Global Polarization of Λ hyperons in Au+Au collisions at STAR

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In non-central collisions, the initial longitudinal flow velocity depends on $x$. 
In non-central collisions, the initial longitudinal flow velocity depends on $x$, which makes the initial angular momentum.

Becattini et al.,
PRC77, 024906 (2008)
Global Polarization of $\Lambda$

$\star$ Non-zero angular momentum transfers to $\Lambda$ polarization

- Spin-orbit coupling
  - Spins of $\Lambda$ and anti-$\Lambda$ are aligned with angular momentum $L$

- Spin alignment by B-Field
  - $\Lambda$ spin anti-aligned along $B$
  - Anti-$\Lambda$ spin aligned along $B$
How to measure it?

Parity-violating decay
daughter proton preferentially decays into the direction of $\Lambda$’s spin (opposite for anti-$\Lambda$)

$$P_H = \frac{8}{\pi \alpha} \frac{\langle \sin(\Psi_1 - \phi^*_p) \rangle}{\text{Res}(\Psi_1)} \text{sgn}_\Lambda$$

$\phi^*_p$: $\phi$ of daughter proton in $\Lambda$ rest frame
$\Psi_1$: 1st-order event plane
$s\text{gn}_\Lambda$: 1 for $\Lambda$, -1 for anti-$\Lambda$
$\alpha$: $\Lambda$ decay parameter ($=0.642\pm0.013$)

STAR, PRC 76, 024915 (2007)
Figure 2: Charged particles from a single Au+Au collision ionize the gas in the TPC, forming tracks that curve in the magnetic field of the detector. The tracks are reconstructed in three dimensions, making them relatively easy to distinguish, but are projected onto a single plane in this figure. As the tracks exit at the outer radius, they leave a signal in the Time-of-Flight (TOF) detector. The species of charged particles is determined by the amount of ionization in the TPC and the flight time as measured by TOF. Charged daughters from the weak decay $L \rightarrow p + p$ are extrapolated backwards, and the parent is identified through topological selection. A clear peak at the $L$ mass, obtained by summing over many events, is observed in the invariant-mass distribution, shown in the inset.

The overall angular momentum, $\hat{J}_{\text{sys}}$, as shown schematically in figure 3.

Recently, Takahashi et al. reported the first observation of a coupling between the vorticity and the overall angular momentum.
Positive signals in $\sqrt{s_{NN}}=7.7-62.4$ GeV

○ vorticity!
The fluid vorticity may be estimated from the data using the hydrodynamic relation
\[ \frac{\partial \mathbf{v}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{v} = -\nabla p + \mu \Delta \mathbf{v}, \]
where \( \mathbf{v} \) is the velocity field, \( p \) is the pressure, \( \mu \) is the dynamic viscosity, and \( \Delta \) is the Laplacian operator. The shear viscosity to entropy density ratio \( \eta/s \) is a crucial parameter in heavy-ion collisions, controlling the fluctuations of the system. In the hydrodynamic stage, the initial state fluctuations start to dominate in mid-central collisions, whereas in peripheral collisions, the pattern and magnitude of fluctuations do not have a regular pattern, therefore the distribution of the shear viscosity varies at two selected collision energies.

We observe that the total angular momentum distribution shows a steadily increasing trend towards peripheral collisions, indicating that the polarization vector of \( \Lambda \) hyperons at these collision energies includes both positive and negative parts, which is calculated in the model for 20-50% central Au-Au collisions.

The larger signal in lower energy collisions indicates that the initial angular momentum is largest at high energy. This is consistent with the excitation function of the fireball, as shown in Fig. 8.

