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

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For the STAR collaboration
03/18/17
• $|L| \sim 10^3 \hbar$ 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 → Global Polarization

- Vortical or QCD spin-orbit: Lambda and Anti-Lambda spins aligned with L
Magnetic field \( \rightarrow \) **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

\[
\Lambda \text{s with Polarization } \vec{P} \text{ follow the distribution:}
\]
\[
dN\over{d\Omega}\hat{\vec{P}}^* = \frac{1}{4\pi} (1 + \alpha \vec{P} \cdot \hat{\vec{p}}_p^*) = \frac{1}{4\pi} (1 + \alpha P \cos \theta^*)
\]
\[
\alpha = 0.642 \pm 0.013 \quad [\text{measured}]
\]
\[
\hat{\vec{p}}_p^* \text{ is the daughter proton momentum direction in the } \Lambda \text{ frame (note that this is opposite for } \bar{\Lambda})
\]
\[
0 < |\vec{P}| < 1: \quad \vec{P} = \frac{3}{\alpha} \hat{\vec{p}}_p^*
\]
How to quantify the effect (II)

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

Statistics-limited experiment: we report acceptance-integrated polarization,

$$P_{\text{ave}} \equiv \int d\beta_\Lambda \frac{dN}{d\beta_\Lambda} \bar{P}(\beta_\Lambda) \cdot \hat{L}$$

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

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

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

** if $\nu_1 \cdot y > 0$ in BBCs $\varphi_\beta = \Psi_{EP}$, if $\nu_1 \cdot y < 0$ in BBCs $\varphi_\beta = \Psi_{EP} + \pi$
• Measured Lambda and Anti-Lambda polarization

• Includes results from previous STAR null result (2007)

• $\overline{P}_H(\Lambda)$ and $\overline{P}_H(\bar{\Lambda}) > 0$ implies positive vorticity

• $\overline{P}_H(\bar{\Lambda}) > \overline{P}_H(\Lambda)$ would imply magnetic coupling

Global polarization measure

arXiv:1701.06657
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

• \( \bar{P}_H(\Lambda) \) and \( \bar{P}_H(\bar{\Lambda}) > 0 \) implies positive vorticity

• \( \bar{P}_H(\bar{\Lambda}) > \bar{P}_H(\Lambda) \) would imply magnetic coupling
• Magneto-hydro equilibrium interpretation

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

• for small polarization:

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

• vorticity from addition:

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

• B from the difference:

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

\[ \hbar = k_B = 1 \]

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

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

\[ \text{PRIMARY + FEED-DOWN POLARIZATION} \]

\[ \text{VERTICAL COMPONENT} \]
Accounting for polarized feeddown

**PRIMARY + FEED-DOWN POLARIZATION**

**VERTICAL COMPONENT**

<table>
<thead>
<tr>
<th>PRIMARY</th>
<th>MEASURED</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda^+ )</td>
<td>( \Sigma^0 )</td>
</tr>
<tr>
<td>( \uparrow )</td>
<td>( \downarrow )</td>
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</table>

<table>
<thead>
<tr>
<th>( J^P )</th>
<th>( \mu )</th>
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</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda )</td>
<td>( \frac{1}{2}^+ )</td>
<td>-0.613</td>
<td>( \Sigma^*^- )</td>
</tr>
<tr>
<td>( \Sigma^0 )</td>
<td>( \frac{1}{2}^+ )</td>
<td>+0.79</td>
<td>( \Sigma^*^0 )</td>
</tr>
<tr>
<td>( \Xi^- )</td>
<td>( \frac{1}{2}^+ )</td>
<td>-0.651</td>
<td>( \Sigma^{*+} )</td>
</tr>
<tr>
<td>( \Xi^0 )</td>
<td>( \frac{1}{2}^+ )</td>
<td>-1.25</td>
<td></td>
</tr>
</tbody>
</table>
Accounting for polarized feeddown

