Evolution of Λ polarization in the hadronic phase of heavy-ion collisions

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Using the AMPT+MUSIC+URQMD hybrid model, we study the global and local spin polarizations of Λ hyperons as functions of the freeze-out temperature of the spin degree of freedom in the hadronic phase of Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV. Including contributions from both the thermal vorticity and thermal shear of the hadronic matter, we find that with the spin freeze-out temperature dropping from the hadronization temperature of 160 MeV to 110 MeV at the kinetic freeze-out, both the global and local spin polarizations of Λ hyperons due to the thermal vorticity decrease by a factor of 2, while those due to the thermal shear decrease quickly and become negligibly small at 140 MeV. Our results thus suggest that it is important to take into account the evolution of the spin degree of freedom in the hadronic stage of relativistic heavy-ion collisions when theoretically predicted global and local Λ spin polarizations are compared with the experimental measurements.

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I. INTRODUCTION

In noncentral heavy ion collisions at relativistic energies, a large amount of orbital angular momentum from the two colliding nuclei is transferred to the produced quark-gluon plasma (QGP), creating thus the most vortical fluid, of the order of 10^{21}–10^{22} s^{-1}, in known physical systems [1–7]. Due to their spin-orbit interactions, quarks in the QGP and Λ hyperons formed after the hadronization become polarized along the direction of the total orbital angular momentum [8,9], as observed in experiments by the STAR Collaboration [1,10]. Because of the nonuniformity of the vorticity field, local structures in the Λ spin polarization have also been found both in theoretical studies [11–13] and in experimental measurements [14]. Although various theoretical models, such as those based on the hydrodynamic approach [15–21], the transport approach [13,22–25], and the nonequilibrium chiral kinetic approach [26–28], have successfully described the measured Λ global spin polarization, most of them have failed to explain the measured Λ local spin polarizations. A plausible explanation of the latter has been provided in the chiral kinetic approach through the induced quadrupolar axial charge distribution in the transverse plane of a heavy ion collision [27,28]. Also, it has recently been pointed out that including the thermal shear contribution, in addition to that from the usual thermal vorticity, in the fluid dynamic approach can potentially describe the measured azimuthal angle dependence of Λ local spin polarizations [29–32]. Indeed, the correct azimuthal angle dependence is obtained in the "strange memory" scenario of Ref. [33], which assumes that the Λ spin polarization is identical to its strange quark spin polarization as in the quark coalescence model for Λ production [26], after including contributions from both thermal vorticity and thermal shear. A similar result can also be achieved in the "isothermal local equilibrium" scenario of Ref. [34], in which particlization is assumed to take place at a constant temperature to eliminate the contribution from its space-time gradients in the calculation of the thermal vorticity and shear [34]. In these hydrodynamic studies, the Cooper-Frye formula used for particlization only includes the conversion of fluid angular momentum into particle spins at certain decoupling temperature without taking into account of the spin current in the fluid, which requires a further modification of the Cooper-Frye formula [35] or the use of the quark coalescence model [26,36] to take into account explicitly the spin polarization of the quarks in the QGP.

In almost all these theoretical studies, the Λ spin polarization in a heavy ion collision is calculated at the end of the partonic phase and compared to experimental measurements. Since the strength of the vorticity field decreases as the hadronic matter expands [3], it is of interest to study how the Λ polarization changes during the hadronic evolution of heavy ion collisions. In this work, we study the time evolution of the global and local Λ spin polarizations during the expansion of the hadronic matter produced in noncentral Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV by using the MUSIC+URQMD hybrid model. Because of the lack of a dynamical description of the

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spin degree of freedom in the hadronic transport model, we assume that they are in thermal equilibrium with the vorticity field in the expanding hadronic matter and study the dependence of Λ spin polarizations on the temperature.

The paper is organized as follows: In Sec. II, we discuss the relations between the spin polarization of a spin-1/2 fermion and the thermal vorticity and shear in a hadronic matter. We then present the numerical results from our study on the global and local spin polarization of Λ hyperons at different freeze-out temperatures for the spin degree of freedom. Finally, a brief conclusion and discussion is given in Sec. IV.

