Global and local polarization of $\Lambda$ hyperons in Au+Au collisions from STAR

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Important features in non-central heavy-ion collisions

Strong magnetic field

\[ B \sim 10^{13} \, \text{T} \]
\[ (eB \sim \text{MeV}^2 \, (\tau = 0.2 \, \text{fm})) \]

Orbital angular momentum

\[ L \sim 10^5 \hbar \]

→ Chiral magnetic effect
Chiral magnetic wave

→ Vorticity and particle polarization
Chiral vortical effect


In non-central collisions, the initial collective longitudinal flow velocity depends on $x$.

\[ \omega_y = \frac{1}{2} (\nabla \times v)_y \approx -\frac{1}{2} \frac{\partial v_z}{\partial x} \]
Global polarization


- Non-zero angular momentum transfers to the spin degrees of freedom (polarization)
  - Particles’ and anti-particles’ spins are aligned with angular momentum $L$

- Magnetic field align particle’s spin
  - Particles’ and antiparticles’ spins are aligned oppositely along $B$ due to the opposite sign of magnetic moment
STAR Detectors

- Full azimuthal and large rapidity coverage
- Excellent particle identification

TPC $dE/dx$ vs momentum/charge

TOF $1/\beta$ vs momentum/charge
How to measure the polarization?

Parity-violating decay of hyperons

Daughter baryon is preferentially emitted in the direction of hyperon’s spin (opposite for anti-particle)

\[
\frac{dN}{d\Omega^*} = \frac{1}{4\pi} \left( 1 + \alpha_H \mathbf{P}_H \cdot \mathbf{p}_p^* \right)
\]

\( \mathbf{P}_H \): Λ polarization
\( \mathbf{p}_p^* \): proton momentum in the Λ rest frame
\( \alpha_H \): Λ decay parameter
(\( \alpha_\Lambda = -\bar{\alpha}_\Lambda = 0.642 \pm 0.013 \))

\( \Lambda \to p + \pi^- \)
(BR: 63.9%, \( c \tau \approx 7.9 \) cm)

Projection onto the transverse plane

Angular momentum direction can be determined by spectator deflection (spectators deflect outwards)

- S. Voloshin and TN, PRC94.021901(R)(2016)

Ψ₁: azimuthal angle of \( b \)
\( \phi_p^* \): \( \phi \) of daughter proton in Λ rest frame

\( P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{\text{Res}(\Psi_1)} \)

ZDC-SMD

C. Patrignani et al. (PDG), Chin. Phys. C 40, 100001 (2016)
Signal extraction with Λ hyperons

\[ P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{\text{Res}(\Psi_1)} \]

\[ \langle \sin(\Psi_1 - \phi_p^*) \rangle^{\text{obs}} = (1 - f^B_{\text{BG}}(M_{\text{inv}}))\langle \sin(\Psi_1 - \phi_p^*) \rangle^{\text{BG}} + f^B_{\text{BG}}(M_{\text{inv}})\langle \sin(\Psi_1 - \phi_p^*) \rangle^{\text{BG}} \]

\[ \alpha_H = -\alpha_{\bar{H}} \]

STAR, PRC98, 014910 (2018)
First observation of fluid vortices in HIC

Positive polarization signal at lower energies!
- polarization looks to increase in lower energies
- anti-Λ is systematically larger than Λ

Becattini, Karpenko, Lisa, Upsal, and Voloshin, PRC95.054902 (2017)

\[ \omega = (P_\Lambda + P_{\bar{\Lambda}}) \frac{k_B T}{\hbar} \]
\[ \sim 0.02-0.09 \text{ fm}^{-1} \]
\[ \sim 0.6-2.7 \times 10^{22} \text{s}^{-1} \] (T=160 MeV)

The most vortical fluid ever observed!
Possible probe of magnetic field

Extracted Physical Parameters

• Significant vorticity signal
  – Hints at falling with energy, despite increasing J
  – \( \sigma \) average for 7.7-39 GeV

