Vorticity measurements from the STAR experiment at RHIC

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Outline

- Brief introduction on vorticity and polarizaiton
- Analysis process
- Recent STAR experiment results
  - Hyperon global polarization
  - Hyperon polarization along beam direction
- Summary and outlook
Orbital angular momentum/magnetic field in heavy ion collisions

Orbital angular momentum

\[ L \sim \frac{A b \sqrt{s}}{2} \sim 10^6 \hbar \]

Expected to have strong magnetic field

\[ eB \sim \gamma \alpha_{EM} \frac{Z}{b^2} \sim 10^{18} G \sim 10^{14} T \]

(RHIC Au+Au200 GeV, b=10 fm)
Vorticity in heavy ion collisions

Orbital angular momentum

Local fluid vorticity  \( \omega = \frac{1}{2} \nabla \times \mathbf{v} \)

The most vortical fluid  \( \sim 10^{20} - 10^{21} \text{s}^{-1} \)

(Au+Au@RHIC at \( b=10 \text{ fm} \))

X.-G. Deng, X.-G. Huang, et al. PRC 101, 064908

Energy dependence of initial vorticity

\[
-\langle \omega \rangle (\text{fm}^{-1}) \quad \text{UrQMD} \quad \text{HIJING}
\]

\[
\begin{align*}
\sqrt{s} (\text{GeV}) & \\
5 & \quad 0.08 \\
10 & \quad 0.06 \\
50 & \quad 0.04 \\
100 & \quad 0.02 \\
500 & \quad 0.00 \\
1000 & \quad 0.00 \\
5000 & \quad 0.00 \\
\end{align*}
\]
Vorticity and polarization

The most vortical fluid $\sim 10^{20} - 10^{21} \text{s}^{-1}$
(Au+Au@RHIC at $b=10$ fm)

Local fluid vorticity $\omega = \frac{1}{2} \nabla \times v$

Leads to global polarization along $L$ though spin-orbit coupling

Global polarization measurement

- “Self-analyzing”, parity-violating weak decay channel of hyperons
  - Daughter baryon is preferentially emitted in the direction of the hyperon spin

\[
\frac{dN}{d\Omega^*} = \frac{1}{4\pi} (1 + \alpha_H P_H \cos \theta^*)
\]

- \(\alpha_H\): hyperon decay parameter
- \(P_H\): hyperon polarization
- \(\theta^*\): polarization angle

<table>
<thead>
<tr>
<th>Hyperon</th>
<th>Deacy mode</th>
<th>(\alpha_H)</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Lambda) (uds)</td>
<td>(\Lambda \rightarrow p + \pi^-)</td>
<td>0.732</td>
<td>1/2</td>
</tr>
<tr>
<td>(\Xi^-) (dss)</td>
<td>(\Xi^- \rightarrow \Lambda + \pi^-)</td>
<td>-0.401</td>
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</tr>
<tr>
<td>(\Omega^-) (sss)</td>
<td>(\Omega^- \rightarrow \Lambda + K^-)</td>
<td>0.0157</td>
<td>3/2</td>
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Hyperon Decay mode

\(\Lambda \rightarrow p + \pi^-\)

(BR:63.9%,\(c\tau \sim 7.9\)cm )

PDG2021

2024/6/11
Global polarization measurement

- “Self-analyzing”, parity-violating weak decay channel of hyperons
  - Daughter baryon is preferentially emitted in the direction of the hyperon spin
  - Measured via the distribution of the azimuthal angle of the hyperon decay baryon (in the hyperon rest frame) with respect to the reaction plane.

\[
P_\Lambda = \frac{8}{\pi_0} \frac{1}{A_0} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{\text{Res}(\Psi_1)}
\]

\[
\alpha_\Lambda = -\alpha^*_\Lambda = 0.732 \pm 0.014
\]

- \(A_0\): Acceptance correction factor
- \(\Psi_1\): First-order event plane angle
- \(\text{Res}(\Psi_1)\): Event plane resolution

STAR, PRC76, 024915 (2007)
Observation of $\Lambda$ global polarization

- STAR, first measurement in AuAu 200 GeV, $P_H < 2\%$
  
  PRC 76, 024915 (2007)

- STAR, first observation in BES-I
  

- STAR, high precise $P_H$ at 200 GeV
  
  PRC 90, 014910 (2018)

- ALICE, LHC energy region
  
  PRC 101, 044611 (2020)

- STAR, $P_H$ at 3 GeV
  
  PRC 104, L061901 (2021)

- HADES energy region, consistent with STAR
  
  PLB 835, 137506 (2022)

- STAR, $P_H$ at 19.6 and 27 GeV BES-II, no splitting
  
  PRC108,014910(2023)

- STAR, new recent results
  
  BES-II Preliminary 7.7-17.3GeV
  
  $\Lambda, \Xi^-$ global polarization
Energy dependence of $\Lambda$ global polarization

- Significant collision energy dependence, described well by various theoretical models:
  - Liang and Wang, PRL 94, 102301(2005),
  - Voloshin, nucl-th/0410089
  - I. Karpenko and F. Becattini, EPJC(2017)77:213, UrQMD+vHLLE
  - H. Li et al., PRC 96, 054908 (2017), AMPT
  - Becattini, Rept. Prog. Phys. 85, No.12, 122301 (2022)
  - QW, Liang, Ma (editors), ActaPhys. Sin. 72, No. 7 & 11 (2023)
  - .......