II. SPIN POLARIZATION OF A FERMION IN THERMAL EQUILIBRIUM

The spin polarization of a fermion in a thermal medium of temperature T depends on the four-temperature vector $\beta = u/T$, where u is the four-flow velocity of the local medium. To the leading order in the gradient of β, the spin polarization vector S of a fermion of mass m and four-momentum p at four space-time coordinate x can be written as [29–32]

$$S^\mu(x,p) = -\frac{1}{8m}(1-n_F)\epsilon^{\mu\nu\rho\sigma}p_\nu\varpi_{\rho\sigma}(x) - \frac{1}{4m}(1-n_F)\epsilon^{\mu\nu\rho\sigma}p_\nu\frac{n_\rho p^\lambda\xi_{\lambda\sigma}(x)}{n\cdot p}. \quad (1)$$

In the above,

$$\varpi_{\rho\sigma} = \tfrac{1}{2}(\partial_\sigma\beta_\rho - \partial_\rho\beta_\sigma), \quad \xi_{\rho\sigma} = \tfrac{1}{2}(\partial_\sigma\beta_\rho + \partial_\rho\beta_\sigma) \quad (2)$$

are the thermal vorticity and thermal shear of the medium, respectively, n_F is the Fermi-Dirac distribution function, and n is a unit four-vector that specifies the frame of reference. Although different forms of S^μ are used in Refs. [29–32], they all become the same if n is taken to be the flow field u in the fluid, which we adopt in this work. Our calculation using Eq. (2) is similar to that in Ref. [33] but different from that based on the assumption of isothermal local equilibrium adopted in Ref. [34], where both the spatial and temporal gradients of the temperature are neglected, i.e., only contributions from the kinetic vorticity and shear are included.

By decomposing the two terms in Eq. (1) into the two components

$$\boldsymbol{\varpi}_T = \frac{1}{2}\left[\nabla\left(\frac{u^0}{T}\right) + \partial_t\left(\frac{\boldsymbol{u}}{T}\right)\right] - u^0\boldsymbol{f} + \boldsymbol{u}f^0,$$
$$\boldsymbol{\varpi}_S = \frac{1}{2}\nabla\times\left(\frac{\boldsymbol{u}}{T}\right) + \boldsymbol{u}\times\boldsymbol{f}, \quad (3)$$

with

$$u^0 = \gamma, \quad \boldsymbol{u} = \gamma\boldsymbol{v},$$
$$f^0 = \frac{p^\lambda\xi_{0\lambda}}{u\cdot p}, \quad \boldsymbol{f} = -(f_1, f_2, f_3), \quad f_i = \frac{p^\lambda\xi_{i\lambda}}{u\cdot p}, \quad (4)$$

Eq. (1) can be rewritten as

$$S^0(x,p) = \frac{1}{4m}\boldsymbol{p}\cdot\boldsymbol{\varpi}_S,$$
$$\boldsymbol{S}(x,p) = \frac{1}{4m}(E_p\boldsymbol{\varpi}_S + \boldsymbol{p}\times\boldsymbol{\varpi}_T), \quad (5)$$

where $E_p = \sqrt{m^2+\boldsymbol{p}^2}$ and $\boldsymbol{p}$ are, respectively, the temporal and spatial components of the four-momentum p.

Boosting the spin vector S^μ in the fluid frame to the rest frame of the particle, one finds the spin polarization $\boldsymbol{P}$ of a spin-1/2 particle measured in experiments to be

$$\boldsymbol{P} = 2\left[\boldsymbol{S} - \frac{\boldsymbol{p}\cdot\boldsymbol{S}}{E_p(E_p+m)}\boldsymbol{p}\right]. \quad (6)$$

III. NUMERICAL RESULTS

To study the evolution of Λ spin polarization in the hadronic phase of a heavy ion collision, we first use the MUSIC hydrodynamic model [37] with the initial conditions taken from a multiphase transport (AMPT) model [38] to simulate the QGP phase of the collision. After converting the fluid elements on the freeze-out hypersurface into hadrons by the Cooper-Frye formula, we adopt the URQMD model [39,40] to simulate the evolution of these hadrons due to their scatterings. This hybrid approach has successfully described various soft hadronic observables, such as the charged particle yields as well as their transverse momentum spectra and flow anisotropies in relativistic heavy ion collisions at energies available at both the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC) [41–43].

