Observation of global hyperon polarization in non-central heavy ion collisions

Mike Lisa, Ohio State University for the STAR Collaboration
• Motivation
  – angular momentum and plasma substructure
  – CME / CVE – the need for quantitative “non-chiral” input
  – global hyperon polarization as a unique probe

• First observation of global hyperon polarization
  – Analysis details: acceptance, resolution correction
  – $v_{s_{NN}}$-dependence and splitting for Lambdas and AntiLambdas
    • & comparison with prev. result
  – Feed-down correction

• Model-dependent estimate of B-field and plasma vorticity

• Summary & Outlook
Non-central collisions - $J \sim 10^4 \hbar$

- Is angular momentum distributed thermally?
- Does it generate a “spinning QGP?”
  - consequences?
- How does that affect fluid/transport?
  - Vorticity: $\vec{\omega} = \vec{\nabla} \times \vec{v}$
- How would it manifest itself in data?
- Relevance to novel phenomena?
Rotational & Irrotational Vortices

Rigid-body-like vortex
$$\nu \propto r$$

$${\bar{\omega}} = \nabla \times \vec{v}$$

Irrotational vortex – e.g. tub drain
$$\nu \propto 1/r$$

This one is like the moon, always facing 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-femtosscopic structure of the “perfect fluid” and its generation
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

Figure 12: (color online) Mean values of thermal vorticity components at the freeze-out as a function of $\eta/s$. Note that the $\omega_{x\eta}$, $\omega_{y\eta}$, $\omega_{x\tau\eta}$ have been multiplied by $1/\tau$. 
Contributors to **Global Polarization**

- **Vortical or QCD spin-orbit:**
  - fluid cell emits polarized particles \( P \propto \omega \)
  - Becattini, Csernai, Torrieri, Gyulassy, Gao, Liang, Wang, Sorin...

\[
\begin{align*}
\vec{P}_\Lambda & \parallel +\hat{J}_{\text{sys}} \\
\vec{P}_{\bar{\Lambda}} & \parallel +\hat{J}_{\text{sys}}
\end{align*}
\]
Contributors to Global Polarization

- **Vortical or QCD spin-orbit:**
  - fluid cell emits polarized particles $P \propto \omega$
  - Becattini, Csernai, Torrieri, Gyulassy, Gao, Liang, Wang, Sorin...

- **Magnetic coupling**
  - particles polarized according to magnetic moment $P \propto \hat{\mu} \cdot \hat{B}$

\[
\begin{align*}
\overline{P}_\Lambda \parallel + \hat{J}_{\text{sys}} & \quad \overline{P}_{\overline{\Lambda}} \parallel + \hat{J}_{\text{sys}} \\
\overline{P}_\Lambda \parallel - \hat{J}_{\text{sys}} & \quad \overline{P}_{\overline{\Lambda}} \parallel + \hat{J}_{\text{sys}}
\end{align*}
\]
Input needed to extract physics from CME/CVE

\[ \vec{J} = \frac{N_c \mu_5}{2\pi^2} \left[ \text{tr}(V AQ) \vec{B} + \text{tr}(V AB) 2 \mu_B \vec{\omega} \right] \]

\( CME \quad CVE \)

Kharzeev & Son PRL 106 062301 (2011)

\( SU(3) : \)

\[ J_E = \frac{N_c \mu_5}{3\pi^2} B \quad \rightarrow \text{separation of +/- along \( \vec{B} \)} \]

\[ J_B = \frac{N_c \mu_5}{\pi^2} \mu_B \vec{\omega} \quad \rightarrow \text{separation of \( B/\bar{B} \) along \( \vec{\omega} \)} \]

CME and CVE hold promise to access fundamental features of QCD

- Novel phenomena are among RHIC’s most exciting and visible new results

To put these discoveries on firmer footing, we need calibrated estimates of B-field and vorticity

Hyperon polarization: non-“chiral”, independent and likely unique measure
Ingredients needed: $\tilde{P}_\Lambda$ and $\hat{J}$

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

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

$\alpha = 0.642$ [measured]

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

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

E. Cummins, Weak Interactions (McGraw-Hill, 1973)
Ingredients needed: $\vec{P}_\Lambda$ and $\hat{J}$ system

$\Lambda, \bar{\Lambda}$ reconstructed in TPC+TOF for $|y| < 1$

Forward BBCs estimate Reaction Plane: $\vec{B} \parallel \vec{\omega} \parallel \hat{J}_{sys}$

