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

Isaac Upsal
SDU/BNL
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Relativistic Heavy-Ion Collisions

Initial energy density

QGP phase

Hadronization

Hadron gas phase

Kinetic freeze-out

Final detected particle distributions

Collision overlap zone

Pre-equilibrium dynamics

Viscous hydrodynamics

Collision evolution

Free streaming

τ ~ 0 fm/c  τ ~ 1 fm/c

τ ~ 10 fm/c  τ ~ 10^{15} fm/c

Isaac Upsal - June 2018
From a (lumpy) initial state, solve hydro equations:

\[ d_\mu T^{\mu\nu} = 0 \]
\[ T^{\mu\nu} = \alpha u^\mu u^\nu - (\rho + \Pi) \Delta^{\mu\nu} + \pi^{\mu\nu} \]

\[ u^\mu d_\mu \Pi = -\frac{1}{\tau_\Pi} (\Pi + \xi \theta) - \frac{1}{2} \Pi \frac{\xi T}{\tau_\Pi} d_\lambda \left( \frac{\tau_\Pi}{\xi T} u^\lambda \right) \]

& many more terms...
Final state particles from hydro

System cools & expands → Hadronization & “Freeze-out”
- emitted particles reflect properties of parent fluid cell (Cooper-Frye)
  - chemical potentials, thermal & collective velocities

QGP fluid: colored quarks deconfined

emitted hadron (color confined)

fluid cell at freeze-out
At mid-rapidity:

\( \otimes \vec{B} \otimes \vec{L} \)

|L| \( \sim 10^3 \) \( \hbar \) in non-central collisions

- How much is transferred to particles at mid-rapidity?
- Does angular momentum get distributed thermally?
- How does that affect fluid/transport?
  - Vorticity: \( \vec{\omega} \equiv \frac{1}{2} \hat{\nabla} \times \hat{\mathbf{v}} \)
- How would it manifest itself in data?
Vortices

Classical Vorticity: $\vec{\omega} = \frac{1}{2} \vec{\nabla} \times \vec{v}$

Rigid-body-like Vortex
$\vec{v} \propto r$

Irrotational Vortex
$\vec{v} \propto \frac{1}{r}$

Like the moon, always the same side toward Earth

Notice the rotation, or lack thereof, in the fluid elements
HIC Vorticity formation

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

\[ \omega = \frac{1}{2} \nabla \times \vec{v} \approx \frac{1}{2} \frac{\partial v_z}{\partial x} \]
Vorticity $\rightarrow$ 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**: Lambda and Anti-Lambda spins aligned, and Anti-Lambdas anti-aligned
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Barnett effect

- Nice parallel in **Barnett effect**
- **BE**: uncharged object rotating with angular velocity $\omega$ magnetizes
  \[ M = \chi \omega / \gamma \]
- $\gamma$ = gyromagnetic ratio, $\chi$ = magnetic susceptibility.
- Inverse of Einstein-de Haas effect,

  *Science 15 42 (1915); Phys. Rev. 6, 239–270 (1915)*

- **Einstein-de Haas effect**, (only published experiment of Einstein!)
- **EdHE**: Magnetic field induces rotation

How to quantify the effect (I)

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

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

0 < |\vec{P}| < 1: \quad \vec{P} = \frac{3}{\alpha} \hat{p}_p^*
Ingredients: Using STAR

Protons and pions reconstructed in STAR TPC and TOF for $|\eta|<1$

TPC: Tracking + PID
TOF: PID

Event planes found using (forward/backward) BBCs
$3.4 < |\eta| < 5$
Ingredients: Using STAR (PID)

Protons and pions reconstructed in STAR TPC and TOF for $|\eta| < 1$

- **TPC**: Tracking + PID
- **TOF**: PID
Ingredients: Using STAR (tracking)

Protons and pions reconstructed in STAR TPC and TOF for $|\eta| < 1$

TPC: Tracking + PID
TOF: PID

Lambdas are found topologically using identified protons and pions.
Ingredients: Using STAR (Event Plane)

