  - what drives energy dependence of $P$?
  - Increase statistics by order of magnitude
    - stat. errorbars reduced by $\sim 3$
  - Improve 1$^{st}$-order RP resolution by $2x$
    - stat. errorbars reduced by another $\sim 2$

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>5.0</th>
<th>7.7</th>
<th>9.1</th>
<th>11.5</th>
<th>13.0</th>
<th>14.5</th>
<th>19.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{B}$ (MeV)</td>
<td>550</td>
<td>420</td>
<td>370</td>
<td>315</td>
<td>290</td>
<td>250</td>
<td>205</td>
</tr>
<tr>
<td>BES I (MEvts)</td>
<td>---</td>
<td>4.3</td>
<td>---</td>
<td>11.7</td>
<td>---</td>
<td>24</td>
<td>36</td>
</tr>
<tr>
<td>Rate (MEvts/day)</td>
<td>0.25</td>
<td>1.7</td>
<td>2.4</td>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BES I $\mathcal{L}$ ($1 \times 10^{25}$/cm$^2$/sec)</td>
<td>0.13</td>
<td>1.5</td>
<td>2.1</td>
<td>4.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BES II (MEvts)</td>
<td>100</td>
<td>160</td>
<td>230</td>
<td>250</td>
<td>300</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>eCooling (Factor)</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>11</td>
<td>15</td>
</tr>
<tr>
<td>Beam Time (weeks)</td>
<td>14</td>
<td>9.5</td>
<td>5.0</td>
<td>3.0</td>
<td>2.5</td>
<td>3.0</td>
<td></td>
</tr>
</tbody>
</table>
Thanks for your attention
Effect of (Anti)Sigma feed-down

\[ \Sigma^0 \rightarrow \Lambda + \gamma \]

- A significant fraction (~30%) of our Lambdas are actually feed-down from Sigma0
- The daughter Lambda tends to have spin direction opposite that of the parent Sigma

(p-wave decay)

Scenario 1: spin of all primary particles \((\Lambda, \Sigma^0, \bar{\Lambda}, \bar{\Sigma}^0)\) aligned with \(\vec{J}_{\text{system}}\), due to vorticity (or whatever):

\[ \Rightarrow \text{primary } \Lambda \text{ (and } \bar{\Lambda} \text{)} \text{ aligned with } \vec{J}_{\text{system}}, \text{ but secondary } \Lambda \text{ (and } \bar{\Lambda} \text{)} \text{ aligned against } \vec{J}_{\text{system}} \]

Thus, for vorticity-induced polarization, feed-down tends to damp the signal. STAR’s 2004 paper estimated < 30% damping effect

Scenario 2: polarization through coupling of particle magnetic moment to B-field of the system

\[ \vec{\mu}_\Lambda = (-0.613 \mu_N) \vec{S}_\Lambda \Rightarrow \vec{S}_{\Lambda[\text{primary}]} \text{ will be antialigned with } \vec{J}_{\text{system}} \quad \left( \vec{S}_{\Lambda[\text{primary}]} \parallel -\vec{J}_{\text{system}} \right) \]

\[ \vec{\mu}_{\Sigma^0} = (+0.79 \mu_N) \vec{S}_{\Sigma^0} \Rightarrow \vec{S}_{\Sigma^0} \text{ will be aligned with } \vec{J}_{\text{system}} \quad \left( \vec{S}_{\Sigma^0} \parallel +\vec{J}_{\text{system}} \right) \]

\[ \Rightarrow \text{daughter } \Lambda \text{’s will be antialigned with } \vec{J}_{\text{system}} \quad \left( \vec{S}_{\Lambda[\text{secondary}]} \parallel -\vec{J}_{\text{system}} \right) \]

Similar argument for the antiparticles, where both the primary and secondary \(\bar{\Lambda}\) align with \(\vec{J}_{\text{system}}\)

Thus, for magnetic-coupling-induced polarization, feed-down goes in the same direction as the signal from primary Lambdas.
Effect of (Anti)Sigma feed-down

\[
\Sigma_0^+ \rightarrow \Lambda^+ + \gamma
\]

(p-wave decay)

- A significant fraction of our Lambdas are actually feed-down from Sigma0
- The daughter Lambda tends to have spin direction opposite that of the parent Sigma

Under assumption that \( \Sigma^0 \) polarizes as \( \Lambda \) does:

\[
P_{\text{primary } \Lambda} = \frac{1 + \frac{N_{\Sigma^0}}{N_{\text{prim } \Lambda}}}{1 - \frac{1}{3} \frac{N_{\Sigma^0}}{N_{\text{prim } \Lambda}}} P_{\text{measured } \Lambda} \equiv K_{\Sigma^0 \rightarrow \Lambda} P_{\text{measured } \Lambda}
\]

<table>
<thead>
<tr>
<th>model</th>
<th>N[Sigma0]/N[Lambda]</th>
<th>K[Sigma0-&gt;Lambda]</th>
</tr>
</thead>
<tbody>
<tr>
<td>“isospin effect” (COSY-11) (*)</td>
<td>1/3</td>
<td>1.5</td>
</tr>
<tr>
<td>THERMUS with, w/o resonances (*)</td>
<td>0.36-0.67</td>
<td>1.5-2.2</td>
</tr>
<tr>
<td>“Coalescence” (*)</td>
<td>0.2-1.0 (1.0?)</td>
<td>1.3-3</td>
</tr>
<tr>
<td>Chemical equilibrium with T=150 MeV</td>
<td>0.59</td>
<td>2</td>
</tr>
<tr>
<td>STAR estimate from p-Lambda paper</td>
<td>0.73</td>
<td>2.3</td>
</tr>
<tr>
<td>(*) G. Van Buren (STAR) nucl-ex/0412034</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Conservative range: 1.5-2.5
Previous STAR result


\[ \langle \vec{S}_\Lambda^* \cdot \hat{L} \rangle = -\frac{1}{2} P_\Lambda \]

A 1.7-sigma signal seen for Anti-Lambdas at 62.4 GeV?