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Local and global Λ polarization in a vortical fluid

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Abstract

We compute the fermion spin distribution in the vortical fluid created in off-central high energy heavy-ion collisions. We employ the event-by-event (3+1)D viscous hydrodynamic model. The spin polarization density is proportional to the local fluid vorticity in quantum kinetic theory. As a result of strong collectivity, the spatial distribution of the local vorticity on the freeze-out hyper-surface strongly correlates to the rapidity and azimuthal angle distribution of fermion spins. We investigate the sensitivity of the local polarization to the initial fluid velocity in the hydrodynamic model and compute the global polarization of Λ hyperons by the AMPT model. The energy dependence of the global polarization agrees with the STAR data.

Keywords: Vorticity, Polarization, Spin distribution and correlation

1. Introduction

Recently the STAR collaboration has measured the polarization of Λ and Λ̄ hyperons [1]. They observed that (a) the global polarization decreases with collision energies; (b) the polarization for Λ̄ is always bigger than Λ at the same beam energy. These two features are very important to quantitatively constrain the fluid vorticity of the strongly coupled quark-gluon plasma (sQGP) and the magnitude of the magnetic field through the spin-vorticity and spin-magnetic coupling [2–4]. The measured beam energy dependence is consistent with the predictions of the hydrodynamic or transport model [2, 5–10]. The difference between Λ and Λ̄ is caused by (1) pauli-blocking – it is more difficult to polarize Λs than Λ̄s when there are more fermions than anti-fermions [11]; (2) the spin-magnetic coupling – it generates opposite contributions to Λ and Λ̄ [2–4]. This difference provides a unique opportunity to determine the magnetic field created in heavy-ion collisions. In this note, we investigate the effect of the initial flow on the local Λ polarization within a

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(3+1)D viscous hydrodynamic model and the beam energy dependence of the global Λ polarization within A Multi-Phase Transport (AMPT) [12] model. This study deepens our understanding of the most vortical fluid ever produced [1].

2. Λ polarization from (3+1)D viscous fluid dynamics

We employ the CLVisc model [10, 13] to solve the energy-momentum conservation equation together with extended second-order Israel-Stewart equations for the shear viscosity,

$$\nabla_\mu T^{\mu\nu} = 0; \quad \Delta^{\mu\nu\alpha\beta} u^\lambda \nabla_\lambda \pi_{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - \eta\sigma^{\mu\nu}) - \frac{4}{3}\pi^{\mu\nu}\theta + 2\pi_\lambda^{\langle\mu}\omega^{\nu\rangle\lambda} - \frac{\lambda_3}{\tau_\pi}\omega_\lambda^{\langle\mu}\omega^{\nu\rangle\lambda} \tag{1}$$

with $T^{\mu\nu} \equiv \varepsilon u^\mu u^\nu - P\Delta^{\mu\nu} + \pi^{\mu\nu}$ being the energy-momentum tensor, ε the energy density, u^μ the fluid four-velocity normalized as $u_\mu u^\mu = 1$, P the pressure, $\Delta^{\mu\nu} \equiv g^{\mu\nu} - u^\mu u^\nu$ the transverse projector obeying $u_\mu\Delta^{\mu\nu} = 0$. The η is the shear viscosity, τ_π is the relaxation time, $\sigma^{\mu\nu} \equiv 2\Delta^{\mu\nu\alpha\beta}\nabla_\alpha u_\beta$ is the symmetric shear tensor, $\omega^{\mu\nu} \equiv \Delta^{\mu\alpha}\Delta^{\nu\beta}(\nabla_\alpha u_\beta - \nabla_\beta u_\alpha)$ is the anti-symmetric vorticity tensor and $\theta \equiv \nabla_\mu u^\mu$ is the expansion rate. $\Delta^{\mu\nu\alpha\beta} \equiv \frac{1}{2}(\Delta^{\mu\alpha}\Delta^{\nu\beta} + \Delta^{\mu\beta}\Delta^{\nu\alpha}) - \frac{1}{3}\Delta^{\mu\nu}\Delta^{\alpha\beta}$ is the double projector that renders the contracted tensor traceless and transverse to the fluid four-velocity. We observed that the coupling between $\pi^{\mu\nu}$ and $\omega^{\mu\nu}$ only introduces a small difference. The self-coupling term of $\omega^{\mu\nu}$ has an undetermined coefficient λ_3, which leads to a breakdown of the program for fluctuating initial conditions with $\lambda_3 = 1$. So these two terms are not included in the present work. The local polarization density on the freeze-out hyper-surface reads [11, 14],

