Role of Vorticity and Viscosity on the Polarization of Λ-hyperon at Relativistic Energies

Captain R. Singh[1],[*] Bhagyarathi Sahoo[1], and Raghunath Sahoo[1]
[1] *Department of Physics, Indian Institute of Technology Indore, Simrol, Indore - 453552, INDIA*

Introduction

In scenarios like QGP being a vortical fluid, the partons are supposed to be polarized and as a result, hadrons produced at the chemical freezeout boundary are also thought to be polarized. Such a non-zero polarization of $\Lambda(\bar{\Lambda})$ hyperons have been observed in heavy-ion collisions at ALICE and STAR Collaborations. This has led to an exploration of potential sources for hyperon polarization. It is anticipated that in peripheral heavy ion collisions, the initial orbital angular momentum (OAM) gives rise to vorticity, which is primarily responsible for the spin polarization of hyperons. Besides the OAM, there are other sources of vorticity, such as shear viscosity, magnetic field, inhomogeneous transverse expansion, and others that may contribute to hyperon polarization. In the present study, we consider a viscous medium with non-zero vorticity, which is coupled with the spin of the particles and gives rise to spin polarization in the system. Here, the spin polarization tensor is obtained using a tensor decomposition with the help of Ref. [2]. We obtained the global spin polarization of Λ-hyperon using the vortical QGP evolution. This study offers a qualitative understanding of the QGP medium evolution and spin polarization of hyperons in heavy-ion collisions.

Formalism

In a recent study on second-order causal dissipative hydrodynamics, we examined how vorticity influences the behavior of viscous quark-gluon plasma (QGP) and compared it with the behavior of an ideal QGP. Our findings revealed that the evolution of the medium is highly dependent on the initial temperature (T), the viscous term (ϕ), and the vorticity (ω). Furthermore, the coupling of vorticity and viscosity introduces complexity into the evolution, giving rise to oscillations in its dissipation [1]. In this work, we have utilized evolving thermal vorticity ($\bar{\omega}$) to predict the polarization of Λ-hyperon in relativistic heavy-ion collisions using the mean spin vector of spin-1/2 particle with four-momentum p, given as;

$$S^{\mu}(p) = -\frac{\epsilon^{\mu\rho\sigma\tau}p_{\tau}}{8m_{\Lambda}} \frac{\int_{\Sigma} d\Sigma_{\lambda}p^{\lambda}\ f(x,p)(1-f(x,p))\bar{\omega}_{\rho\sigma}}{\int_{\Sigma} d\Sigma_{\lambda}p^{\lambda}\ f(x,p)}$$

Here $f(x,p)$ is Fermi-Dirac distribution function and $d\Sigma_{\lambda}$ is the decoupling hypersurface. Since the mass of the Λ ($m_{\Lambda} \approx 1.2$ GeV) is much larger than the temperature (T = 0.350 GeV) being considered in this study, we assumed that $1 - f(x,p) \approx 1$. The integration of individual hypersurface elements can be carried out if one expands the distribution function in a geometric series. Further, we have obtained the Λ-hyperon polarization following two methods:

Method I: We assume the hadronization happens in the decoupling hypersurface where τ = constant, $T = T_{dec} = 170$ and derive the corresponding mean spin vector;

$$S_y = \frac{1}{4m_{\Lambda}} \frac{\displaystyle\int_{\gamma} \tau r E\, \frac{\omega}{T_{dec}} \sum_{n=1}^{\infty} m_T I_0\left(O_1\right) K_1\left(O_2\right) dr}{\displaystyle\int_{\gamma} \tau r \sum_{n=1}^{\infty} m_T I_0\left(O_1\right) K_1\left(O_2\right) dr}$$

where I's, K's are Bessel functions and $O_1 = n\frac{p_T}{T}\sinh y_T$, $O_2 = n\frac{m_T}{T}\cosh y_T$.

Method II: In this method we consider a relation between r and τ,

$$r = r_0\left[1 + \frac{2}{3}\frac{(\tau-\tau_0)^{3/2}}{r_0\tau_0^{1/2}}\right]$$

and replaced the integration on r with τ in the above equation.

In the rest frame of the particle, the spin vector is $S^{*\mu} = (0, \mathbf{S}^{*})$, which is obtained by using the Lorentz transformation as:

$$\mathbf{S}^{*} = \mathbf{S(p)} - \frac{\mathbf{S\cdot p}}{\mathbf{E(E+m)}}\mathbf{p}$$

Finally the net spin polarization of Λ is given by, $\mathbf{P} = 2\mathbf{S^{*}}$.

