Shear-induced spin polarization and "strange memory" in heavy-ion collisions

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Abstract. We discuss the theory of the spin polarizations induced by hydrodynamic gradients, which includes a newly discovered shear-induced polarization (SIP) term. In the phenomenological study using a hydrodynamic model, we discover that the local polarization contributed by SIP is substantial and has the "same sign" as the experimental measurements. Also, we find that the "sign" property of the local polarization observed in experiments seems to be related to "memory" effects on the polarizations of strange quarks in quark-gluon plasma.

1 Introduction

In the non-central ultra-relativistic heavy-ion collisions, a significant amount of orbital angular momentum is deposited into the quark-gluon plasma (QGP) created in these high-energy collisions. Considering the spin-orbit coupling, it has be proposed [1] that the orbital angular momentum of the rotating QGP could induce a global (spin) polarization of the hyperons. This global polarization has been observed later in the ground-breaking experiment [2] and the predictions using the thermal-vorticity formula [3–5] agree well with experimental measurements [6]. Besides the global polarization, there are proposals that the local structures of the hydrodynamic gradients [7–9] can lead to local spin polarization phenomena. However, the pattern of the local polarizations predicted [8] using thermal-vorticity formula demonstrate the "opposite sign" compared to experimental results [10, 11]. This discrepancy is sometimes called the "spin sign puzzle". On the other hand, it should be noted that the thermal-vorticity formula only has the temperature-gradient-induced and vorticity induced polarizations, while to our knowledge, the question that whether other hydrodynamic gradients, such as shear-stress tensor, could induce polarizations, has not been studied before. In the following, based on our recent works [12, 13], we will answer this question and elaborate the new formula of polarization including the newly discovered shear-induced polarization (SIP) term. Then, we will study the phenomenology of SIP, especially on local polarizations, and discuss the insights related to the "memory" effects on the strange quark polarizations in QGP phase.

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2 Theoretical formalism

The observables of the spin polarizations are closely related to the axial current in phase space $\mathcal{A}^\mu$. The expression of $\mathcal{A}^\mu$ can be obtained from a linear response theory or chiral kinetic theory, detailed in our recent works [12, 13]. Here, we will mainly discuss some extra physics and equivalent forms of $\mathcal{A}^\mu$, as well as its relations to the results in other works [14]. At first, we rewrite the final expression of $\mathcal{A}^\mu$ at momentum p^μ in Ref [13] as

$$\mathcal{A}^\mu = \frac{1}{2}n_0(1-n_0)\left\{\beta\epsilon^{\mu\nu\alpha\lambda}p_\nu\partial^\perp_\alpha u_\lambda + 2\epsilon^{\mu\nu\alpha\lambda}u_\nu p_\alpha\,\partial_\lambda\beta - 2\beta\frac{p_\perp^2}{\varepsilon_0}\epsilon^{\mu\nu\alpha\rho}u_\nu Q_\alpha^{\ \lambda}\sigma_{\rho\lambda}\right\} \tag{1}$$

where $\beta = 1/T$ is the inverse temperature and u^μ is flow velocity. The $n_0 \equiv n(\beta\varepsilon_0)$ with $n(x) = 1/(e^x+1)$ and $\varepsilon_0 = p\cdot u$. The projection of a generic vector V^μ is defined as $V^\mu_\perp = \Delta^{\mu\nu}V_\nu$ where $\Delta^{\mu\nu} = \eta^{\mu\nu} - u^\mu u^\nu$. Also, $Q^{\mu\nu} \equiv -p^\mu_\perp p^\nu_\perp/p^2_\perp + \Delta^{\mu\nu}/3$ is a quadrupole tensor and $\sigma^{\mu\nu} = \partial_\perp^{(\mu}u^{\nu)} - \Delta^{\mu\nu}\partial\cdot u/3$ is the shear strength tensor, where $\partial_\perp^{(\alpha}u^{\lambda)} \equiv (\partial^\alpha_\perp u^\lambda + \partial^\lambda_\perp u^\alpha)/2$.

The three terms in the "{...}" of Eq. (1) are vorticity-induced polarization (VoIP), T-gradient-induced polarization (TIP, spin Nernst effect) and shear-induced polarization (SIP). Since $(p^2_\perp/\varepsilon_0)\epsilon^{\mu\nu\alpha\rho}u_\nu Q_\alpha^{\ \lambda}\sigma_{\rho\lambda} \equiv \varepsilon_0^{-1}\epsilon^{\mu\nu\alpha\rho}u_\nu\, p_\rho p^\lambda\partial^\perp_{(\alpha}u_{\lambda)}$, both the TIP and SIP share a universal form $\epsilon^{\mu\nu\alpha\lambda}u_\nu p_\alpha\, F_\lambda$ where the "force" F_λ is proportional to either $\partial_\lambda\beta$ or $p^\alpha\partial^\perp_{(\lambda}u_{\alpha)}$ [15]. Thus, both of them can be understood as a generalized spin hall effects [16].

