Space-time evolution and description of the spin polarization in the Bjorken hydrodynamical scenario

Rajeev Singh

rajeev.singh@ifj.edu.pl

in collaboration with:
Radoslaw Ryblewski (IFJ PAN), Wojciech Florkowski (IF UJ)
and Avdhesh Kumar (IFJ PAN)

References:

ZIMANYI SCHOOL’19
Dec 2 - Dec 6
Budapest, Hungary
Outline:

- Motivation
- Methodology
- Results
- Summary and Future Work
Motivation:

First positive measurements of global spin polarization of $\Lambda$ hyperons by STAR

\[ P_{\Lambda} \approx \frac{1}{2} \frac{\omega}{T} + \frac{\mu_{\Lambda} B}{T} \]

\[ P_{\overline{\Lambda}} \approx \frac{1}{2} \frac{\omega}{T} - \frac{\mu_{\Lambda} B}{T} \]

Becattini, F., Karpenko, I., Lisa, M., Upsal, I., Voloshin, S., PRC 95, 054902 (2017)

…the hottest, least viscous – and now, most vortical – fluid produced in the laboratory …

\[ \omega = \left( P_{\Lambda} + P_{\overline{\Lambda}} \right) k_B T/\hbar \sim 0.6 - 2.7 \times 10^{22} \text{s}^{-1} \]

Motivation:

- Non-central relativistic heavy ion collisions creates global rotation of matter. This may induce spin polarization reminding us of Einstein and de-Haas effect and Barnett effect.

Figure: Einstein and De Haas and Barnett Effects
Motivation:

- Non-central relativistic heavy ion collisions creates global rotation of matter. This may induce spin polarization reminding us of Barnett effect and Einstein and de-Haas effect.
- Emerging particles are expected to be globally polarized with their spins on average pointing along the systems angular momentum.

Figure: Schematic view of non-central heavy-ion collisions.
Other works:

Other theoretical models used for the heavy-ions data interpretation dealt mainly with the spin polarization of particles at freeze-out, where the basic hydrodynamic quantity giving rise to spin polarization is the ‘thermal vorticity’ expressed as \( \varpi_{\mu\nu} = -\frac{1}{2}(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu) \).


Hydro calculation of \( P_z \)
F. Becattini and I. Karpenko,
PRL 120.012302 (2018)
Our hydrodynamic framework:

- Solving the standard perfect-fluid hydrodynamic equations without spin
- Determination of the spin evolution in the hydrodynamic background
- Determination of the Pauli-Lubanski (PL) vector on the freeze-out hypersurface
- Calculation of the spin polarization of particles in their rest frame
- The spin polarization obtained is a function of the three-momenta of particles and can be directly compared with the experiment
In this work, we use relativistic hydrodynamic equations for polarized spin 1/2 particles to determine the space-time evolution of the spin polarization in the system using forms of the energy-momentum and spin tensors proposed by de Groot, van Leeuwen, and van Weert (GLW).


The calculations are done in a boost-invariant and transversely homogeneous setup. We show how the formalism of hydrodynamics with spin can be used to determine physical observables related to the spin polarization required for the modelling of the experimental data.


Our hydrodynamic formulation does not allow for arbitrary large values of the spin polarization tensor, hence we have restricted ourselves to the leading order terms in the $\omega_{\mu\nu}$.
Spin polarization tensor:

The spin polarization tensor $\omega_{\mu\nu}$ is anti-symmetric and can be defined by the four-vectors $\kappa^{\mu}$ and $\omega^{\mu}$,

$$\omega_{\mu\nu} = \kappa_{\mu} U_{\nu} - \kappa_{\nu} U_{\mu} + \epsilon_{\mu\nu\alpha\beta} U^{\alpha} \omega^{\beta},$$

Using these constraints,

$$\kappa \cdot U = 0, \quad \omega \cdot U = 0$$

We can express $\kappa_{\mu}$ and $\omega_{\mu}$ in terms of $\omega_{\mu\nu}$, namely

$$\kappa_{\mu} = \omega_{\mu\alpha} U^{\alpha}, \quad \omega_{\mu} = \frac{1}{2} \epsilon_{\mu\alpha\beta\gamma} \omega^{\alpha\beta} U^{\gamma}$$
Conservation of charge:

\[ \partial_{\alpha} N^{\alpha}(x) = 0, \]

where, \( N^{\alpha} = nU^{\alpha}, \quad n = 4 \sinh(\xi) \ n_0(T). \)

The quantity \( n_0(T) \) defines the number density of spinless and neutral massive Boltzmann particles,

\[ n_0(T) = \langle p \cdot U \rangle_0 = \frac{1}{2\pi^2} \ T^3 \ \hat{m}^2 K_2(\hat{m}) \]

where, \( \langle \cdots \rangle_0 \equiv \int dP (\cdots) e^{-\beta \cdot p} \) denotes the thermal average, \( \hat{m} \equiv m/T \) denotes the ratio of the particle mass \( m \) and the temperature \( T \), and \( K_2(\hat{m}) \) denotes the modified Bessel function.