Event planes found using (forward/backward) BBCs $3.4 < |\eta| < 5$
How to quantify the effect (II)

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

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

$$P_{AVE} = \frac{8}{\pi \alpha} \frac{\langle \sin(\phi_b-\phi_p^*) \rangle}{R_{EP}^{(1)}}$$

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

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

** if $v_1 \cdot y > 0$ in BBCs $\phi_b = \Psi_{EP}$, if $v_1 \cdot y < 0$ in BBCs $\phi_b = \Psi_{EP} + \pi$
Global polarization measure

- Measured Lambda and Anti-Lambda polarization
- Includes results from previous STAR null result (2007)
- $\overline{P}_H(\Lambda) > \overline{P}_H(\bar{\Lambda}) > 0$ implies positive vorticity
- $\overline{P}_H(\bar{\Lambda}) > \overline{P}_H(\Lambda)$ would imply magnetic coupling
Global polarization measure

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

We can study more fundamental properties of the system

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

STAR, arXiv: 1805.04400
**Vortical and Magnetic Contributions**

- Magneto-hydro equilibrium interpretation

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

- 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:

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

**But**, even with topological cuts, significant feed-down from \( \Sigma^0, \Xi^{0/-}, \Sigma^{*\pm/0} \) … which themselves will be polarized...


**STAR, arXiv: 1805.04400**

**But**, even with topological cuts, significant feed-down from \( \Sigma^0, \Xi^{0/-}, \Sigma^{*\pm/0} \) … which themselves will be polarized...

**Vortical and Magnetic Contributions**

But, even with topological cuts, significant feed-down from $\Sigma^0$, $\Xi^{0/-}$, $\Sigma^*/0^0$... which themselves will be polarized...

Accounting for polarized feeddown

PRIMARY + FEED-DOWN POLARIZATION
VERTICAL COMPONENT

\[ \text{primary} \]
\[ \wedge^+ \rightarrow \Sigma^0 \rightarrow \Xi^- \rightarrow \Xi^0 \rightarrow \Sigma^*+ \rightarrow \Sigma^*+ \rightarrow \wedge^+(1580) \text{ etc.} \]
Accounting for polarized feeddown

**Primary + Feed-down Polarization**

**Vertical Component**

\[ \Lambda^+ \rightarrow \Sigma^0 \uparrow \rightarrow \Xi^- \rightarrow \Xi^- \rightarrow \Sigma^* \rightarrow \Sigma^* \rightarrow \Lambda(1580) \rightarrow \text{etc} \]

- Primary:
  - $\Lambda^+$
  - $\Sigma^0$
  - $\Xi^-$
  - $\Xi^-$
  - $\Sigma^*$
  - $\Sigma^*$
  - $\Lambda(1580)$
  - etc.

- Measured:
  - $\Lambda^+$
  - $\Sigma^0$
  - $\Xi^-$
  - $\Xi^-$
  - $\Sigma^*$
  - $\Sigma^*$
  - $\Lambda(1580)$
  - etc.

\[ J^P \quad \mu \quad \Sigma^* \quad \Lambda \]

- $\Lambda$: $\frac{1}{2}^+$, $-0.613$
- $\Sigma^0$: $\frac{1}{2}^+$, $0.79$
- $\Xi^-$: $\frac{1}{2}^+$, $-0.651$
- $\Xi^-$: $\frac{1}{2}^+$, $-1.25$
- $\Sigma^*$: $\frac{3}{2}^+$, $-2.41$
- $\Sigma^*$: $\frac{3}{2}^+$, $0.30$
- $\Xi^+$: $\frac{3}{2}^+$, $3.02$