To determine the local temperature and flow field as well as their temporal and spacial gradients in the hadronic matter, we use the coarse-grained method with the time step $\Delta t = 0.5$ fm/c and the cell size $\Delta x = \Delta y = 0.5$ fm and $\Delta\eta = 0.2$, where $\eta = \frac{1}{2}\ln\frac{t+z}{t-z}$ is the space-time rapidity. In this method, the temperature T of a local cell is calculated from the energy density in the cell at its rest frame by using the equation of state from the lattice QCD calculations [44]. The flow field $\boldsymbol{v}$ in a cell of volume ΔV, i.e., the hadron number current $J^\mu = \frac{1}{\Delta V}\sum p_i^\mu/E_i$ in the cell, can be calculated from the average velocity of the N hadrons in the cell according to

$$\boldsymbol{v}(t,x,y,z) = \frac{\sum_i \frac{\boldsymbol{p}_i}{E_i}}{N}, \quad (7)$$

where $\mathbf{p}_i$ and E_i are the momentum and energy of the ith hadron in the cell. For hadrons in local thermal equilibrium, it gives the same velocity in the energy-momentum tensor that is used in hydrodynamic calculations.

To illustrate how Λ spin polarizations are affected by the temperature at which the spin degrees of freedom freeze-out in relativistic heavy ion collisions, we consider in the present study Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV and 20–60% centrality. As in the experimental measurements at RHIC by the STAR Collaboration [14], we only include Λ hyperons of $|\eta| < 1$ and $p_T > 0.15$ GeV/c in our analysis. In Fig. 1, we first show by the solid red line the global spin polarization of Λ ($\overline{\Lambda}$) hyperons calculated from the thermal vorticity along the direction of the total angular momentum of the hadronic matter as a function of the local temperature in the hadronic matter. It is seen that if the spin degree of freedom freezes out at $T_s = 160$ MeV, which is usually assumed in the literature [21,22,26] as mentioned in the Introduction, the Λ global polarization is 5.3×10^{-3} and is close to the value in Ref. [21] based on the same AMPT+MUSIC hybrid approach

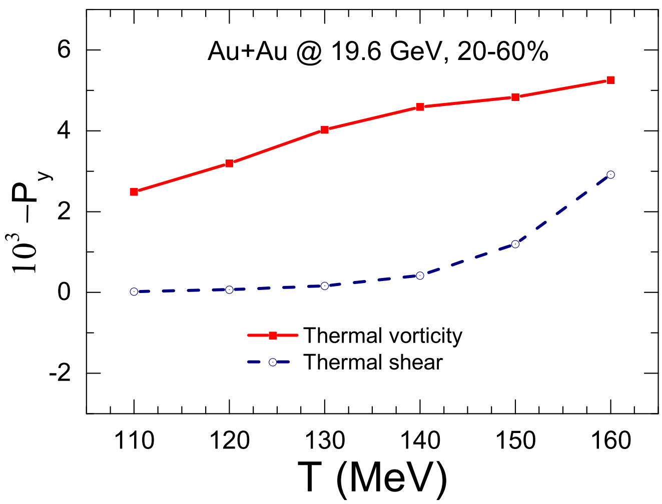

FIG. 1. Spin freeze-out temperature dependence of Λ hyperon spin polarization along the total angular momentum direction due to the thermal vorticity and the thermal shear in an expanding hadronic matter.