$$P^\mu \equiv \frac{d\Pi^\mu(p)/d^3 p}{dN/d^3 p} = \frac{\hbar}{4m}\frac{\int d\Sigma_\alpha p^\alpha \Omega^{\mu\nu} p_\nu f(1-f)}{\int d\Sigma_\alpha p^\alpha f}, \tag{2}$$

where m is the fermion mass, $d\Sigma_\alpha$ is the hyper-surface determined by the freeze-out temperature $T_f = 0.137$ GeV, and $\Omega^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}\nabla_\rho\beta_\sigma$ is the thermal vorticity with $\beta_\sigma = u_\sigma/T$. Because of strong collectivity, the momentum distribution of the local polarization density is directly related to the local vorticity distribution in space-time [4].
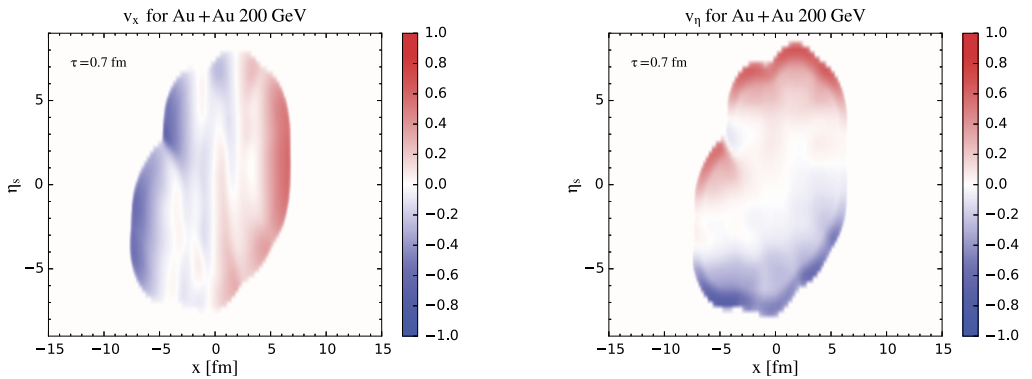

Fig. 1. The in-plane v_x and v_η distribution at $\tau = 0.7$ fm after fluid dynamic evolution from fluctuating initial energy density distributions at $\tau_0 = 0.4$ fm from AMPT model.

The AMPT model is employed to generate the initial energy density with the global angular momentum given by the asymmetry between forward and backward going participants separated by the impact parameter in the transverse plane. We start with the first assumption that at high beam energies there is only Bjorken flow at initial stage which leads to $v_x = v_y = v_\eta = 0$. In this case the deposited angular momenta are caused
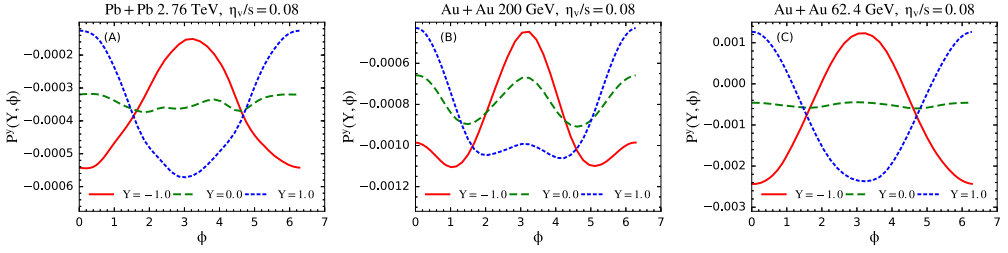
Fig. 2. The rapidity and azimuthal angle distribution of Λ spin projected to y direction for Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV (left), Au+Au $\sqrt{s_{NN}}$ = 200 GeV (middle) and Au+Au $\sqrt{s_{NN}}$ = 62.4 GeV (right) collisions.