- Possible difference between $\Lambda$ and $\bar{\Lambda}$

\[
\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.732
\]
Energy dependence of $\Lambda$ global polarization

- Greatly improved precision from Beam Energy Scan phase-II
- More significant global polarization in lower energies
Energy dependence of $\Lambda$ global polarization: from BES-II

- New STAR preliminary results at $\sqrt{s_{NN}} = 7.7$-17.3 GeV from BES-II
- Significant improvement in precision was achieved, collision energy dependence consistent with BES-I
Magnetic field effect of global polarization: from BES-II

- No splitting between $\Lambda$ and $\bar{\Lambda}$ global polarization within uncertainties
- Upper limit on late stage magnetic field
  - 95% confidence level: STAR, PRC 108,014910(2023)
  - $B < 9.4 \times 10^{12} \, T$ at 19.6 GeV
  - $B < 1.4 \times 10^{13} \, T$ at 27 GeV
Longer system lifetime dilutes the vorticity/polarization

Collision system size dependence of global polarization?
System size dependence of \( \Lambda \) global polarization

- Significant global polarization observed in isobar collisions, \( P_\Lambda \) and \( P_{\bar{\Lambda}} \) increase with centrality
System size dependence of $\Lambda$ global polarization

- Significant global polarization observed in isobar collisions, $P_\Lambda$ and $P_{\bar{\Lambda}}$ increase with centrality.
- Global polarization of $\Lambda + \bar{\Lambda}$ are consistent between Ru+Ru, Zr+Zr and Au+Au collisions within uncertainty.

Model results from arXiv:2201.12970v1
Possible larger Xi global polarization than Lambda due to earlier production and vorticity evolution

- Via daughter Lambda angle distribution in Xi rest frame
- Via daughter Lambda polarization with spin transfer factor ($C_{\Xi^-\rightarrow\Lambda} = 0.944$)

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi} (1 + \alpha_H P_H \cos \theta^*)$$

$\alpha_H$ : hyperon decay parameter
$P_H$ : hyperon polarization
$\theta^*$ : polarization angle

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Energy dependence of $\Xi^- + \Xi^+$ global polarization

- Significant $\Xi^- + \Xi^+$ global polarization observed in Au+Au at 19.6 and 27 GeV
- $\Xi^- + \Xi^+$ global polarization measurement at lower BES-II energies underway
Local vorticity and polarization in heavy ion collisions

Elliptic flow indicates stronger expansion in-plane than out of plane

Lead to polarization along the beam direction ($P_z$)

\[ \langle \cos \theta_p^* \rangle = \int \frac{dN}{d\Omega^*} \cos \theta_p^* d\Omega^* = \alpha \Lambda P_z \langle (\cos \theta_p^*)^2 \rangle \]

\[ P_z = \frac{\langle \cos \theta_p^* \rangle}{\alpha \Lambda \langle (\cos \theta_p^*)^2 \rangle} \]

[STAR, PRL 123, 132301 (2019)]
Azimuthal angle dependence of $P_z$

- Clear azimuthal angle dependence observed in Au+Au and isobar collisions at 200 GeV
- New developments, Shear Induced Polarization (SIP), can describe trend of data
System size dependence of $P_z$

- $P_z$ from isobar collision comparable to Au+Au and Pb+Pb
- No significant system size dependence observed at same energy
Energy dependence of $P_z$

- $P_z$ in Au+Au collisions comparable from 7.7 to 200 GeV, Pb+Pb collision at 5.02 TeV
  
- No significant collision energy dependence observed, hints of sign change at 7.7 GeV
  
- $0.098 \pm 0.014$ (stat.) $^{+0.019}_{-0.018}$ (syst.) in Au+Au 200 GeV  
  
- $0.082 \pm 0.011$ (stat.) $\pm 0.014$ (syst.) in Pb+Pb 5.02 TeV

Model: X. Wu et al., PRC 105 (2022) 064909
$P_z$ from higher harmonic flow

- Measurements $P_z$ relative to higher harmonic event planes provide new insights into polarization phenomena
$P_z$ relative to third order event plane

- Significant $P_z$ w.r.t third-order event plane observed
- $P_z$ w.r.t second-order event plane increases with centrality
- Comparable $P_z$ w.r.t second and third order event plane, indicating $v_3$-driven polarization
- Hydrodynamic models with shear term reasonably describe the data for central collisions, but not for peripheral collisions