Karpenko and Becattini, arXiv:1610.0477

\( J \) vs \( \sqrt{s_{NN}} \)

20-50% central

T. Niida, QCD Chirality Workshop 2017
The fluid vorticity may be estimated from the data using the hydrodynamic relation

where the initial state fluctuations start to dominate in collisions, where it starts to fluctuate largely from event to event for the most central events (where the impact parameter is zero) and most peripheral ones (where the particlization energy is much less). We thus conclude that the observed trend is the result of an integrated polarization calculated in the model for 20-50% central Au-Au collisions. As it has been mentioned, the parameters of the model are taken to monotonically depend on collision energy density includes both positive and negative parts, therefore the distribution of total angular momentum scaled by total energy of the fireball has a maximum at certain range of collision energy in the model. Now we have to understand the excitation function of total angular momentum for 20-50% central Au-Au collisions, which is calculated in the model. Karpenko and Becattini, arXiv:1610.0477

When increasing the collisions energy:

- Longer lifetime of system would dilute the polarization
- Smaller longitudinal flow velocity at mid-$\eta$ due to baryon transparency
Figure 4: The average polarization $P_H$ (where $H = L$ or $L$) from 20-50% central Au+Au collisions is plotted as a function of collision energy. The results of the present study ($p_s < 40$ GeV) are shown together with those reported earlier for 62.4 and 200 GeV collisions, for which only statistical errors are plotted. Boxes indicate systematic uncertainties.

Positive signals in $\sqrt{s_{NN}}=7.7$-62.4 GeV
- vorticity!
- systematically $P_H(\Lambda) < P_H(\text{anti-}\Lambda)$
- implying a contribution from B-field

For small polarization,

$$P_\Lambda \simeq \frac{1}{2} \frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

$$P_{\bar{\Lambda}} \simeq \frac{1}{2} \frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

Becattini, Karpenko, Lisa, Upps, and Voloshin
arxiv1610.02506 (2016)
Accounting for feed-down

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

- One needs to correct it before extracting physical parameters

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


$f_{\Lambda R}$ : fraction of Λ originating from parent $R$

$C_{\Lambda R}$ : coefficient of spin transfer from parent $R$ to Λ

$S_R$ : parent particle’s spin

$\mu_R$ : magnetic moment of particle $R$
Extracted vorticity and B-field

- Vorticity
  - \( \omega / T \sim 2\text{-}10\% \) \((\hbar = 1, \ k_B = 1)\)
  - \( \omega \sim 0.02\text{-}0.09 \text{ fm}^{-1} \)
    (when assuming \( T=160 \text{ MeV} \))

FIG. 12. Averaged vorticity \( \langle \omega_y \rangle \) from the AMPT model as a function of time at varied beam energy \( \sqrt{s_{NN}} \) for fixed impact parameter \( b = 7 \text{ fm} \). The solid curves are from a fitting formula (see text for details).
Extract vorticity and B-field

- **Vorticity**
  - $\omega/T \sim 2$-10% ($\hbar = 1, \ k_B = 1$)
  - $\omega \sim 0.02$-$0.09$ fm$^{-1}$
    (when assuming $T=160$ MeV)

- **Magnetic field**
  - Possible direct measure of B-field, but the data are consistent with zero
  - Need more events
Previous results at 200 GeV (using year 2004 data) were consistent with zero.

→ Can we see the signal when using recent data with more statistics?

- previous study used
  - year 2004 data ~9M events
- new study used
  - year 2011 data ~350M events
Non zero signal of $P_H$ at $\sqrt{s_{NN}} = 200$ GeV

$\sim 0.18\% \pm 0.08$

(syst. uncert. $\sim 0.06\%$ for $\Lambda$)

- no significant difference between $\Lambda$ and anti-$\Lambda$
- close to viscous-hydro + UrQMD calculation

$v$HLEE+UrQMD

Karpenko and Becattini, arXiv:1610.0477
Centrality dependence of $P_{H}$

- Weak centrality dependence for $\Lambda$
- Looks to slightly increase in peripheral events for anti-$\Lambda$

STAR Preliminary

Au+Au 200 GeV
$|\eta|<1$, $0.4<p_{T}<6$ GeV/c

Centrality [%]