by the asymmetric distribution of the matter for $x > 0$ (projectile side) and $x < 0$ (target side), for one specific space-time rapidity. This asymmetry is shown in Fig. 1. The local vorticity is 0 in the initial stage and generated during the fluid evolution. As shown in Fig. 2, the polarization are shifted to the $-y$ direction which is the direction of the global angular momentum. Locally, the azimuthal angle distribution for P^y has a cosine structure which indicates a vortex ring [10]. The helicity of the vortex ring is opposite for forward and backward rapidity. The polarization at mid-rapidity shows a weaker azimuthal angle dependence. The maximal magnitude of the polarization at 62.4 GeV is about 5 times that at 2.76 TeV.
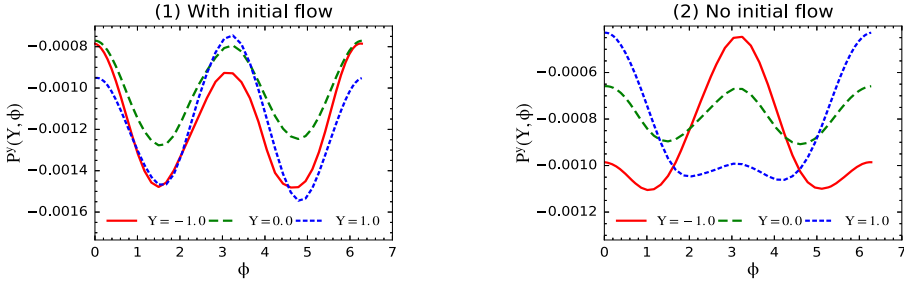

Fig. 3. The rapidity and azimuthal angle distribution of Λ spin projected to y direction P^y for (1) with initial transverse flow, (2) without initial transverse flow.

For comparison, we compute the local polarization of Λ by the CLVisc model with the initial transverse flow v_x and v_y given by the energy-momentum tensor $T^{\mu\nu}$ of initial partons by the AMPT. With this configuration, the deposited initial angular momenta are not only given by the matter asymmetry (between $x > 0$ and $x < 0$) but also by the v_x gradients along η. As a result, the local polarization at $\Phi = 0$ now has the similar magnitude to that at $\Phi = \pi$ as shown in Fig. 3. This dramatic change indicates that the local polarization of Λ hyperons around mid-rapidity may provide rigorous constraints on the initial transverse flow.

3. Global Λ polarization from AMPT

We also compute the energy dependence of the global Λ polarization within the AMPT model. The fluid velocity and vorticity field are computed from the event average of the four-momentum of all particles in each space-time cell. We consider two impact parameters $b = 7$ fm and 9 fm at each specific collision energy. The product of the vorticity field Ω_{zx} and the Λ distribution f_Λ is integrated over on the hyper-surface to obtain the global Λ polarization. The numerical result with both primary Λ and feed-down contributions

agrees with experimental data semi-quantitatively. The energy dependence is investigated in details using the distribution of f_Λ and Ω_{zx}. A visualization of these two quantities in the reaction plane indicates that the angular momentum deposition at mid-rapidity is quite small for high beam energies, which is consistent with the Bjorken scaling scenario. This scaling is broken for low beam energies with large asymmetry between the forward and backward going participants, which gives rise to a tilted shape at the mid-rapidity, see Ref. [15] for details.
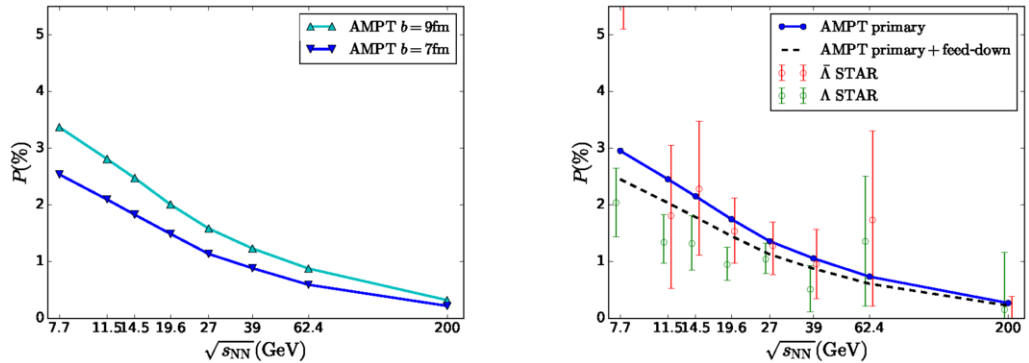
Fig. 4. (Left) The global polarization of Λ from AMPT model for 2 different impact parameters $b = 7$ fm and 9 fm (approximating $20 - 50\%$ collisions). (Right) The global polarization of Λ from AMPT model – the average results of $b = 7$ fm and $b = 9$ fm in the left panel, for with (dashed line) and without (solid line) feed-down contribution from Σ decay, vs. data from STAR [1].

4. Acknowledgements

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