• Magnetic field
  – Positive value, \( \sigma \) average for 7.7-39 GeV

\[ P = \Lambda \frac{B}{\mu_N} \]

\[ B = (P_\Lambda - \bar{P})k_BT/\mu_N \]

\( \approx 5.0 \times 10^{13} \ [\text{Tesla}] \)

\( \mu_N : \Lambda \) magnetic moment

Extracted B-field is close to our expectation.
Need more data with better precision → BES-II and Isobaric collisions

Positive signal at $\sqrt{s_{NN}} = 200$ GeV

$P_H(\Lambda) \ [%] = 0.277 \pm 0.040\text{(stat)} \pm 0.039\text{(sys)}$

$P_H(\bar{\Lambda}) \ [%] = 0.240 \pm 0.045\text{(stat)} \pm 0.061\text{(sys)}$

- 5-7$\sigma$ significance, comparable to the combined result of 7.7-39 GeV

- Feed-down $\sim$15%-20% reduction of $P_H$ (model-dependent)

Becattini, Karpenko, Lisa, Upps, and Voloshin, PRC95.054902 (2017)

UrQMD+vHLLE: I. Karpenko and F. Becattini, EPJC(2017)77:213
Centrality dependence of $P_H$

In most central collision $\rightarrow$ no initial angular momentum
As expected, the polarization decreases in more central collisions

STAR Au+Au $\sqrt{s_{NN}} = 200$ GeV
$0 < p_T < 6$ GeV/c
$|\eta| < 1$

AMPT model, Y. Jiang et al., PRC94, 044910 (2016)

0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.12
0.10
0.08
0.06
0.04
0.02
0.00

| (fm⁻¹)

Time (fm/c)

1 fm
3 fm
5 fm
7 fm
9 fm

$|\langle \omega_y \rangle |$ (fm⁻¹)

0
2
4
6
8

Peripheral
Central
dependence of $P_H$

- Shear flow structure/initial flow velocity would be stronger in forward/backward region
- Expect rapidity dependence of the polarization

I. Karpenko and F. Becattini, EPJC(2017)77:213

The data do not show significant $\eta$ dependence
- Maybe due to baryon transparency at higher energy
- Also due to event-by-event C.M. fluctuations
\( p_T \) dependence of \( P_H \)

- No significant \( p_T \) dependence, as expected from the initial angular momentum of the system.
- Hydrodynamic model underestimates the data. Initial conditions affect the magnitude and dependence on \( p_T \).

3D viscous hydrodynamic model with two initial conditions (ICs)
- UrQMD IC
- Glauber with source tilt IC

F. Becattini and I. Karpenko, PRL120.012302, 2018
Azimuthal angle dependence of $P_H$

- Larger polarization in in-plane than in out-of-plane
- Opposite to hydrodynamic model! (larger in out-of-plane)

I. Karpenko and F. Becattini, EPJC(2017)77:213
A polarization vs. charge asymmetry?

Chiral Separation Effect

B-field + massless quarks + non-zero $\mu_v \rightarrow$ axial current $J_5$

( spin alignment + spin and momentum in (anti)parallel for RH(LH) quarks)

- $\Lambda$ polarization may have a contribution from the axial current $J_5$ induced by B-field (Chiral Separation Effect), S. Shlichting and S. Voloshin
- Use charge asymmetry $A_{ch}$ instead of $\mu_v$

$$\mu_v/T \propto \frac{\langle N_+ - N_- \rangle}{\langle N_+ + N_- \rangle} = A_{ch}$$
$\Lambda$ polarization vs charge asymmetry?