$P_{H}$

box: syst. uncert.
No significant $p_T$ dependence was observed within current uncertainties
$\eta$ dependence of $P_H$

- No significant $\eta$ dependence within current uncertainties

STAR Preliminary

Au+Au 200 GeV
20%-60%, 0.4<$p_T<$6 GeV/c

$P^H$ vs $\eta$

box: syst. uncert.
Λ polarization vs charge asymmetry?

\[ J_5 \propto \mu_v B \]

- Idea (S. Shlichting and S. Voloshin, in preparation)
  - Λ polarization may be related to the axial current \( J_5 \)
  - Use (kaon) charge asymmetry instead of \( \mu_v \)

\[
\frac{\mu_v}{T} \propto \frac{\langle N_+ - N_- \rangle}{\langle N_+ + N_- \rangle} \quad \text{or} \quad \frac{\mu_v}{T} \propto \frac{\langle N_{K^+} - N_{K^-} \rangle}{\langle N_{K^+} + N_{K^-} \rangle}
\]
Charge asymmetry dependence of $P_H$

No clear trend within current uncertainties. Need more events…
STAR has made the first observation of $\Lambda$ global polarization in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$-200 GeV

- Clear signal of vorticity from the medium in non-central heavy-ion collisions
- Current data cannot distinguish the difference between $\Lambda$ and anti-$\Lambda$, but the difference may lead to a possible direct measurement of the magnetic field
- Preliminary results for $\sqrt{s_{NN}} = 200$ GeV also show non-zero signal of $\Lambda$ polarization ($P_H = 0.18% \pm 0.08\%$)
- First look at charge asymmetry dependence of $\Lambda$ polarization

Outlook

- STAR upgrade for BES- II
- Connection to other observables

→see next slides
STAR upgrade for BES-II

- iTPC upgrade
  - extend $\eta$ coverage from $|\eta|<1$ to $|\eta|<1.5$
  - $p_T>60$ MeV
  - improve dE/dx resolution
  - ready in 2019

- eTOF upgrade
  - $-1.6<\eta<-1.1$
  - extend forward PID capability
  - mid-rapidity coverage in Fixed Target Program
  - ready in 2019

- EPD upgrade
  - $2.1<|\eta|<5.1$
  - improve EP resolution
  - independent trigger
  - ready in 2018

Expect significant improvements in BES-II
Possible relation to other observables

**Vorticity**

![Image of vorticity](http://example.com/vorticity.png)

**Directed flow**

![Image of directed flow](http://example.com/directed_flow.png)

Best description of $v$ with vorticity!

**B-field, conductivity, CME…**

![Image of magnetic field and conductivity](http://example.com/field_conductivity.png)

McLerran and Skokov,

**Tilted source via HBT**

![Image of tilted source](http://example.com/tilted_source.png)

Lisa, Heinz, and Wiedemann,
PLB489 (2000) 287
Lisa et al.(E895), PLB496 (2000) 1

Vorticity is an important piece
for further understanding the picture of HIC!

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Fig. 8 Directed flow of pions at $\eta/s = 0.1$ and $\eta_m = 2.0$ compared with STAR data [22]


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*T. Niida, QCD Chirality Workshop 2017*
Back up
Effect of non-zero chemical potential

R. Fang, L. Pang, Q. Wang, and X. Wang, PRC94, 024904 (2016)

\[ R = \frac{P_\Lambda}{P_{\text{anti-}\Lambda}} \]

\[ \beta_m = \frac{m}{T} \]

~ 1.1GeV/(160-200)MeV

~ 5.5-6.8
Previous results at $\sqrt{s_{NN}} = 200\text{GeV}$

Previous $\Lambda$ polarization result in Au+Au 200 GeV (year2004) was zero-consistent.

- 3+1D viscous hydro+cascade model predicts $P^* \sim 0.2\%$
  for Au+Au 200 GeV.