Correlate $\vec{p}_p^*$ and $\hat{J}_{sys}$

STAR BES energies 7.7, 11.5, 14.5, 19.6, 27, 39 GeV Au+Au collisions

Also compare to previously published 62.4, 200 GeV analysis, using ZDC for Reaction Plane
Statistics-limited: we report integrated polarization, $\bar{P}_H \equiv \int d\bar{\beta}_\Lambda \frac{dN}{d\bar{\beta}_\Lambda} \bar{P}(\bar{\beta}_\Lambda) \cdot \hat{J}_{\text{sys}}$

$$\bar{P}_H = \frac{8}{\pi \alpha} \frac{\langle \sin(\phi_p^* - \Psi_{\text{EP}}^{(1)}) \rangle}{R_{\text{EP}}^{(1)}}$$

where the average is over events and $\Lambda$s [1]

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

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

Ingredients needed: $\tilde{P}_\Lambda$ and $\mathbf{j}_{\text{sys}}$

Event-plane resolution
- best for mid-central collisions
- significantly worse at higher energy

$$\bar{P}_H = \frac{8}{\pi\alpha} \frac{\langle \sin(\phi_p^* - \Psi_{\text{EP}}^{(1)}) \rangle}{R_{\text{EP}}^{(1)}}$$

Forward BBCs estimate Reaction Plane: $\bar{B} \parallel \bar{\omega} \parallel \mathbf{j}_{\text{sys}}$

$$\delta \bar{P}_H \propto \left( \frac{R_{\text{EP}}^{(1)} \sqrt{\# \Lambda}}{\sqrt{\# \Lambda}} \right)^{-1}$$
First clear positive signal of global polarization in heavy ion collisions!

- systematic errors vanishingly small beneath statistical errors

Both Lambdas and AntiLambdas show positive polarization

- vorticity, spin-orbit mechanism dominant

Splitting?

- suggests additional magnetic effect

Signal falls with energy – physics or simply loss of resolution?

<table>
<thead>
<tr>
<th>$s_{\text{NN}}$ (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>3.6(\sigma)</td>
<td>3.5(\sigma)</td>
<td>2.4(\sigma)</td>
<td>3.1(\sigma)</td>
<td>3.5(\sigma)</td>
<td>1.1(\sigma)</td>
</tr>
<tr>
<td>anti-$\Lambda$</td>
<td>2.2(\sigma)</td>
<td>2.1(\sigma)</td>
<td>1.1(\sigma)</td>
<td>2.4(\sigma)</td>
<td>2.9(\sigma)</td>
<td>1.6(\sigma)</td>
</tr>
</tbody>
</table>

Marginal significance for one energy. Ensemble & trend adds confidence.
First clear positive signal of global polarization in heavy ion collisions!

- systematic errors vanishingly small beneath statistical errors

Both Lambda and AntiLambda show positive polarization

- vorticity, spin-orbit mechanism dominant

Splitting?

- suggests additional magnetic effect

Signal falls with energy – physics or simply loss of resolution?

<table>
<thead>
<tr>
<th>$s_{NN}$ (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>3.5σ</td>
<td>2.4σ</td>
<td>3.1σ</td>
<td>3.5σ</td>
<td>1.1σ</td>
</tr>
<tr>
<td>anti-$\Lambda$</td>
<td>2.2σ</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.
First clear positive signal of global polarization in heavy ion collisions!

- systematic errors vanishingly small beneath statistical errors

Both Lambda and AntiLambda show positive polarization

- vorticity, spin-orbit mechanism dominant

Splitting?

- suggests additional magnetic effect

Signal falls with energy – physics or simply loss of resolution?
First clear positive signal of global polarization in heavy ion collisions!
- systematic errors vanishingly small beneath statistical errors

Both Lambdas and AntiLambdas show positive polarization
- vorticity, spin-orbit mechanism dominant

Splitting?
- suggests additional magnetic effect

Signal falls with energy – physics or simply loss of resolution?

Small systematic error from combinatoric background subtraction
Previous STAR result

Phys RevC 76, 024915 (2007) concluded null signal (2% limit)

\[ P_H[2007] = -\overline{P_H} \]

oops

- Black circle: 200 GeV (20-70% \( \sigma_{TOT} \))
- Red square: 62.4 GeV (0-80% \( \sigma_{TOT} \))
Complete energy range

Large uncertainties, but previous results follow trend established at BES
Extracting Vortical and Magnetic Contributions

- The data reveals a dominant common component and suggests a small splitting.
- Magneto-hydrodynamics interpretation:
  - vortical component is the average
  - magnetic component is the difference
    - coupling to $\mu_B$ may produce similar effect
      [Becattini, Wang, Sorin...]