The factor, \( 4 \sinh(\xi) = 2 \left( e^{\xi} - e^{-\xi} \right) \) accounts for spin degeneracy and presence of both particles and antiparticles in the system and the variable \( \xi \) denotes the ratio of the chemical potential \( \mu \) and the temperature \( T \), \( \xi = \mu/T \).
Conservation of energy and linear momentum:

\[ \partial_\alpha T^\alpha_\beta (x) = 0 \]

where the energy-momentum tensor \( T^\alpha_\beta \) has the perfect-fluid form:

\[ T^\alpha_\beta (x) = (\varepsilon + P) U^\alpha U^\beta - Pg^\alpha_\beta \]

with energy density \( \varepsilon = 4 \cosh(\xi) \varepsilon(0)(T) \) and pressure \( P = 4 \cosh(\xi) P(0)(T) \)

The auxiliary quantities are:

\[ \varepsilon(0)(T) = \langle (p \cdot U)^2 \rangle_0 \] and \( P(0)(T) = -(1/3) \langle p \cdot p - (p \cdot U)^2 \rangle_0 \)

are the energy density and pressure of the spin-less ideal gas respectively. In case of ideal relativistic gas of classical massive particles,

\[ \varepsilon(0)(T) = \frac{1}{2\pi^2} T^4 \hat{m}^2 \left[ 3K_2 (\hat{m}) + \hat{m}K_1 (\hat{m}) \right], \]
\[ P(0)(T) = Tn(0)(T) \]

Above conservation laws provide closed system of five equations for five unknown functions: \( \xi, T \), and three independent components of \( U^\mu \).
Conservation of total angular momentum:

\[ \partial_\mu J^{\mu,\alpha\beta}(x) = 0, \quad J^{\mu,\alpha\beta}(x) = -J^{\mu,\beta\alpha}(x) \]

Total angular momentum consists of orbital and spin parts:

\[ J^{\mu,\alpha\beta}(x) = L^{\mu,\alpha\beta}(x) + S^{\mu,\alpha\beta}(x), \]

\[ L^{\mu,\alpha\beta}(x) = x^\alpha T^{\mu\beta}(x) - x^\beta T^{\mu\alpha}(x) \]

Since the energy-momentum tensor is symmetric, the conservation of the angular momentum implies the conservation of its spin part.

\[ \partial_\lambda J^{\lambda,\mu\nu}(x) = 0, \quad \partial_\mu T^{\mu\nu}(x) = 0 \quad \Rightarrow \quad \partial_\lambda S^{\lambda,\mu\nu}(x) = T^{\nu\mu}(x) - T^{\mu\nu}(x) \]

Hence, the spin tensor \( S^{\mu,\alpha\beta}(x) \) is separately conserved in GLW formulation.
Conservation of spin angular momentum:

$$\partial_\alpha S_{GLW}^{\alpha,\beta\gamma}(x) = 0$$

GLW spin tensor in the leading order of $\omega_{\mu\nu}$ is:

$$S_{GLW}^{\alpha,\beta\gamma} = \cosh(\xi) \left( n(0) (T) U^\alpha \omega^{\beta\gamma} + S_{\Delta GLW}^{\alpha,\beta\gamma} \right)$$

Here, $\omega^{\beta\gamma}$ is known as spin polarization tensor, whereas the auxiliary tensor $S_{\Delta GLW}^{\alpha,\beta\gamma}$ is:

$$S_{\Delta GLW}^{\alpha,\beta\gamma} = A(0) U^\alpha U^\delta [U^{[\beta \omega \gamma]}_{\delta}] + B(0) \left( U^{[\beta \Delta^{\alpha \delta \omega \gamma]}_{\delta}}_{\delta} + U^\alpha \Delta^{\delta [\beta \omega \gamma]}_{\delta} + U^\delta \Delta^{\alpha [\beta \omega \gamma]}_{\delta} \right),$$

with,

$$B(0) = -\frac{2}{\hat{m}^2} s(0)(T)$$

$$A(0) = -3B(0) + 2n(0)(T)$$
Basis for boost invariant and transversely homogeneous systems:

For our calculations, it is useful to introduce a local basis consisting of following 4-vectors,

\[
U^\alpha = \frac{1}{\tau} (t, 0, 0, z) = (\cosh(\eta), 0, 0, \sinh(\eta)),
\]

\[
X^\alpha = (0, 1, 0, 0),
\]

\[
Y^\alpha = (0, 0, 1, 0),
\]

\[
Z^\alpha = \frac{1}{\tau} (z, 0, 0, t) = (\sinh(\eta), 0, 0, \cosh(\eta)).
\]

where, \(\tau = \sqrt{t^2 - z^2}\) is the longitudinal proper time and \(\eta = \ln((t + z)/(t - z))/2\) is the space-time rapidity.

The basis vectors satisfy the following normalization and orthogonal conditions:

\[
U \cdot U = 1
\]

\[
X \cdot X = Y \cdot Y = Z \cdot Z = -1,
\]

\[
X \cdot U = Y \cdot U = Z \cdot U = 0,
\]

\[
X \cdot Y = Y \cdot Z = Z \cdot X = 0.
\]
We use the following decomposition of the vectors $\kappa^\mu$ and $\omega^\mu$,

\[
\kappa^\alpha = C_{\kappa U} U^\alpha + C_{\kappa X} X^\alpha + C_{\kappa Y} Y^\alpha + C_{\kappa Z} Z^\alpha,
\]

\[
\omega^\alpha = C_{\omega U} U^\alpha + C_{\omega X} X^\alpha + C_{\omega Y} Y^\alpha + C_{\omega Z} Z^\alpha.
\]

Here, the scalar coefficients are functions of the proper time $\tau$ only due to boost invariance. Since $\kappa \cdot U = 0$, $\omega \cdot U = 0$, therefore

\[
\kappa^\alpha = C_{\kappa X} X^\alpha + C_{\kappa Y} Y^\alpha + C_{\kappa Z} Z^\alpha,
\]

\[
\omega^\alpha = C_{\omega X} X^\alpha + C_{\omega Y} Y^\alpha + C_{\omega Z} Z^\alpha.
\]

$\omega_{\mu\nu} = \kappa_\mu U_\nu - \kappa_\nu U_\mu + \epsilon_{\mu\nu\alpha\beta} U^\alpha \omega^\beta$ can be written as,

\[
\omega_{\mu\nu} = C_{\kappa Z}(Z_\mu U_\nu - Z_\nu U_\mu) + C_{\kappa X}(X_\mu U_\nu - X_\nu U_\mu) + C_{\kappa Y}(Y_\mu U_\nu - Y_\nu U_\mu) + \epsilon_{\mu\nu\alpha\beta} U^\alpha (C_{\omega Z} Z^\beta + C_{\omega X} X^\beta + C_{\omega Y} Y^\beta)
\]

In the plane $z = 0$ we find:

\[
\omega_{\mu\nu} = \begin{bmatrix}
0 & C_{\kappa X} & C_{\kappa Y} & C_{\kappa Z} \\
-C_{\kappa X} & 0 & -C_{\omega Z} & C_{\omega Y} \\
-C_{\kappa Y} & C_{\omega Z} & 0 & -C_{\omega X} \\
-C_{\kappa Z} & -C_{\omega Y} & C_{\omega X} & 0
\end{bmatrix}
\]
**Boost-Invariant form of fluid dynamics with spin:**

- **Conservation law of charge** can be written as:
  \[ U^\alpha \partial_\alpha n + n \partial_\alpha U^\alpha = 0 \]
  Therefore, for Bjorken type of flow we can write,
  \[ \dot{n} + \frac{n}{\tau} = 0 \]

- **Conservation law of energy-momentum** can be written as:
  \[ U^\alpha \partial_\alpha \varepsilon + (\varepsilon + P) \partial_\alpha U^\alpha = 0 \]
  Hence for the Bjorken flow,
  \[ \dot{\varepsilon} + \frac{(\varepsilon+P)}{\tau} = 0 \]
Boost-Invariant form of fluid dynamics with spin:

Using the equations,

\[
S_{\Delta GLW}^{\alpha, \beta \gamma} = A_{(0)} U^{\alpha} U^{\delta} [U^\beta U^\gamma]_\delta \\
+ B_{(0)} \left( U^{[\beta} \Delta^\alpha_{\delta} U^\gamma \right)_\delta + U^\alpha \Delta^\delta_{[\beta} U^\gamma \right]_\delta + U^\delta \Delta^\alpha_{[\beta} U^\gamma \right]_\delta ,
\]

and

\[
S_{GLW}^{\alpha, \beta \gamma} = \cosh(\xi) \left( n_{(0)} (T) U^{\alpha} U^{[\beta} U^\gamma + S_{\Delta GLW}^{\alpha, \beta \gamma} \right)
\]

in

\[
\partial_{\alpha} S_{GLW}^{\alpha, \beta \gamma} (x) = 0
\]