S. Alzharni et al., PRC 106.014905

STAR, PRL 131, 202301 (2023)
Summary

Global polarization

- Significant improvement in precision was achieved in BES-II
- No splitting observed between $\Lambda$ and $\bar{\Lambda}$ global polarization in Au+Au collisions at 7.7 - 27 GeV and $^{96}\text{Ru} + ^{44}\text{Ru}$, $^{96}\text{Zr} + ^{40}\text{Zr}$ collisions at 200 GeV
- No collision system size dependence between Ru+Ru, Zr+Zr and Au+Au collisions at 200 GeV
- Significant $\Xi^- + \Xi^+$ global polarization observed at 19.6, 27 GeV, measurements in lower energies underway

Polarization along beam direction ($P_z$)

- First observation of polarization along beam direction ($P_z$) w.r.t third-order event plane
- No significant system size dependence of $P_z$ observed at same energy
- No significant collision energy dependence of $P_z$ observed
Global polarization

- Significant improvement in precision was achieved in BES-II
- No splitting observed between $\Lambda$ and $\bar{\Lambda}$ global polarization in $Au+Au$ collisions at 7.7 - 27 GeV and $^{96}_{44}Ru + ^{96}_{44}Ru$, $^{96}_{40}Zr + ^{96}_{40}Zr$ collisions at 200 GeV
- No collision system size dependence between $Ru+Ru$, $Zr+Zr$ and $Au+Au$ collisions at 200 GeV
- Significant $\Xi^- + \bar{\Xi}^+$ global polarization observed at 19.6, 27 GeV, measurements in lower energies underway

Polarization along beam direction ($P_Z$)

- First observation of polarization along beam direction ($P_Z$) w.r.t third-order event plane
- No significant system size dependence of $P_Z$ observed at same energy
- No significant collision energy dependence of $P_Z$ observed
Back Up
Global polarization collision energy dependence

- Significant global polarization centrality dependence observed
- Lambda and AntiLambda global polarization are consistent
- No observed dependence of global polarization on $p_T$

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STAR detector and $\Lambda/\bar{\Lambda}$ reconstruction

Event plane reconstruction:
- Time Projection Chamber
- Zero Degree Calorimeters

$\Lambda/\bar{\Lambda}$ reconstruction:
- Time Projection Chamber
- Time Of Flight

- $\Lambda \rightarrow p + \pi^-$
- $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$
- Background fraction < 3%

2024/6/11
- Event plane reconstruction:
  - Time Projection Chamber
  - Event Plane Detector
  - Zero Degree Calorimeters

- $\Lambda/\bar{\Lambda}$ reconstruction:
  - Time Projection Chamber
  - Time Of Flight
Significant global polarization observed, $P_\Lambda$ and $P_{\bar{\Lambda}}$ increase with centrality.

No significant difference between $P_\Lambda$ and $P_{\bar{\Lambda}}$ in Ru+Ru and Zr+Zr collisions.

Global polarization of $\Lambda + \bar{\Lambda}$ are consistent between Ru+Ru and Zr+Zr collisions.
Local polarization in Ru+Ru&Zr+Zr at 200 GeV

- Significant local polarization w.r.t second-order event plane observed in isobar collisions
- First observation of local polarization w.r.t the third-order event plane

STAR, PRL 131, 202301 (2023)
Local polarization $p_T$ dependence is observed

Observed $p_T$ dependence similar to that of elliptic ($v_2$) and triangular ($v_3$) flow

Results are consistent between isobar and Au+Au collisions

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

STAR, PRL 131, 202301 (2023)
Global polarization in Ru+Ru, Zr+Zr and Au+Au at 200 GeV

- Global polarization of $\Lambda$ and $\bar{\Lambda}$ are consistent in isobar and Au+Au collision systems

Model results from arXiv:2201.12970v1
Energy dependence of $P_z$

- $P_z$ from isobar collision comparable to Au+Au and Pb+Pb
  - No significant system size dependence observed at same energy
- $P_z$ in Au+Au collisions comparable from 7.7 to 200 GeV, Pb+Pb collision at 5.02 TeV
  - No significant collision energy dependence observed

Model: X. Wu et al., PRC 105 (2022) 064909
Global polarization in Au+Au with BES-II data (19.6, 27 GeV)

- No splitting of $\Lambda / \bar{\Lambda}$ observed

<table>
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<tr>
<th>Au+Au</th>
<th>19.6 GeV</th>
<th>27 GeV</th>
</tr>
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<tr>
<td>$P_{\bar{\Lambda}} - P_\Lambda$ (%)</td>
<td>$-0.018 \pm 0.127$ (stat.) $\pm 0.024$ (sys.)</td>
<td>$0.109 \pm 0.118$ (stat.) $\pm 0.022$ (sys.)</td>
</tr>
</tbody>
</table>

- Upper limit on late stage magnetic field
  - 95% confidence level
  - $B < 9.4 \times 10^{12} \ T$ at 19.6 GeV
  - $B < 1.4 \times 10^{13} \ T$ at 27 GeV

$|B| \approx \frac{T_s |P_{\bar{\Lambda}} - P_\Lambda|}{2 |\mu_A|}$, using hydrodynamics

$T_s = 150 \text{ MeV}$: the temperature of the emitting source
$\mu_A = -1.93 \times 10^{-14} \text{ MeV/T}$: the magnetic moment of the $\Lambda$ hyperon