Accounting for polarized feeddown

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

\[ \begin{align*}
\Lambda & \rightarrow \Sigma^0 \rightarrow \Xi^- \rightarrow \Xi^+ \\
\Sigma^0 & \rightarrow \Lambda (1580) \text{ etc.} \\
\Xi^- & \rightarrow \Xi^0 + \Xi^+ \\
\Xi^0 & \rightarrow \Xi^+ \\
\Xi^+ & \rightarrow \Xi^0 + \Xi^+ \\
\Xi & \rightarrow \Xi^0 + \Xi^+ \\
\end{align*} \]

\[ \begin{align*}
\Lambda: & \quad J^P = \frac{1}{2}^+ \\
\Sigma^0: & \quad J^P = \frac{1}{2}^+ \\
\Xi^-: & \quad J^P = \frac{1}{2}^+ \\
\Xi^0: & \quad J^P = \frac{1}{2}^+ \\
\Xi^+: & \quad J^P = \frac{3}{2}^+ \\
\end{align*} \]

Accounting for polarized feed-down

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

- \( f_{\Lambda R} \) = 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
- \( \nu_R \) is the magnetic moment of particle \( R \)
- overlines denote antiparticles

From a statistical hadronization model with STAR measurements as parameter inputs (THERMUS)

** \( \hbar = k_B = 1 \)**
Extracted Physical Parameters

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

- Magnetic field
  - $\mu_N \equiv \frac{e\hbar}{2m_p}$, where $m_p$ is the proton mass
  - Positive value, $1.5\sigma$ average for 7.7-39 GeV
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

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

Jiang et al, PRC 94 044910 (2016)

\[ \left| \langle \omega_y \rangle \right| (\text{fm}^{-1}) \]

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 \( \sqrt{s_{NN}} = 4.65 + 4.65 \text{ GeV} \).

<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>
Polarization ~ theory expectation (I)

- 3+1D viscous hydrodynamics
  - Not very sensitive to shear viscosity
  - Very sensitive to initial conditions
- Expectation: falling with $\sqrt{s}$


Compare “feed-down corrected” curve in dashed magenta line


arXiv: 1805.04400
Polarization ~ theory expectation (II)

AMPT

Hydro
Magnetic field:

• Expected sign

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

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

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

• But... consistent with zero
  – A definitive statement requires improved statistics/EP determination

B field BES II Projection

- Using statistics from the BES-II + 27 GeV BUR (excepting 9.1 GeV)
- Assuming present centerpoints 9.6σ result
  - Clearly 7 GeV is a statistical blip
- If only 11-27 GeV are used maybe expect ~6σ result for BES-II
Comparison of QGP superlatives

- Supercell tornado
- Ocean flow
- Jupiter’s spot
- Soap bubbles
- Superfluid nanodroplets
- QGP!!
- STAR
- Sun spots
- Fridge magnets
- Explosive charges
- Nat’l High Magnetic Field Lab
- Pulsars
- Magnetars
- QGP??
Connection: CVE

- Polarization not inherently chiral

- Large uncertainty term, $\mu_5$, in the delta correlator (related to Chern–Simons)

- For neutral baryons (Lambdas) correlator predicts separation of $B^#$ along vorticity, $\omega$

$$ J_E = \frac{N_c}{3\pi^2} \frac{\mu_5}{\mu_B} \omega $$

STAR PRC 81 54908 (2010)
Connection: CME

• Large theoretical uncertainty on $B$ (orders of magnitude $+ \sqrt{s_{NN}}$)

• Large uncertainty term, $\mu_5$, in the delta correlator (related to Chern–Simons)

• For charged particles CME predicts separation of +/- along $B$

\[ J_E = \frac{N_c \mu_5}{3\pi^2} B \]
Azimuthal dependence (I)

- Naively collision starts with strongest vorticity gradient in plane
- A model predicts the opposite dependence
- The dependence of $P_H$ on $\phi - \Psi_1$ tests spin local thermal equilibrium and model initial conditions

Karpenko & Becattini EPJC (2017) 77:213
Azimuthal dependence (II)

- In opposition to the model prediction, STAR sees a *larger* polarization in in-plane than in out-of-plane.
- Represents an important tension in the measurement.

Biao Tu, poster @ QM18
Centrality

- Signal increasing with decreasing centrality falls well in line with theory.