If we combine half of TIP with VoIP and another half of TIP with SIP, one can get another equivalent form with only two terms

$$\mathcal{A}^\mu = \frac{1}{2}n_0(1-n_0)\left\{\epsilon^{\mu\nu\alpha\lambda}p_\nu\partial_\alpha(\beta u)_\lambda - \frac{2}{\varepsilon_0}\epsilon^{\mu\nu\alpha\rho}u_\nu\, p_\rho p^\lambda\partial_{(\alpha}(\beta u)_{\lambda)}\right\}. \tag{2}$$

Note that the $\mathcal{A}^\mu$ will still stay the same if we replace all ∂_α by $\partial^\perp_\alpha$ in Eq. (2) since the superficial acceleration contributions ($(u\cdot\partial)u_\alpha$) in the first and second term in the "{...}" will cancel each other. This $\mathcal{A}^\mu$ is equivalent to the result in Ref [14] if we select the "medium rest frame" ($t^\mu = u^\mu$). The first term in the "{...}" is the thermal vorticity contribution. Analogically, $\partial_{(\mu}(\beta u)_{\nu)}$ is named as thermal-shear in Ref [14]. However, using the identity $(u\cdot\partial)u_\alpha = -\beta^{-1}\partial^\perp_\alpha\beta + O(\partial^2)$ from ideal hydrodynamic equation, we can get another equivalent form of $\mathcal{A}^\mu$ as

$$\mathcal{A}^\mu = \frac{1}{2}n_0(1-n_0)\left\{\epsilon^{\mu\nu\alpha\lambda}p_\nu\partial_\alpha(\beta u)_\lambda - \beta\frac{2}{\varepsilon_0}\epsilon^{\mu\nu\alpha\rho}u_\nu\, p_\rho p^\lambda\sigma_{\alpha\lambda}\right\}. \tag{3}$$

The $(u\cdot\partial)u_\alpha$ and the $\partial_\alpha\beta$ in the second term of Eq. (2) will cancel each other. Thus, only the shear part $\beta\,\sigma_{\alpha\lambda}$ out of the thermal-shear $\partial_{(\mu}(\beta u)_{\nu)}$ truly contributes to the polarization at the leading order of gradients in our framework.

With the expressions of $\mathcal{A}^\mu$, we employ the freezeout formula as that used in Ref [3]

$$P^\mu(\boldsymbol{p}) = \frac{\int d\Sigma^\alpha p_\alpha\,\mathcal{A}^\mu(x,\boldsymbol{p};m)}{2m\int d\Sigma^\alpha p_\alpha n(\beta\varepsilon_0)} \tag{4}$$

to convert the $\mathcal{A}^\mu$ into the polarization P^μ related to experimental observables.

3 Phenomenological study

We employ the 3+1-d hydrodynamics (MUSIC + AMPT initial conditions) used in Ref [17] to study the phenomenology in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV, where the local polarizations of P_z (beam direction) and $(-P_y)$ (out-plane direction) are calculated for **two scenarios**. In the "Lambda equilibrium" scenario, we will calculate the Lambda polarization in the early hadronic phase using the mass $m = 1.116$ GeV. In the "strange memory" scenario, we will calculate the strange quark polarization P_s at the late QGP phase with an effective mass $m = 0.3$ GeV. The chemical freezeout condition is $E_f = 0.65\,\mathrm{GeV/fm}^3$ ($T_f \sim 165$ MeV) for both scenarios, where the qualitative features of the results remain the same with a different choice of E_f or T_f within the reasonable range. We will further illustrate the physics of the two scenarios later in the context of the phenomenological results.

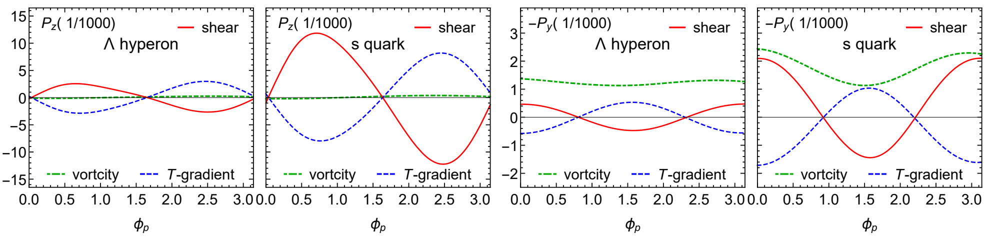

Figure 1. The P_z and $(-P_y)$ of VoIP (vorticity), TIP (T-gradient), SIP (shear) for two scenarios.