For small polarization, vortical and magnetic contributions add:

\[
P_\Lambda = P_V + P_M \quad P_\bar{\Lambda} = P_V - P_M
\]
Extracting Vortical and Magnetic Contributions

- The data reveals a dominant *common* component and suggests a small splitting.

- Magneto-hydrodynamics interpretation:
  - vortical component is the average
  - magnetic component is the difference
    - coupling to $\mu_B$ may produce similar effect [Becattini, Wang, Sorin...]

- However, must account for $\sim$50-60% feed-down contributions
  - $\sim$75%, including resonances (not done here)

For small polarization, vortical and magnetic contributions add:

\[
P_{\Lambda,\text{primary}} = P_V + P_M \quad \quad P_{\bar{\Lambda},\text{primary}} = P_V - P_M
\]

Even with topological cuts, significant feeddown from $\Sigma^0$, $\Xi^0$, $\Xi^-$...

... which, themselves, will likely be polarized...
Accounting for (polarized) feed-down

• Assume other hadrons, $X$, are polarized by the same vortical and magnetic mechanisms as the Lambdas

\[ P_X = P_{V,X} + P_{M,X} \quad P_{\bar{X}} = P_{V,X} - P_{M,X} \]
Accounting for (polarized) feed-down

• Assume other hadrons, $X$, are polarized by the same vortical and magnetic mechanisms as the Lambdas

\[
\begin{align*}
P_X &= P_{V,X} + P_{M,X} \\
\bar{P}_X &= P_{V,X} - P_{M,X}
\end{align*}
\]

• Relationship to Lambdas:
  – Common vortical polarization:

\[
P_{V,X} = P_{V,\Lambda} \equiv P_V
\]
Accounting for (polarized) feed-down

• Assume other hadrons, \(X\), are polarized by the same vortical and magnetic mechanisms as the Lambdas

\[
P_X = P_{V,X} + P_{M,X} \quad \quad P_{\bar{X}} = P_{V,X} - P_{M,X}
\]

• Relationship to Lambdas:
  – Common vortical polarization:
    \[
P_{V,X} = P_{V,\Lambda} \equiv P_V
\]
  – Magnetic coupling proportional to dipole moment:
    \[
P_{M,X} \propto \mu_X B \quad \rightarrow \quad P_{M,X} = \frac{\mu_X}{\mu_\Lambda} P_M
\]

\[
\begin{align*}
\mu_\Lambda &= -0.613\mu_N \\
\mu_{\Xi^-} &= -0.651\mu_N \\
\mu_{\Sigma^0} &= +0.613\mu_N \\
\mu_{\Xi^0} &= -1.25\mu_N
\end{align*}
\]
Accounting for (polarized) feed-down

• Assume other hadrons, $X$, are polarized by the same vortical and magnetic mechanisms as the Lambdas

\[ P_X = P_{V,X} + P_{M,X} \quad P_{X} = P_{V,X} - P_{M,X} \]

• Relationship to Lambdas:
  – Common vortical polarization:
    \[ P_{V,X} = P_{V,\Lambda} \equiv P_{V} \]
  – Magnetic coupling proportional to dipole moment:
    \[ P_{M,X} \propto \mu_X B \quad \Rightarrow \quad P_{M,X} = \frac{\mu_X}{\mu_\Lambda} P_M \]
    \[ \mu_\Lambda = -0.613 \mu_N \quad \mu_{\Xi^-} = -0.651 \mu_N \]
    \[ \mu_{\Sigma^0} = +0.613 \mu_N \quad \mu_{\Xi^0} = -1.25 \mu_N \]

• Polarization transfer:

\[ X^{\uparrow} \rightarrow \Lambda^{\uparrow} + \cdots \rightarrow P_{\Lambda, \text{daughter}} = F_X P_X \]
\[ F_{\Sigma^0} = -\frac{1}{3} \]
\[ F_{\Xi^-} = +0.927 \]
\[ F_{\Xi^0} = +0.900 \]
Calculated polarization of primary Λ

- Corrected for polarized feeddown – model-dependent
- 8% polarization!!
- Significant (2-5 sigma level) vortical polarization, falling with energy
- Magnetic polarization consistent w/ 0 at all energies, but “wants” to be < 0 – (P_M<0 expected)
- Statistical errors dominate – systematic uncertainties from UrQMD versus THERMUS feeddown estimates