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[*] Electronic address: `captainriturajsingh@gmail.com`

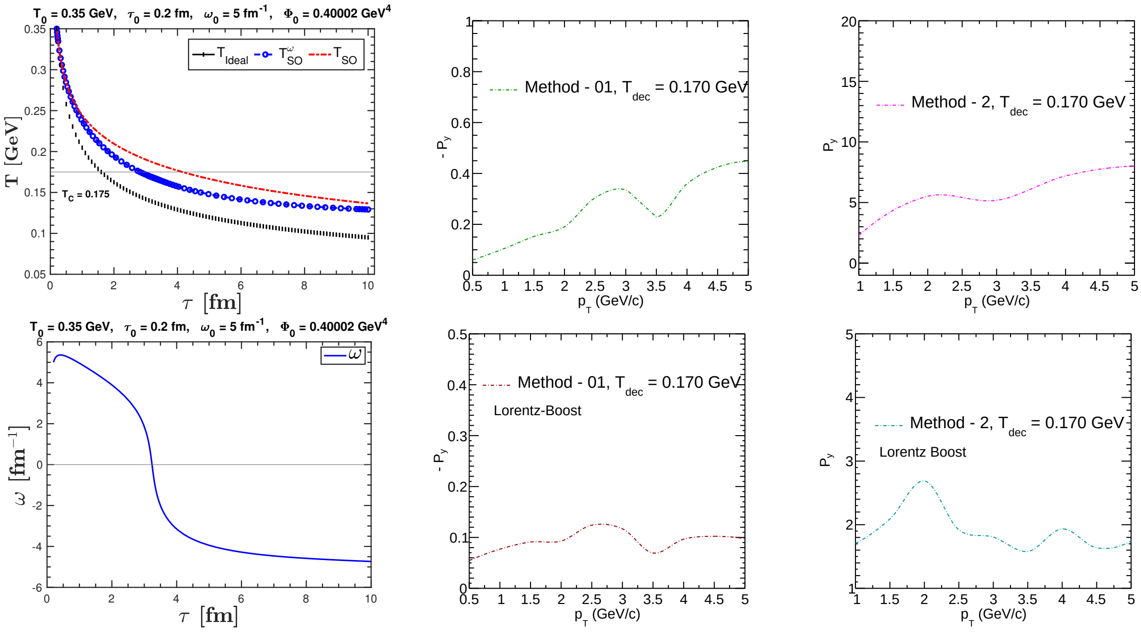

FIG. 1: (Color Online) **In the First Column:** Temperature cooling for non-viscous T_{ideal}, viscous with second-order correction T_{SO} and vorticity-viscosity coupling T^{ω}_{SO} cases are shown corresponding to the initial conditions: T = 0.35 GeV, $\tau_0 = 0.2$ fm, $\omega_0 = 5$ fm^{-1}, $\phi_0 = 0.40002$ GeV^4 at the top. Vorticity (ω) evolution is shown with time at bottom of the column. **In the Second & Third Column:** Λ-hyperon polarization with p_T are depicted respective to the Method-I & II (top) and corresponding Lorentz boost cases are shown at bottom.

Results and Discussions

In Figure 1, the T and ω profiles illustrate the evolving dynamics of the medium over time, τ. It shows that coupling between vorticity and viscosity cools down T^{ω}_{SO} slightly faster than T_{SO} due to the resistance of viscosity to changes in vorticity direction. Positive initial vorticity results in faster cooling, almost following the ideal rate. However, the presence of viscosity in the rotating fluid slows down T^{ω}_{SO} cooling compared to T_{ideal}. The ω diffusion with time shows that initially, ω changes with a high rate, but at a later stage, it becomes almost constant in the absence of any other external force, i.e., $\phi = 0$. The negative value of ω in the plot depicts the change in the direction of the rotation. This change in the rotation happens due to the initial fast expansion of the medium and the restriction imposed on it by the rotational motion of the fluid. Such that medium evolution induces the rotation opposite to the initial vorticity. As time increases, vorticity also grows/diffuses in the opposite direction and gets saturated when medium evolution becomes static. This change in the ω is critical to polarization in our formulation. The Λ-hyperon polarization shown in the plots in the second column uses $\omega \approx -2$ fm^{-1} at $\tau = \tau_f$ while for the third column plots ω-integrated over time has been used. However, the change in the polarization pattern is somewhat similar for both cases, though the magnitude for Method 2 is ten times larger than for Method 1. Now, considering the Lorentz boosts for both cases nearly have similar effects, like it reduces the magnitude of the Λ-hyperon polarization at high-p_T while low-p_T ends remains relatively unaffected. As thermal vorticity gives the essence of thermalization and may lead the partons to be polarized, and so the hadrons. Therefore, hadron polarization observed in heavy-ion collisions could be a consequence of the existence of the thermalized QCD matter in such collisions.

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