Λ polarization in heavy-ion collisions at moderately relativistic energies

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Vortical motion of nuclear matter

Vortical motion:  \( \mathbf{\omega} = \frac{1}{2} \mathbf{\nabla} \times \mathbf{v} = \text{Vorticity} \)

Relativistic Vorticity =  \( \omega_{\mu \nu} = \frac{1}{2} ( \partial_\nu u_\mu - \partial_\mu u_\nu ) \)

• Angular momentum \( \rightarrow \) spin polarization
• Similarly to Barnett effect (1915): magnetization by rotation

F. Becattini et al. PRC95 (2017) 054902
Polarization Measurements

**STAR**
- Global $\Lambda$ and anti-$\Lambda$ polarization [Nature 548, 62 (2017)]
- Local polarization of hyperons along the beam direction [PRL 123, 132301 (2019)]
- Measurement of global spin alignment of vector Mesons [NPA 1005 (2021) 121733]
- Global polarization of $\Xi$ and $\Omega$ hyperons at 200 GeV [2012.13601]

At moderately relativistic energies

- STAR-FXT: $\Lambda$ Polarization at 3 GeV [2108.00044 [nucl-ex]]
- NICA: planned in approx. 2025
Motivations

Study of
✓ vortical motion in heavy-ion collisions
✓ mechanism of angular-momentum transfer from orbital one to spin
  ➢ Thermodynamic approach [F. Becattini, et al.] Discussion below
  ➢ Chiral Vortical Effect [Vilenkin (1979); Son and Zhitnitsky (2004)]
  ➢ “Lagrangian approach” [D. Montenegro, L. Tinti and G. Torrieri]
Feasibility of polarization measurements

Threshold collision energies, above which measurements are feasible.

STAR and HADES experience:
global polarization: \((dN/dy)(\text{interaction rate}) \geq 1 \text{ s}\)
local polarization: \((dN/dy)(\text{interaction rate}) \geq 10^4 \text{ s}\)

3FD simulations

<table>
<thead>
<tr>
<th>Facility</th>
<th>BM@N</th>
<th>HIAF</th>
<th>FAIR</th>
<th>NICA</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sqrt{s_{NN}} \ [\text{GeV}])</td>
<td>2.3 - 3.5</td>
<td>2.3 - 4</td>
<td>2.7 - 4.9</td>
<td>4 - 11</td>
</tr>
<tr>
<td>global (\Lambda), (\sqrt{s_{NN}} \gtrsim)</td>
<td>2.3 GeV</td>
<td>2.3 GeV</td>
<td>2.7 GeV</td>
<td>4 GeV</td>
</tr>
<tr>
<td>global (\bar{\Lambda}), (\sqrt{s_{NN}} \gtrsim)</td>
<td>no</td>
<td>3.5 GeV</td>
<td>3 GeV</td>
<td>5 GeV</td>
</tr>
<tr>
<td>local (\Lambda), (\sqrt{s_{NN}} \gtrsim)</td>
<td>2.7 GeV</td>
<td>2.5 GeV</td>
<td>2.7 GeV</td>
<td>6 GeV</td>
</tr>
<tr>
<td>local (\bar{\Lambda}), (\sqrt{s_{NN}} \gtrsim)</td>
<td>no</td>
<td>no</td>
<td>4 GeV</td>
<td>no</td>
</tr>
</tbody>
</table>
3-Fluid Dynamics (3FD)

Target-like fluid:
\[
\partial_\mu J^\mu_t = 0 \\
\partial_\mu T^{\mu\nu}_t = -F^\nu_{tp} + F^\nu_{ft}
\]
Leading particles carry bare charge exchange/medium

Projectile-like fluid:
\[
\partial_\mu J^\mu_p = 0, \\
\partial_\mu T^{\mu\nu}_p = -F^\nu_{pt} + F^\nu_{fp}
\]

Fireball fluid:
\[
J^\mu_f = 0, \\
\partial_\mu T^{\mu\nu}_f = F^\nu_{pt} + F^\nu_{tp} - F^\nu_{fp} - F^\nu_{ft}
\]
Baryon-free fluid 

Total energy-momentum conservation:
\[
\partial_\mu (T^{\mu\nu}_p + T^{\mu\nu}_t + T^{\mu\nu}_f) = 0
\]

Physical Input
✓ Equation of State
✓ Friction
✓ Freeze-out energy density \( \mathcal{E}_{\text{frz}} = 0.4 \, \text{GeV/fm}^3 \)

YI, Russikh, Toneev, PRC 73, 044904 (2006)
QGP Transition in bulk

Deconfinement transition starts at top AGS energies.