STAR, PRC98, 014910 (2018)

STAR Au+Au $\sqrt{s_{NN}} = 200$ GeV 20%-60%

$|\eta|<1$, $0.5<p_T<6$ GeV/c

\begin{align*}
\Lambda: & \quad 0.097 \pm 0.041 \pm 0.043 \text{ [%]} \\
\bar{\Lambda}: & \quad -0.112 \pm 0.045 \pm 0.102 \text{ [%]}
\end{align*}

Slopes of $\Lambda$ and anti-$\Lambda$ seem to be different.
(Statistical significance is $\sim 2\sigma$ level)

Possibly a contribution from the axial current?
Polarization along the beam direction

S. Voloshin, SQM2017  
F. Becattini and I. Karpenko, PRL120.012302 (2018)

\[
\frac{dN}{d\Omega^*} = \frac{1}{4\pi} (1 + \alpha_H \mathbf{P}_H \cdot \mathbf{p}_p^*)
\]

\[
\langle \cos \theta_p^* \rangle = \int \frac{dN}{d\Omega^*} \cos \theta_p^* d\Omega^*
\]

\[
= \alpha_H P_z \langle \cos \theta_p^* \rangle^2
\]

\[
\therefore P_z = \frac{\langle \cos \theta_p^* \rangle}{\alpha_H \langle \cos \theta_p^* \rangle^2}
\]

\[
= \frac{3 \langle \cos \theta_p^* \rangle}{\alpha_H} \quad \text{(if perfect detector)}
\]

\(\alpha_H\): hyperon decay parameter  
\(\theta_p^*\): \(\theta\) of daughter proton in \(\Lambda\) rest frame

Stronger flow in in-plane than in out-of-plane could make local polarization along beam axis!  

Longitudinal component, \(P_z\), can be expressed with \(\langle \cos \theta_p^* \rangle\).  
\(\langle \cos \theta_p^* \rangle^2\) accounts for an acceptance effect.
Polarization along the beam direction

\[
\langle \cos(\theta^* ) \rangle
\]

\[Au+Au \sqrt{s_{NN}} = 200 \text{ GeV}\]

10%-60%

STAR Preliminary

- Effect of $\Psi_2$ resolution is not corrected here

\[\phi-\Psi_2 \text{ [rad]}\]

○ Sine structure as expected from the elliptic flow!

○ Opposite sign to hydrodynamic model and a transport model (AMPT)
  - Hydro model: F. Becattini and I. Karpenko, PRL.120.012302 (2018)

Hydro calculation of $P_z$
F. Becattini and I. Karpenko, PRL.120.012302 (2018)
Centrality dependence of $P_z$ modulation

- Strong centrality dependence as in $v_2$
- Similar magnitude to the global polarization
- ~5 times smaller magnitude than the hydro and AMPT with the opposite sign!

$\langle P_z \sin(2\phi-2\Psi) \rangle [%]$

$\sqrt{s_{NN}} = 200$ GeV

STAR preliminary

$\Lambda$, $\bar{\Lambda}$

$\langle p_T \rangle$ of $\Lambda \sim 1.4$ GeV/c

$0.5 < p_T < 6$ GeV/c

T. Niida, WWND2019
Sign problem in $P_z$

Opposite sign to hydrodynamic model and AMPT model
- F. Becattini and I. Karpenko, PRL.120.012302 (2018)
  3D viscous hydrodynamic model with UrQMD initial condition
  assuming a local thermal equilibrium

Same sign as chiral kinetic approach
- Assuming non-equilibrium of spin degree of freedom
- Smaller quark scattering cross section changes the sign

Suggest incomplete thermal equilibrium of spin degree of freedom
as it develops later in time unlike the global polarization?
Contributions to $P_z$ in hydro

I. Karpenko, QM2018

\[ S^\mu \propto \varepsilon^{\mu \rho \sigma \tau} \sigma_{\rho \sigma} p_{\tau} = \varepsilon^{\mu \rho \sigma \tau} (\partial_{\rho} \beta_{\sigma}) p_{\tau} = \varepsilon^{\mu \rho \sigma \tau} p_{\tau} \partial_{\rho} \left( \frac{1}{T} \right) u_{\sigma} + \frac{1}{T} 2 [\omega^\mu (u \cdot p) - u^\mu (\omega \cdot p)] + \varepsilon^{\mu \rho \sigma \tau} p_{\tau} A_{\sigma} u_{\rho} \]

\[ \text{grad}T \quad \text{temperature gradient} \quad \text{“NR vorticity”} \quad \text{acceleration} \]

Longitudinal quadrupole $f_2$:

$P_z$ dominated by temperature gradient and relativistic term, but not by kinematic vorticity based on the hydro model.