**Primary + Feed-Down Polarization**

**Magnetic Component**

```
\[
\begin{array}{cccccccc}
\text{primary} & \Lambda & \Sigma^0 & \Xi^- & \Xi^+ & \Sigma^*0 & \Sigma^*+ & \Lambda(1580) & \text{etc. + h.t.s.} \\
\downarrow & 1 & -\frac{1}{2} & \frac{3}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{1}{2} & & \\
\text{measured} & \Lambda & | & | & & \Xi^0 & | & & \\
\downarrow & & & & & 0.9 & & & \\
\text{measured} & \Lambda & | & | & & \Xi^0 & | & & \\
\downarrow & & & & & & & & \\
\end{array}
\]
```

**Table: J^P, \mu**

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<th>\mu</th>
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<tr>
<td>\Xi^0</td>
<td>\frac{1}{2}^+</td>
<td>+3.02</td>
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</tbody>
</table>

Becattini, Karpenko, Lisa, Upsal, Voloshin arxiv:1610.02506
Accounting for polarized feeddown

\[
\frac{\omega}{T} = \left[ \frac{2}{3} \sum_R \left( f_{\Lambda R} C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R} C_{\Sigma^0 R} \right) S_R (S_R + 1) \right]^{-1} \left[ \frac{2}{3} \sum_R \left( f_{\Lambda R} C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R} C_{\Sigma^0 R} \right) S_R (S_R + 1) \right] \mu_R
\]

- \( f_{\Lambda R} \) = fraction of \( \Lambda \)'s that originate from parent \( R \to \Lambda \)
- \( C_{\Lambda R} \) = 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

From THERMUS

\[ \hbar = k_B = 1 \]

** \[ P_{\Lambda} \]  

\[ P_{\Lambda}^{\text{meas}} \]

\[
|P_{\Lambda}^{\text{meas}}| = \begin{pmatrix} P_{\Lambda}^{\text{meas}} \\ P_{\Lambda}^{\text{meas}} \end{pmatrix}
\]

<table>
<thead>
<tr>
<th>Decay</th>
<th>( C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>parity-conserving: ( \frac{1}{2}^+ \to \frac{1}{2}^+ ) 0^-</td>
<td>-1/3</td>
</tr>
<tr>
<td>parity-conserving: ( \frac{1}{2}^- \to \frac{1}{2}^+ ) 0^-</td>
<td>1</td>
</tr>
<tr>
<td>parity-conserving: ( \frac{3}{2}^+ \to \frac{1}{2}^+ ) 0^-</td>
<td>1/3</td>
</tr>
<tr>
<td>parity-conserving: ( \frac{3}{2}^- \to \frac{1}{2}^+ ) 0^-</td>
<td>-1/5</td>
</tr>
<tr>
<td>( \Xi^0 \to \Lambda + \pi^0 )</td>
<td>+0.900</td>
</tr>
<tr>
<td>( \Xi^- \to \Lambda + \pi^- )</td>
<td>+0.927</td>
</tr>
<tr>
<td>( \Sigma^0 \to \Lambda + \gamma )</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

**TABLE I.** Polarization transfer factors \( C \) (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:

\[ \frac{\omega}{T} \approx 2 - 10\% \]

\[ \omega \approx 0.02 - 0.09 \, fm^{-1} \quad (T_{\text{assumed}} = 160 \, MeV) \]

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

\[
\begin{align*}
\langle \omega \rangle & \sim 2 - 10\% \\
\omega & \approx 0.02 - 0.09 \, fm^{-1} \\
& (T_{\text{assumed}} = 160 \, MeV)
\end{align*}
\]

Csernai et al, PRC90 021904(R) (2014)

Jiang et al, PRC94 044910 (2016)
• 3+1D viscous hydrodynamics
  • Not very sensitive to shear viscosity
  • Very sensitive to initial conditions
• Expectation: falling with $\sqrt{s}$
**Magnetic field:**
- Expected sign

\[ B \sim 10^{14} \text{ Tesla} \]
\[ eB \sim 1 m^2_{\pi} \sim 0.5 \text{ fm}^{-2} \]

- 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

**Diagram:**
- Graph showing the dependence of magnetic field (B) on the square root of the center-of-mass energy (\( \sqrt{s_{NN}} \))
- The magnetic field is plotted against the electrical conductivity effect of QGP.
Summary I

• 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 $\sqrt{s_{NN}}$
    * ~6σ 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