Contracting the final equation with \( U^\beta X^\gamma, U^\beta Y^\gamma, U^\beta Z^\gamma, Y^\beta Z^\gamma, X^\beta Z^\gamma \) and \( X^\beta Y^\gamma \).

\[
\begin{bmatrix}
L(\tau) & 0 & 0 & 0 & 0 & 0 \\
0 & L(\tau) & 0 & 0 & 0 & 0 \\
0 & 0 & L(\tau) & 0 & 0 & 0 \\
0 & 0 & 0 & P(\tau) & 0 & 0 \\
0 & 0 & 0 & 0 & P(\tau) & 0 \\
0 & 0 & 0 & 0 & 0 & P(\tau)
\end{bmatrix}
\begin{bmatrix}
\dot{C}_\kappa X \\
\dot{C}_\kappa Y \\
\dot{C}_\kappa Z \\
\dot{C}_\omega X \\
\dot{C}_\omega Y \\
\dot{C}_\omega Z
\end{bmatrix}
= \begin{bmatrix}
Q_1(\tau) & 0 & 0 & 0 & 0 & 0 \\
0 & Q_1(\tau) & 0 & 0 & 0 & 0 \\
0 & 0 & Q_2(\tau) & 0 & 0 & 0 \\
0 & 0 & 0 & R_1(\tau) & 0 & 0 \\
0 & 0 & 0 & 0 & R_1(\tau) & 0 \\
0 & 0 & 0 & 0 & 0 & R_2(\tau)
\end{bmatrix}
\begin{bmatrix}
C_\kappa X \\
C_\kappa Y \\
C_\kappa Z \\
C_\omega X \\
C_\omega Y \\
C_\omega Z
\end{bmatrix}
\]

where,

\[
L(\tau) = A_1 - \frac{1}{2} A_2 - A_3,
\]

\[
P(\tau) = A_1,
\]

\[
Q_1(\tau) = - \left[ \dot{L} + \frac{1}{\tau} \left( L + \frac{1}{2} A_3 \right) \right],
\]

\[
Q_2(\tau) = - \left( \dot{L} + \frac{\xi}{\tau} \right),
\]

\[
R_1(\tau) = - \left[ \dot{P} + \frac{1}{\tau} \left( P - \frac{1}{2} A_3 \right) \right],
\]

\[
R_2(\tau) = - \left( \dot{P} + \frac{P}{\tau} \right).
\]

\[
A_1 = \cosh(\xi) \left( n_{(0)} - B_{(0)} \right),
\]

\[
A_2 = \cosh(\xi) \left( A_{(0)} - 3B_{(0)} \right),
\]

\[
A_3 = \cosh(\xi) B_{(0)}
\]
Background evolution:

Initial baryon chemical potential $\mu_0 = 800$ MeV
Initial temperature $T_0 = 155$ MeV
Particle mass $m = 1116$ MeV

Initial and final proper time is $\tau_0 = 1$ fm and $\tau_f = 10$ fm, respectively.

Figure: Proper-time dependence of $T$ divided by its initial value $T_0$ (solid line) and the ratio of baryon chemical potential $\mu$ and temperature $T$ re-scaled by the initial ratio $\mu_0 / T_0$ (dotted line) for a boost-invariant one-dimensional expansion.
Spin polarization evolution:

Figure: Proper-time dependence of the coefficients $C_{\kappa X}$, $C_{\kappa Z}$, $C_{\omega X}$ and $C_{\omega Z}$. The coefficients $C_{\kappa Y}$ and $C_{\omega Y}$ satisfy the same differential equations as the coefficients $C_{\kappa X}$ and $C_{\omega X}$.
Spin polarization of particles at the freeze-out:

Average spin polarization per particle $\langle \pi_{\mu}(p) \rangle$ is given as:

$$\langle \pi_{\mu} \rangle = \frac{E_p \frac{d\Pi_{\mu}(p)}{d^3p}}{E_p \frac{dN(p)}{d^3p}}$$

where, the total value of the Pauli-Lubański vector for particles with momentum $p$ is:

$$E_p \frac{d\Pi_{\mu}(p)}{d^3p} = -\frac{\cosh(\xi)}{(2\pi)^3m} \int \Delta\Sigma_{\lambda} p^\lambda e^{-\beta \cdot p} \tilde{\omega}_{\mu\beta} p^\beta$$

momentum density of all particles is given by:

$$E_p \frac{dN(p)}{d^3p} = \frac{4 \cosh(\xi)}{(2\pi)^3} \int \Delta\Sigma_{\lambda} p^\lambda e^{-\beta \cdot p}$$

and freeze-out hypersurface is defined as:

$$\Delta\Sigma_{\lambda} = U_{\lambda} dxdy \tau d\eta$$

Assuming that freeze-out takes place at a constant value of $\tau$ and parameterizing the particle four-momentum $p^\lambda$ in terms of the transverse mass $m_T$ and rapidity $y_p$, we get:

$$\Delta\Sigma_{\lambda} p^\lambda = m_T \cosh (y_p - \eta) dxdy \tau d\eta$$
Polarization vector $\langle \pi^*_\mu \rangle$ in the local rest frame of the particle can be obtained by using the canonical boost. Using the parametrizations $E_p = m_T \cosh(y_p)$ and $p_z = m_T \sinh(y_p)$ and applying the appropriate Lorentz transformation we get,

$$
\langle \pi^*_\mu \rangle = \frac{1}{8m} \begin{pmatrix}
0 \\
\left( \frac{\sinh(y_p)p_\mu}{m_T \cosh(y_p)+m} \right) \left[ \chi \left( C_{\kappa x} T_y - C_{\kappa y} T_x \right) + 2C_{\omega z} T_T \right] + \frac{\chi \rho_\mu \cosh(y_p) (C_{\omega x} T_x + C_{\omega y} T_y)}{m_T \cosh(y_p)+m} + 2C_{K z} T_y - \chi C_{\omega x} m_T \\
\left( \frac{\sinh(y_p)p_\mu}{m_T \cosh(y_p)+m} \right) \left[ \chi \left( C_{\kappa x} T_y - C_{\kappa y} T_x \right) + 2C_{\omega z} T_T \right] + \frac{\chi \rho_\mu \cosh(y_p) (C_{\omega x} T_x + C_{\omega y} T_y)}{m_T \cosh(y_p)+m} - 2C_{K z} T_x - \chi C_{\omega y} m_T \\
- \left( \frac{m \cosh(y_p)+m_T}{m_T \cosh(y_p)+m} \right) \left[ \chi \left( C_{\kappa x} T_y - C_{\kappa y} T_x \right) + 2C_{\omega z} T_T \right] - \frac{m \sinh(y_p) (C_{\omega x} T_x + C_{\omega y} T_y)}{m_T \cosh(y_p)+m}
\end{pmatrix}
$$

where,

$$
\chi \left( \hat{m}_T \right) = \left( K_0 \left( \hat{m}_T \right) + K_2 \left( \hat{m}_T \right) \right) / K_1 \left( \hat{m}_T \right),
\hat{m}_T = m_T / T
$$
Figure: Components of the PRF mean polarization three-vector of $\Lambda$'s. The results obtained with the initial conditions $\mu_0 = 800$ MeV, $T_0 = 155$ MeV, $C_{\kappa,0} = (0, 0, 0)$, and $C_{\omega,0} = (0, 0.1, 0)$ for $y_p = 0$. 
Summary:

- We have discussed relativistic hydrodynamics with spin based on the GLW formulation of energy-momentum and spin tensors.
- For boost invariant and transversely homogeneous set-up we show how our hydrodynamic framework with spin can be used to determine the spin polarization observables measured in heavy ion collisions.
- Since we worked with 0+1 dimensional expansion, our results cannot be compared with the experimental data.
- Our future work is to extend our hydrodynamic approach for 1+3 dimensions and interpret the experimental data correctly.
Thank you for your attention!
Back-Up Slides
Measuring polarization in experiment:

**Parity-violating decay of hyperons**

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

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

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

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

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

Source: C. Patrignani et al. (PDG), Chin. Phys. C 40, 100001 (2016)

**Projection onto the transverse plane**

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

\(-\phi_p^*\)

- \(\phi_p^*\): \(\phi\) of daughter proton in \(\Lambda\) rest frame

- \(\psi_1\): azimuthal angle of \(b\)

\(P_H = \frac{8}{\pi \alpha_H} \frac{\sin(\psi_1 - \phi_p^*)}{\text{Res}(\psi_1)}\)

Source: T. Niida, WWND 2019
Figure: Einstein-De Haas Effect
Figure: Barnett Effect
Figure: Schematic view of STAR Detector

- Full azimuthal and large rapidity coverage
- Excellent particle identification