<table>
<thead>
<tr>
<th></th>
<th>(v_{s_{NN}})</th>
<th>7.7</th>
<th>11.5</th>
<th>14.5</th>
<th>19.6</th>
<th>27</th>
<th>39</th>
<th>62.4</th>
<th>BES ave</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_V)</td>
<td>(2.7\sigma)</td>
<td>(3.0\sigma)</td>
<td>(1.9\sigma)</td>
<td>(3.5\sigma)</td>
<td>(4.5\sigma)</td>
<td>(2.1\sigma)</td>
<td>(1.6\sigma)</td>
<td>(5.4\sigma)</td>
<td></td>
</tr>
</tbody>
</table>

\[ |s_{NN}| (GeV) \]

\(\bar{P}_M\) (%)

\(\bar{P}_V\) (%)
Extracting vorticity and B-field from data

- Nonrelativistic equilibrium limit:
  \[ N \propto \exp\left( \vec{S}_H \cdot \vec{\omega} / T + \mu_H \cdot \vec{B} / T \right) \]

Model-dep.

STAR Preliminary
Au+Au 20-50%

systematic uncertainties from model variation in feeddown
Extracting vorticity and B-field from data

- Nonrelativistic equilibrium limit:
  \[ N \propto \exp\left( \vec{S}_H \cdot \vec{\omega} / T + \mu_H \cdot \vec{B} / T \right) \]

- Thermal vorticity:
  \[ \frac{\omega}{T} \approx 2 \overline{P}_V \approx 2 - 16\% \]
  \[ \omega \approx 0.02 - 0.16 \text{ fm}^{-1} \]

* Using \( T = 200 \text{ MeV} \)

Systematic uncertainties from model variation in feeddown

STAR Preliminary
Au+Au 20-50%

M.A. Lisa - Strangeness in Quark Matter - Lawrence Berkeley National Lab - June 2016
Extracting vorticity and B-field from data

- Nonrelativistic equilibrium limit:
\[ N \propto \exp\left( \vec{S}_H \cdot \vec{\omega} / T + \mu_H \cdot \vec{B} / T \right) \]

- Thermal vorticity:
\[ \frac{\omega}{T} \approx 2 \bar{P}_V \approx 2 - 16\% \]
\[ \omega \approx 0.02 - 0.16 \text{ fm}^{-1} \]

- Magnetic field
\[ B \approx \frac{T}{\mu_\Lambda} \bar{P}_M \]
\[ B\left[ m_\pi^2 \right] = B\left[ 10^{14} \text{ Tesla} \right] \approx \bar{P}_M \left[ \% \right] \]

- Systematic uncertainties from model variation in feeddown

* Using T=200 MeV

Model-dep.
Vorticity \sim theory expectation

- Thermal vorticity:

\[ \frac{\omega}{T} \approx 2 \bar{P}_V \approx 2 - 16\% \]

\[ \omega \approx 0.02 - 0.16 \text{ fm}^{-1} \]

* Using T=200 MeV

\[
\begin{align*}
\omega &\approx 0.02 - 0.16 \text{ fm}^{-1} \quad \text{*} \\
\omega &\approx 0.02 - 0.16 \text{ fm}^{-1} \\
\frac{\omega}{T} &\approx 2 \bar{P}_V \approx 2 - 16\% \\
10^{2} |s_{NN}| (\text{GeV}) &
\end{align*}
\]

STAR Preliminary

M.A. Lisa - Strangeness in Quark Matter - Lawrence Berkeley National Lab - June 2016
B-field ~ theory expectation

- Magnetic field

\[ B \approx \frac{T}{\mu_\Lambda} \bar{P}_M \]

\[ B\left[m^2_\pi\right] = B\left[10^{14}\ \text{Tesla}\right] \approx \bar{P}_M\left[\%\right] \]

- \( \bar{P}_M \) suggests B-field ~ “right” magnitude

- A definitive statement requires more statistics/better EP determination

---

Model-dep.