How small is the kinematic vorticity?
Can we estimate it with the blast-wave model?
Blast-wave model

- Hydro inspired model parameterized with freeze-out condition assuming the longitudinal boost invariance
  - Freeze-out temperature $T_f$
  - Radial flow rapidity $\rho_0$ and its modulation $\rho_2$
  - Source size $R_x$ and $R_y$
    \[
    \rho(r, \phi_s) = \tilde{r}[\rho_0 + \rho_2 \cos(2\phi_b)]
    \]
    \[
    \tilde{r}(r, \phi_s) = \sqrt{(r \cos \phi_s)^2/R_x^2 + (r \sin \phi_s)^2/R_y^2}
    \]
- Calculate vorticity at the freeze-out using the parameters extracted from spectra, $v_2$, and HBT fit
  \[
  \langle \omega_z \sin(2\phi) \rangle = \frac{\int d\phi_s \int r dr I_2(\alpha_t)K_1(\beta_t)\omega_z \sin(2\phi_b)}{\int d\phi_s \int r dr I_0(\alpha_t)K_1(\beta_t)}
  \]
  \[
  \omega_z = \frac{1}{2} \left( \frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y} \right),
  \]
  $u$: local flow velocity, $l_n$, $K_n$: modified Bessel functions


FIG. 2. Schematic illustration of an elliptical subshell of the source. Here, the source is extended out of the reaction plane ($R_y > R_x$). Arrows represent the direction and magnitude of the flow boost. In this example, $\rho_2 > 0$ [see Eq. (4)].

$\phi_s$: azimuthal angle of the source element
$\phi_b$: boost angle perpendicular to the elliptical subshell
$\omega_z$ and $P_z$ from the BW model

e.g. Blast-wave fit to spectra and $v_2$

Data:
PHENIX, PRC69.034909 (2004)
PHENIX, PRC93.051902(R) (2016)

Calculated vorticity $\omega_z$ shows the sine modulation. Assuming a local thermal equilibrium, $z$-component of polarization is estimated as follows:

$$P_z \approx \frac{\omega_z}{(2T)}$$
**P_z modulation from the BW model**

- **AMPT model**
  - opposite sign and 5 times larger in magnitude

- **Blast-wave model**
  - simple estimate for kinematic vorticity
  - similar magnitude to the data
  - inclusion of HBT in the fit affects the sign in peripheral collisions

BW parameters obtained with HBT: STAR, PRC71.044906 (2005)
Summary

- Observation of non-zero $\Lambda$ global polarization at $\sqrt{s_{\text{NN}}} = 7.7$-$62.4$ GeV, and later at 200 GeV
  - Polarization decreases at higher energies, qualitatively consistent with the models
  - Larger signal in more peripheral collisions
  - Larger signal in in-plane than in out-of-plane, opposite to the hydrodynamic model
  - No significant dependence on $p_T$ and $\eta$
  - Charge-asymmetry dependence ($\sim 2\sigma$ level) with a possible relation to the axial current induced by B-field
- $\Lambda$ polarization along the beam direction at $\sqrt{s_{\text{NN}}} = 200$ GeV
  - Quadrupole structure of the polarization relative to the 2$^{\text{nd}}$-order event plane, as expected from the elliptic flow
  - Strong centrality dependence as in the elliptic flow
  - Sign problem among different models and data, but the blast-wave model predicts the same sign and similar magnitude to the data
Back up
**Feed-down effect**