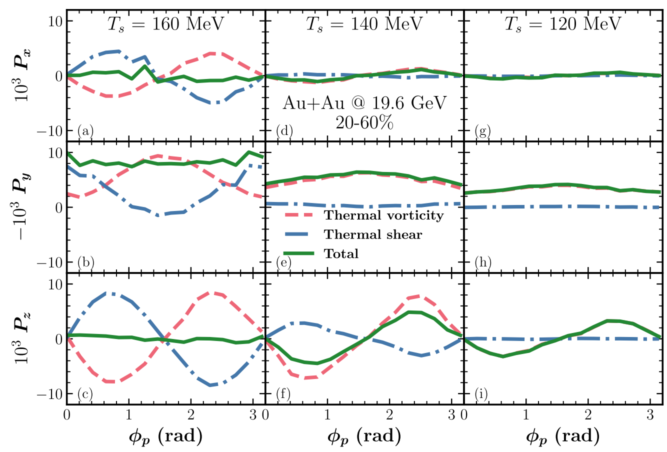

FIG. 2. The azimuthal angle dependence of the local spin polarizations P_x, $-P_y$, and P_z of Λ hyperons generated by thermal vorticity and thermal shear at the spin freeze-out temperatures T_s =160, 140, and 120 MeV.

without the URQMD afterburner. With decreasing temperature as the hadronic matter expands, the Λ global spin polarization decreases to 2.5×10^{-3} at the kinetic freeze-out temperature of $T_s = 110$ MeV, when hadron momentum spectra and anisotropies stop changing. The above result thus shows that the Λ global spin polarization has a strong temperature dependence in the expanding hadronic matter if it continues to be in thermal equilibrium.

Shown by the blue dashed line in Fig. 1 is the Λ global spin polarization generated by the thermal shear in the hadronic matter, i.e., the second term in the right-hand side of Eq. (1), as a function of local temperature. It is seen that at $T_s =$ 160 MeV, the Λ global polarization due to the thermal shear is about $2.9 \times 10^{-3}$and is slightly less than half of that due to the thermal vorticity. We note that the total spin polarization of Λ hyperons due to the thermal shear should have been zero without the cut of $p_T \geqslant 0.15$ GeV/c and $|\eta| < 1$ in the Λ momentum and space-time rapidity. With decreasing spin freeze-out temperature, the Λ global spin polarization due to the thermal shear decreases faster compared to that due to the thermal vorticity, and it becomes negligible at $T_s = 140$ MeV.

The local spin polarization of Λ hyperons, as a function of its azimuthal angle in the transverse plane of a heavy ion collision, was recently extensively studied [12,14,27,28]. It is found in Refs. [33,34] that both thermal vorticity and thermal shear are important in determining the local spin polarization. In the left panels (a), (b), and (c) of Fig. 2 we show, respectively, the spin polarizations P_x, $-P_y$, and P_z of Λ hyperons generated by the thermal vorticity (red dashed lines) and the thermal shear (blue dash-dotted lines) as functions of the azimuthal angle ϕ_p of the Λ transverse momentum if the spin degree of freedom freezes out at $T_s = 160$ MeV. It is seen that $-P_y$ (left-middle panel) and P_z (left-lower panel) have the forms of $-\cos(2\phi_p)$ and $-\sin(2\phi_p)$, respectively, due to the thermal vorticity and $\cos(2\phi_p)$ and $\sin(2\phi_p)$, respectively, due to the thermal shear, which are similar to the findings in Refs. [31,33,34]. However, such an oscillatory azimuthal angle dependence essentially disappears in the total Λ local spin polarizations P_y and P_z after adding the two contributions, which disagrees with the experimental measurements [14], unless one adopts either the "strange memory" scenario as in Ref. [33] or the "isothermal local equilibrium" scenario as in Ref. [34]. In the present work, we focus on the effect of hadronic evolution on the Λ spin polarization and postpone the study of the above two scenarios for future work.

In the left-upper panel (a) of Fig. 2, we also show for the first time the azimuthal angle dependence of P_x generated by the thermal vorticity and thermal shear. It is seen that P_x has the form of $-\sin(2\phi_p)$ due to the thermal vorticity and the form of $\sin(2\phi_p)$ due to the thermal shear. The total P_x after adding the two oscillatory contributions is, however, negligible.