**STAR Preliminary**

---

**Gursoy, Kharzeev & Rajagopal**

PRC **89** 054905 (2014)

---

**effect of QGP electrical conductivity**
Crucial to discovery

- Magnetic field

\[ B \approx \frac{T}{\mu_\Lambda} \bar{P}_M \]

\[ B \left[ m^2_\pi \right] = B \left[ 10^{14} \ \text{Tesla} \right] \approx \bar{P}_M \left[ \% \right] \]

- \( \bar{P}_M \) suggests B-field \(~\) “right” magnitude

- A definitive statement requires more statistics/better EP determination

- A definitive statement is crucial, to put CME discovery on solid ground

\[ J_E = \frac{N_c \mu_5}{3\pi^2} B \rightarrow \text{separation of +/- along } \vec{B} \]

Want field for \( \nu_{s_{NN}} \) \( \geq \sim 20 \ \text{GeV} \)

With EPD upgrade and 3-week run at 27 GeV, could get \( \sim 5\sigma \) measurement in 2018
A crucial upgrade to STAR

\[ \delta \overline{P}_H \propto \left( R_{EP}^{(1P)} \sqrt{N_{\text{events}}} \right)^{-1} \]

Improved EP resolution and statistics
\[ \rightarrow p_T, \text{ centrality dependence of } P_V \]
\[ \rightarrow \sim 4-5\sigma \text{ measurement of B-field} \]

See talks by Jinlong Zhang (Thursday)
& Alex Schmah (Friday)
Next steps – experimental: BES II

See talks by Jinlong Zhang (Thursday) & Alex Schmah (Friday)

<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>$\mu_B$ (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 $\mathcal{L}$</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></td>
<td>(1x$10^{25}$/cm²sec)</td>
<td></td>
<td></td>
<td></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>

BES-II ~ 2019-2020

- Dedicated **high-statistics** running
- Collider (e-cooling) & detector upgrades
- Finer-grained measurements
- Better control on initial conditions (RP)
- Forward tracking/PID
- fixed-target mode – full coverage of FAIR energies
- **Detector upgrades**
Summary I – extreme conditions

• non-central heavy ion collisions may create QGP with vorticity
  – generated by early shear viscosity, persists through low viscosity
  – fundamental feature of any fluid, unmeasured and nonconvergent theory for QGP
    • 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 discovery of chiral effects on firm ground
• **Global hyperon polarization**: unique probe of vorticity & B-field
  – non-exotic or chiral
  – quantitative input to calibrate chiral phenomena

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

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

• **BES-II: Statistics & upgrades will allow characterization & model discrimination**
  – but B-field for $\sqrt{s_{NN}} > \sim 20$ GeV required to calibrate/establish CME
Thanks for your attention
END
Splitting effect of finite $\mu_B$

\[ \frac{\mu_B}{T} = \frac{1}{2} \]
\[ \frac{\mu_B}{T} = 1 \]
\[ \frac{\mu_B}{T} = 2 \]

Fang et al, arxiv:1604.0403
Accounting for (polarized) feed-down

- Midrapidity contributions, including STAR efficiency & cuts
- Feed-down contribution depends on energy, model

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda'_{\Lambda}$</td>
<td>0.51</td>
<td>0.47</td>
<td>0.46</td>
<td>0.44</td>
<td>0.43</td>
<td>0.43</td>
<td>0.41</td>
<td>0.40</td>
</tr>
<tr>
<td>$\lambda_{\Sigma^0}$</td>
<td>0.33</td>
<td>0.31</td>
<td>0.31</td>
<td>0.30</td>
<td>0.29</td>
<td>0.29</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>$\lambda_{\Xi^0}$</td>
<td>0.07</td>
<td>0.10</td>
<td>0.10</td>
<td>0.11</td>
<td>0.12</td>
<td>0.12</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>$\lambda_{\Xi^-}$</td>
<td>0.08</td>
<td>0.10</td>
<td>0.11</td>
<td>0.12</td>
<td>0.13</td>
<td>0.13</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>$\lambda_{\Xi^0}$</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
</tr>
</tbody>
</table>

**TABLE II. Fractional yields from THERMUS for STAR energies.**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda'_{\Lambda}$</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
<td>0.69</td>
<td>0.68</td>
<td>0.67</td>
<td>0.66</td>
<td>0.64</td>
</tr>
<tr>
<td>$\lambda_{\Sigma^0}$</td>
<td>0.24</td>
<td>0.23</td>
<td>0.22</td>
<td>0.21</td>
<td>0.21</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>$\lambda_{\Xi^0}$</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
<td>0.06</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>$\lambda_{\Xi^-}$</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
<td>0.06</td>
<td>0.06</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>$\lambda_{other}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{\Lambda}$</td>
<td>0.58</td>
<td>0.59</td>
<td>0.60</td>
<td>0.61</td>
<td>0.61</td>
<td>0.62</td>
<td>0.62</td>
<td>0.63</td>
</tr>
<tr>
<td>$\lambda_{\Sigma^0}$</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.19</td>
</tr>
<tr>
<td>$\lambda_{\Xi^0}$</td>
<td>0.11</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>$\lambda_{\Xi^-}$</td>
<td>0.12</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td>$\lambda_{other}$</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**TABLE III. Fractional yields from UrQMD for BES energies**
Rigid-body-like vortex
\[ \vec{v} = r \hat{r} = \alpha (-y\hat{x}, x\hat{y}, 0) \]