STAR, arXiv: 1805.04400

Jiang et al, PRC90 021904(R) (2014)
Polarization along the beam direction

- Local velocity gradients due to elliptic flow may produce vorticity along beam direction
- This is a brand new area to look!
- Look for sinusoidal polarization structure projected onto the beam direction

S. Voloshin, EPJ Web Conf. 17 (2018) 10700

F. Becattini and I. Karpenko, PRL.120.012302 (2018)

- Clear signal at 200 GeV
- Signal qualitatively disagrees with hydro model

Takafumi Niida, talk @ QM18
Phi Meson Polarization (I)

- Spin alignment can be determined from the angular distribution of the decay products*:

\[
\frac{dN}{d(\cos \theta^*)} = N_0 \times [(1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2 \theta^*]
\]

where \(N_0\) is the normalization and \(\theta^*\) is the angle between the polarization direction \(\vec{L}\) and the momentum direction of a daughter particle in the rest frame of the parent vector meson.

- A deviation of \(\rho_{00}\) from 1/3 signals net spin alignment.


Region of recombination of polarized quarks

\(\rho_{00} > 1/3:\)

\(\rho_{00} = 1/3:\)

\(\rho_{00} < 1/3:\)

Polarized quark fragmentation region
• Polarization measure is made WRT both the first and second order event planes

• Significant deviation from 1/3 is seen for higher energies
Summary 1

• 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 in heavy-ion collisions
    • 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

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

• **Polarization along beam direction** has qualitative tension

• **Systematic dependences** may offer more insight into modeling
  – sign tension for azimuthal dependence
BES-II: 2019-2020

- Collider (e-cooling) & detector upgrades
- Finer-grained measurements
  - what drives energy dependence of $P$?
- Increase statistics by an order of magnitude
  - stat. errors reduced by $\sim 3$
- Improve the avg. 1st-order EP resolution by 2x
  - stat. errors reduced 2x
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 Anti-Lambda spins aligned with L
- (electro)magnetic coupling: Lambdas anti-aligned, and Anti-Lambdas aligned
- Polarization w/ production plane:
  - No integrated effect at midrapidity for Lambda
  - No (known) effect at all for Anti-Lambdas
The Chiral Separation Effect (CSE) is an expected axial current along the direction of an external magnetic field. It has been postulated that the current of axial charges may contribute to the global polarization and effect a dependence of the polarization on charge asymmetry.

\[ A_{ch} = \frac{N_+ - N_-}{N_+ + N_-} \]
Polarization sensitivity to chiral effects (II)

- Hint of a signal slope
  - Lambda and Anti-Lambda have opposite-sign slopes

- Isobaric collision systems are a unique environment to test this effect

STAR Au+Au $\sqrt{s_{NN}} = 200$ GeV 20%-60% $|\eta|<1$, $0.5<p_T<6$ GeV/c

$P_H [%]$

$\Lambda$: $0.097 \pm 0.041 \pm 0.043 [%]$

$\bar{\Lambda}$: $-0.112 \pm 0.045 \pm 0.102 [%]$

STAR, arXiv: 1805.04400
Momentum and pseudorapidity

- No dependence seen on transverse momentum or pseudorapidity

STAR, arXiv: 1805.04400
ALICE Results

- At 2.76TeV ALICE sees a null result
- Strongly supports vorticity falling with beam energy
- No hint of Lambda-AntiLambda difference

\[
\begin{align*}
5-15\% \text{ centrality} &= \begin{cases} 
P_\Lambda &= -0.0001 \pm 0.0013(\text{stat}) \pm 0.0004(\text{syst}) \\
P_\bar{\Lambda} &= 0.0009 \pm 0.0013(\text{stat}) \pm 0.0008(\text{syst}) 
\end{cases} \\
15-50\% \text{ centrality} &= \begin{cases} 
P_\Lambda &= -0.0008 \pm 0.0010(\text{stat}) \pm 0.0004(\text{syst}) \\
P_\bar{\Lambda} &= 0.0005 \pm 0.0010(\text{stat}) \pm 0.0003(\text{syst}) 
\end{cases}
\]

M. Konyushikhin QM 2017 (poster)