- Only ~25% of measured $\Lambda$ and anti-$\Lambda$ are primary, while ~60% are feed-down from $\Sigma^* \to \Lambda \pi$, $\Sigma^0 \to \Lambda \gamma$, $\Xi \to \Lambda \pi$

- Polarization of parent particle $R$ is transferred to its daughter $\Lambda$

\[ S^*_\Lambda = C S^*_R \]

\[ \langle S_y \rangle \propto \frac{S(S+1)}{3} (\omega + \frac{\mu}{S}B) \]

Becattini, Karpenko, Lisa, Upsilon, and Voloshin, PRC95.054902 (2017)

\[
\begin{pmatrix}
\omega_c \\
B_c/T
\end{pmatrix} = \left[ \frac{2}{3} \sum_R \left( J_{\lambda R} C_{\lambda R} - \frac{1}{3} J_{\Sigma^0 R} C_{\Sigma^0 R} \right) S_R (S_R + 1) \right] \left[ \frac{2}{3} \sum_R \left( J_{\lambda R} C_{\lambda R} - \frac{1}{3} J_{\Sigma^0 R} C_{\Sigma^0 R} \right) (S_R + 1) \mu_R \right]^{-1} \begin{pmatrix}
P^\text{meas}_\Lambda \\
P^\text{meas}_\Xi
\end{pmatrix}
\]

<table>
<thead>
<tr>
<th>Decay</th>
<th>$C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parity conserving: $^1/2^+ \to ^1/2^+ 0^-$</td>
<td>$-1/3$</td>
</tr>
<tr>
<td>Parity conserving: $^1/2^- \to ^1/2^+ 0^-$</td>
<td>$1$</td>
</tr>
<tr>
<td>Parity conserving: $^1/2^+ \to ^1/2^+ 0^-$</td>
<td>$1/3$</td>
</tr>
<tr>
<td>Parity-conserving: $^1/2^- \to ^1/2^+ 0^-$</td>
<td>$-1/5$</td>
</tr>
<tr>
<td>$\Sigma^0 \to \Lambda + \pi^0$</td>
<td>$+0.900$</td>
</tr>
<tr>
<td>$\Sigma^- \to \Lambda + \pi^-$</td>
<td>$+0.927$</td>
</tr>
<tr>
<td>$\Sigma^0 \to \Lambda + \gamma$</td>
<td>$-1/3$</td>
</tr>
</tbody>
</table>

15%-20% dilution of primary $\Lambda$ polarization (model-dependent)
Blast-wave parameterization

\[
r_{\text{max}} = R[1 - a \cos(2\phi_s)],
\]
\[
\rho_t = \rho_{t,\text{max}}[r/r_{\text{max}}(\phi_s)][1 + b \cos(2\phi_s)] \approx \rho_{t,\text{max}}(r/R)[1 + (a + b) \cos(2\phi_s)].
\]
\[
\omega_z = 1/2(\nabla \times \mathbf{v})_z \approx (\rho_{t,\text{max}}/R) \sin(n\phi_s)[b_n - a_n].
\]

\(a_n\): spatial anisotropy
\(b_n\): flow anisotropy
\(R\): reference source radius
\(\rho_t\): transverse flow velocity

Quadrupole or sine structure of \(\omega_z\) is expected.

S. Voloshin, arXiv:1710.08934
Systematic uncertainties

Case of 200 GeV as an example

- Event plane determination: ~22%
- Methods to extract the polarization signal: ~21%
- Possible contribution from the background: ~13%
- Topological cuts: <3%
- Uncertainties of the decay parameter: ~2% for Λ, ~9.6% for anti-Λ
- Extraction of Λ yield (BG estimate): <1%

Also, the following studies were done to check if there is no experimental effect:

- Two different polarities of the magnetic field for TPC
- Acceptance effect
- Different time period during the data taking
- Efficiency effect