Dilepton Signature of a First-Order Phase Transition already at 1-2A GeV.

Equilibration at low energies

- Thermodynamic approach
- Chiral Vortical Effect

Longitudinal and transverse pressure in the center
Mechanical equilibration time (★) is comparatively long

Freeze-out is mechanically equilibrium.
This of prime importance for the models.

Chemical equilibration (★) (and hence thermalization) takes longer

The system is thermalized at the freeze-out stage, although it can be reached right before the freeze-out
Thermodynamic approach to polarization

Spin is in thermal equilibrium with other degrees of freedom

Chemical potential for angular momentum
\[ \sigma_{\mu \nu} = \frac{1}{2} (\partial_\nu \beta_\mu - \partial_\mu \beta_\nu) \] = Thermal Vorticity

\[ \beta_\mu = u_\mu / T \] = 4-velocity/Temperature

Mean spin vector of a spin of \( \Lambda \) particle in a relativistic fluid

\[ S^\mu = \frac{1}{8m_\Lambda} \frac{1}{\int d\Sigma \lambda p^\lambda n_\Lambda} \int d\Sigma \lambda p^\lambda n_\Lambda \epsilon^{\mu \nu \rho \sigma} \sigma_{\rho \nu} \]

\( n_\Lambda \) = Fermi-Dirac distribution function, integration over freeze-out hypersurface

Formulation in terms of frozen-out hadronic matter!
Observable global polarization

\[ P_\Lambda^\mu = \frac{\langle S_\Lambda^\mu \rangle}{S_\Lambda} \]  

Polarization of Λ particle, \( S_\Lambda = 1/2 \)

Polarization is measured in the rest frame (*) of Λ particle

\[ S_\Lambda^* = S_\Lambda - \frac{p_\Lambda \cdot S_\Lambda}{E_\Lambda (E_\Lambda + m_\Lambda)} p_\Lambda \]

\[ P_\Lambda = \frac{1}{2m_\Lambda} \left\langle \left( E_\Lambda - \frac{1}{3} \frac{p_\Lambda^2}{E_\Lambda + m_\Lambda} \right) \sigma_{zx} \right\rangle \]  

Global polarization is directed along the y axis.
Thermodynamic global polarization in 3FD

\[
P_\Lambda = \frac{1}{2m_\Lambda} \left\langle \left( E_\Lambda - \frac{1}{3} \frac{p_\Lambda^2}{E_\Lambda + m_\Lambda} \right) \sigma_{zx} \right\rangle \quad \text{averaging with } \Lambda \text{ distribution function, } n_\Lambda
\]

Approximations made in [YI, PRC 103, L031903 (2021)]:

Approximation 1: feed-down from decays of \( \Sigma^0, \Sigma^*, \ldots \) is neglected

Approximation 2: Averaging with energy density, \( \varepsilon \), in stead of \( n_\Lambda \)

Approximation 3: Averaging of (…) and \( \sigma_{zx} \) are decoupled

\[
P_\Lambda \simeq \frac{\langle \sigma_{zx} \rangle}{2} \left( 1 + \frac{2}{3} \frac{\langle E_\Lambda \rangle - m_\Lambda}{m_\Lambda} \right)
\]

Approximation 4: Averaging over central region \([z_{\text{left}}, z_{\text{right}}]\) confined by \(|y| < \Delta y_h/2\)

Hydrodynamical rapidity: \( y_h(z, t) = \frac{1}{2} \ln \frac{\langle u^0 + u^3 \rangle}{\langle u^0 - u^3 \rangle} \) \quad \Delta y_h(t) = y_h(z_{\text{right}}, t) - y_h(z_{\text{left}}, t) \)
Freeze-out for polarization calculation

Usually it is a **local freeze-out**, i.e. cell-by-cell.
The freeze-out procedure starts when the local energy density $< 0.4 \text{ GeV/fm}^3$:
(1) This criterion should be met in the cell and in eight surrounding cells.
(2) At least one of the surrounding cells is empty (border with vacuum).