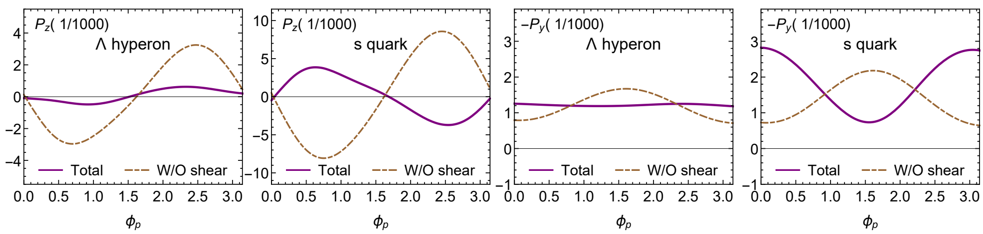

Figure 2. The P_z and $(-P_y)$ of the total (Total) and the total without SIP (W/O shear) for two scenarios. The "W/O shear"≈ "thermal-vorticity induced polarization" considering $(u \cdot \partial)u_\alpha = -\beta^{-1}\partial^\perp_\alpha \beta + O(\partial^2)$.

The Fig. 1 demonstrates how the three terms (VoIP, TIP, SIP) defined in Eq. (1) contribute to local polarizations. In both scenarios, the VoIP is the dominant contribution to the global polarizations (in y direction), but it does not strongly affect the shapes of local polarizations. The shapes of the local polarizations are mostly influenced by TIP and SIP. In all scenarios and directions, the local polarizations from TIP always has the "opposite sign" but those from SIP always has the "same sign" as compared to those observed in experiments [10, 11]. The competitions between TIP and SIP determine the sign of the total local polarizations, which are sensitive to the mass of the spin carrier because the factor $|p_\perp^2|/\varepsilon_0^2$ in SIP term (see Eq. (1)) will enhance with a smaller mass. Thus, in Fig. 2, the total local polarizations in "Lambda equilibrium" scenario have the "opposite sign", while those in "strange memory" scenario (smaller mass) have the "same sign". Note that without SIP, results from both scenarios are of the "opposite sign" and qualitatively similar. It is the SIP that makes a difference. The SIP not only seems to be essential for understanding the "spin sign puzzle" but also provides us opportunities to distinguish the physics behind these two scenarios as discussed below.

The "Lambda equilibrium" scenario assumes the Lambda polarizations are fully equilibrated in hadronic phase, representing the conventional statistical hadronization model (SHM) in the spin physics. In this scenario, we get the overall "opposite sign" (Fig. 2) and do not find any case showing the "same sign" when we repeat the calculations using many different choices of model parameters/setups in our robustness tests. This "opposite sign" behavior in conventional SHM of polarizations has also been confirmed in Ref [18]. Probably, some physics beyond the conventional SHM are important for understanding this local polarization problem. On the other hand, beside SHMs, quark-recombination models (QRMs) are also widely-used in hadronization problems, where a well-known QRM [1] derives a relation $P_\Lambda = P_s$. If we accept this QRM and neglect the evolution of polarizations in hadronic phase, P_Λ observed in experiments is just P_s at the end of the QGP phase, which is an off-equilibrium effect and can be interpreted as the Lambda's (full) "memory" on P_s. In this "strange memory" scenario illustrated above, the local polarizations demonstrate the "same sign". Definitely, the results of the two scenarios are not the final answer to the "spin sign puzzle". Instead, we would like this comparative study provides us some motivations to go beyond the conventional SHM and to develop more microscopic and dynamic models on hadronization and hadronic evolution of the spin physics in heavy-ion collisions.

4 Summary and perspective

We discover a new mechanism–shear-induced polarization (SIP) to generate spin polarization in a fluid. For the first time, the phenomenology of this SIP in heavy-ion collisions has been studied. We find that local polarization from SIP is a major contribution and always has “same sign" as those observed in the experiment. In the study of the two scenarios, we found that without SIP, none of the scenarios can have the "same sign". Including SIP effect, the local polarization still has the "opposite sign" in "Lambda equilibrium" scenario assuming equilibrated Lambda in hadronic phase. On the other hand, in "strange memory scenario" assuming that Lambda hyperon inherits and memorizes the polarization of the strange quarks, the SIP surpasses TIP and the resulting local polarizations demonstrate the "same sign".

As suggested by the study of the two scenarios, we need to develop a sophisticated hadronization model and hadronic spin transport model to obtain quantitative understandings. As discussed [13, 19, 20], the spin polarizations are potentially the probes for many interesting physics in heavy-ion collisions. Quantitative frameworks are indispensable for these tasks. To further improve our understandings, we probably also need to study the spin transports [21, 22] or spin hydrodynamics [23] in QGP, as well as the non-perturbative effects on the spin physics.

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