Parallel flow with shear
\[ \vec{v} = \alpha \hat{z} \]

Irrotational vortex
\[ v \propto 1/r \]

Vorticity:
\[ \vec{\omega} = \vec{\nabla} \times \vec{v} = \alpha \]
\[ \vec{\omega} = \vec{\nabla} \times \vec{v} \neq 0 \]
\[ \vec{\omega} = \vec{\nabla} \times \vec{v} = 0 \]

Flow field:

Absolute velocities around highlighted point

Relative velocities around highlighted point (i.e. in fluid rest frame)

Vorticity examples

Figures by Jorge Stolfi posted on Wikipedia

M.A. Lisa - Strangeness in Quark Matter - Lawrence Berkeley National Lab - June 2016
Unique, quantitative measure

- Thermal vorticity:

\[
\frac{\omega}{T} \approx 2 \bar{P}_V \approx 2 - 16\%
\]

\[
\omega \approx 0.02 - 0.16 \text{ fm}^{-1}
\]

\[
J_B = \frac{N_c \mu_5}{\pi^2} \mu_B \omega \rightarrow \text{separation of } B/\bar{B} \text{ along } \vec{\omega}
\]

For illustrative purposes only

<table>
<thead>
<tr>
<th>(\sqrt{s} \text{ (GeV)})</th>
<th>(\mu_B \text{ (MeV)})</th>
<th>(\omega \text{ (fm}^{-1})</th>
<th>(\mu_B \omega \text{ (MeV/fm)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>420</td>
<td>0.16</td>
<td>68</td>
</tr>
<tr>
<td>11.5</td>
<td>314</td>
<td>0.07</td>
<td>21</td>
</tr>
<tr>
<td>14.5</td>
<td>260</td>
<td>0.05</td>
<td>11</td>
</tr>
<tr>
<td>19.6</td>
<td>205</td>
<td>0.04</td>
<td>8</td>
</tr>
<tr>
<td>27</td>
<td>155</td>
<td>0.04</td>
<td>6</td>
</tr>
<tr>
<td>39</td>
<td>115</td>
<td>0.03</td>
<td>3</td>
</tr>
<tr>
<td>62.4</td>
<td>70</td>
<td>0.04</td>
<td>3</td>
</tr>
<tr>
<td>200</td>
<td>20</td>
<td>~0</td>
<td>0</td>
</tr>
</tbody>
</table>
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)
  - Becattini et al. arxiv:1501.04468

- Collective vorticity in **microscopic transport** (AMPT)
  - Jiang, Lin, and Liao, arxiv:1602.06580

- Similar conclusions based on QCD quark **spin-orbit coupling**
  - Voloshin arxiv:nucl-th/0410089
Topologically-dependent efficiency

Spin-orientation-dependent efficiency (!)

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

\[
\frac{R_\pi}{R_p} = \left| \frac{p_{T,\pi}}{p_{T,p}} \right| \sim \frac{m_\pi}{m_p} \sim \frac{1}{7}
\]

\[\implies \pi \text{ tracking drives } \Lambda \text{ efficiency} \]

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
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 \( \bar{P}_H \)**

HIJING events through simulated STAR detector & tracking
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

![Diagram showing Lambda polarization](image)

- Vortical or QCD spin-orbit:
  - Feed-down dampens the signal

- Magnetic coupling:
  - Feed-down affects signal very little

- Polarization w/ production plane:
  - No integrated effect at midrapidity for Lambda
  - No effect at all for AntiLambdas

\[
\vec{P}_\Lambda \parallel +\hat{J}_{\text{sys}} \quad \vec{P}_\Lambda \parallel +\hat{J}_{\text{sys}}
\]

\[
\vec{P}_\Lambda \parallel -\hat{J}_{\text{sys}} \quad \vec{P}_\Lambda \parallel +\hat{J}_{\text{sys}}
\]

\[
\vec{P}_\Lambda = \vec{P}_\Lambda = 0
\]