Therefore, the actual mean freeze-out energy density

For the polarization calculation
global freeze-out at $\varepsilon_{\text{frz}}$ in the central region
Thermodynamic polarization at moderate energies

Polarization reaches a maximum or a plateau (depending on EoS and centrality) at $\sqrt{s_{NN}} \approx 3$ GeV.

YI, PRC 103, L031903 (2021)
Rapidity window dependence

$|y_h| < 0.6$ upper border, $|y_h| < 0.5$ center line, $|y_h| < 3.5$ lower border

YI, PRC 103, L031903 (2021)

Global polarization increases with increasing width of rapidity window around the midrapidity
Thermodynamic global polarization in 3FD

\[ P_\Lambda = \frac{1}{2m_\Lambda} \left\langle \left( E_\Lambda - \frac{1}{3} \frac{p_\Lambda^2}{E_\Lambda + m_\Lambda} \right) \sigma_{z\chi} \right\rangle \]  
\text{averaging with } \Lambda \text{ distribution function, } n_\Lambda

Approximations made in \textbf{new run of calculations}:

**Approximation 1**: feed-down from decays of \( \Sigma^0 \) and \( \Sigma^* \) is \textbf{taken into account}

**Approximation 2**: Averaging with \( \Lambda \) \textbf{density}, \( \rho_\Lambda \), in stead of \( n_\Lambda \). This is better than \( \varepsilon \).

**Approximation 3**: Averaging of (...) and \( \sigma_{z\chi} \) are \textbf{not decoupled} in \( P_\Lambda \)

**Approximation 4**: Averaging over central region \([z_{\text{left}}, z_{\text{right}}]\) confined by \(|y| < \Delta y_h/2\)

\textbf{Hydrodynamical rapidity}: \( y_h(z, t) = \frac{1}{2} \ln \frac{\langle u^0 + u^3 \rangle}{\langle u^0 - u^3 \rangle} \)  
\( \Delta y_h(t) = y_h(z_{\text{right}}, t) - y_h(z_{\text{left}}, t) \).
Global polarization in new run of 3FD calculations
preliminary results

✓ Averaging with Λ density, $\rho_\Lambda$ instead of $\rho$, noticeably reduces $P_\Lambda$ at $\sqrt{s_{NN}} < 4$ GeV

✓ Decay feed-down noticeably reduces $P_\Lambda$
Rapidity dependence *(preliminary results)*

- **✓ 3FD:** $\Lambda$ polarization increases from midrapidity to forward/backward rapidities
- **✓ 3FD** does not contradict HADES data, but contradicts to STAR-FXT data. **acceptance???


STAR-FXT: 2108.00044

2.7 GeV, $b = 6$ fm
Summary

✓ Prerequisite for polarization models: freeze-out stage is thermalized

✓ 3FD: $\Lambda$ polarization rises with collision energy decrease at $\sqrt{s_{NN}} \leq 7.7$ GeV (experimentally observed)

✓ 3FD: $\Lambda$ polarization reaches a maximum at $\sqrt{s_{NN}} \leq \approx 3$ GeV (experimentally looks like a plateau; acceptance?)

✓ 3FD: $\Lambda$ polarization increases from midrapidity to forward/backward rapidities (STAR-FXT: experimentally decreases; acceptance?)

✓ Decay feeddown noticeably reduces $P_\Lambda$ at $\sqrt{s_{NN}} < 8$ GeV
Backup
Nuclotron-based Ion Collider fAcility (NICA)

Au+Au
\( \sqrt{s_{NN}} = 4 - 11 \text{ GeV} \)

Bi(A=209) beam 2022

Au beam is planned later

Data taking at MPD 2023

Polarization measurements are planned (approx. 2025)

$|x| \leq 2 \text{ fm}, |y| \leq 2 \text{ fm} \text{ and } |z| \leq \gamma_{cm} 2 \text{ fm}, \gamma_{cm} = \text{Lorentz factor of initial motion in cm frame}$

**EoS's:** Khvorostukhin, Skokov, Redlich, Toneev, EPJ C48, 531 (2006)

Slow crossover EoS

lattice QCD: fast crossover

deconfinement transition starts at top AGS energies in both cases.
Chiral vortical effect (CVE)

Axial current

\[ J_5^\nu(x) = -N_c \left( \frac{\mu^2}{2\pi^2} + \kappa \frac{T^2}{6} \right) \epsilon^{\nu\alpha\beta\gamma} u^\alpha \omega_{\beta\gamma} \]

induced by vorticity \( \omega_{\mu\nu} = \frac{1}{2} ( \partial_\nu u_\mu - \partial_\mu u_\nu ) \)

Vilenkin, PRD 20, 1807 (1979); 21, 2260 (1980).

Son and Zhitnitsky, PRD 70, 074018 (2004)

\[ \frac{\mu^2}{2\pi^2} = \text{axial anomaly term is topologically protected} \]

\[ \kappa \frac{T^2}{6} = \text{holographic gravitational anomaly} \]

Landsteiner, Megias, Melgar, Pena-Benitez, JHEP 1109, 121 (2011) [Gauge-gravity correspondence]

Lattice QCD results in \( \kappa = 0 \) in confined phase and \( \kappa \leq 0.1 \) in deconfined phase

[Braguta, et al., PRD 88, 071501 (2013); 89, 074510 (2014)]
Chiral vortical effect (CVE): Coalescence

**Coalescence-like hadronization:** quarks coalesce into hadrons, keeping their polarization.

Λ → ¯Λ polarization splitting is not explained

Only BES-RHIC energies were studied

Axial-vortical-effect (AVE):

Axial-charge conservation at hadronization

\[ P_\Lambda = \int d^3x \left( J_{5s}^0 / u_\gamma \right) / (N_\Lambda + N_{anti-K^*}) \]

\[ P_{anti-\Lambda} = \int d^3x \left( J_{5s}^0 / u_\gamma \right) / (N_{anti-\Lambda} + N_{K^*}) \]

\( u_\gamma \) results from boost to the local rest frame of the matter

Sorin and Teryaev, PRC 95, 011902 (2017)

\( P_\Lambda \) and \( P_{anti-\Lambda} \) are quite different.

Therefore,

\( \Lambda -- \bar{\Lambda} \) splitting can be addressed.
Axial-vortical-effect (AVE) polarization

Baznat, Gudima, Sorin, Teryaev, PRC 97, 041902 (2018)

YI, PRC 102 (2020) 4, 044904

CVE and AVE are hardly applicable below NICA range because the chiral symmetry is spontaneously broken.

\[ \Lambda \rightarrow \bar{\Lambda} \text{ splitting is explained} \]

CVE and AVE are hardly applicable below NICA range because the chiral symmetry is spontaneously broken.
$\Lambda -- \bar{\Lambda}$ polarization splitting: possible solutions

Interaction mediated by massive vector and scalar bosons (Walecka-like model)

Csernai, Kapusta, Welle, PRC 99, 021901 (2019)

Xie, Chen, Csernai, EPJC 81, 12 (2021)

AVE naturally explains the $\Lambda -- \bar{\Lambda}$ splitting
Problem: $\Lambda$ -- $\bar{\Lambda}$ polarization splitting

In the standard thermodynamic approach this splitting is either very small or simply small, if different freeze-out for $\Lambda$ and $\bar{\Lambda}$ is taken into account,


while exp. difference is large at 7.7 GeV, although error bars for $\bar{\Lambda}$ are also large.