In Fig. 3, we further show the Λ spin polarization generated by individual components of the thermal shear. We find that the main contribution to $-P_y$ is from the ξ_{13} component and that to P_z is from the ξ_{11} and ξ_{22} components. According to Eqs. (3), (5), and (6), ξ_{13} contributes to $-P_y$ through a term of the form $p_x^2\xi_{13} \propto [1+\cos(2\phi_p)]\xi_{13}$. For P_z, the contribution from ξ_{11} and ξ_{22} is through a term of the form $p_x p_y(\xi_{11}-\xi_{22}) \propto \sin(2\phi_p)(\xi_{11}-\xi_{22})$, where $(\xi_{11}-\xi_{22})$ is positive because of the positive elliptic flow of the hadronic matter in noncentral Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV.

We have also studied the azimuthal angle dependence of the spin polarization of Λ hyperons generated by the thermal vorticity and thermal shear at a lower temperature of $T_s = 140$ MeV during the later stage of the hadronic evolution by assuming that the spin degree of freedom remains in thermal equilibrium. As shown by the red dashed lines in the middle panels (d), (e), and (f) of Fig. 2, P_x, $-P_y$, and P_z generated by the thermal vorticity at this temperature have the same azimuthal angle dependence as those at $T_s = 160$ MeV. Although P_x and $-P_y$ become smaller at the lower temperature,

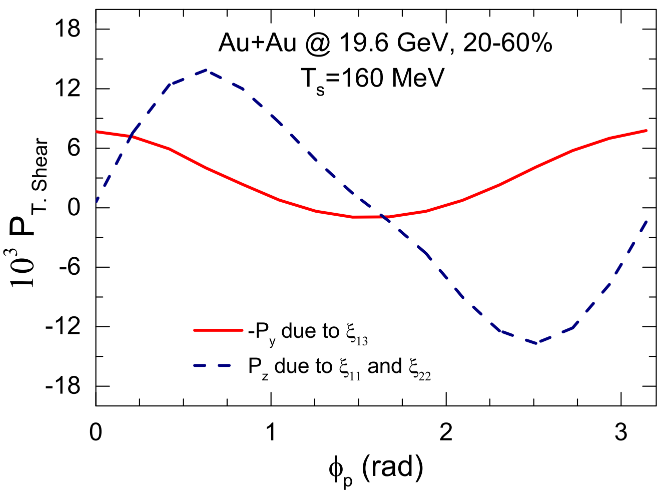

FIG. 3. Azimuthal angle dependence of Λ spin polarization generated by components of the thermal shear at the spin freeze-out temperature $T_s = 160$ MeV.

P_z does not change much with temperature. For the contribution from the thermal shear at $T_s = 140$ MeV, P_x and $-P_y$ become negligible, while P_z decreases by a factor of 3 as shown by the blue dash-dotted lines. By adding contributions from both thermal vorticity and thermal shear, P_x and P_z have the form of $-\sin(2\phi_p)$ and P_y has the form of $-\cos(2\phi_p)$. These results suggest that the Λ local spin polarization depends strongly on its evolution during the hadronic phase of heavy ion collisions.

Finally, we consider an even lower temperature of $T_s =$ 120 MeV, corresponding approximately to the kinetic freeze-out of the expanding hadronic matter, and the results are shown in the right panels (g), (h), and (k) of Fig. 2. It is seen from the red dashed lines that the Λ local spin polarizations P_x, $-P_y$, and P_z generated by the thermal vorticity become even smaller, although they have the same ϕ_p dependence as that at higher temperatures. However, for the Λ spin polarization generated by the thermal shear, its values along all directions x, y, and z become negligibly small. Thus, the total P_x, $-P_y$, and P_z have the same ϕ_p dependence as that at $T_s = 140$ MeV, albeit somewhat smaller.

IV. CONCLUSION AND DISCUSSION

Using the AMPT model initial conditions in the MUSIC hydrodynamic model for the QGP phase, which is followed by the URQMD model for the hadronic phase in relativistic heavy ion collisions, we have studied in this paper the global and local spin polarizations of Λ hyperons as functions of the freeze-out temperature of the spin degree of freedom in the hadronic phase. We have found that both the Λ global and local spin polarizations due to the thermal vorticity decrease by a factor of 2 if the spin freeze-out temperature drops from 160 to 140 MeV, while those due to the thermal shear already becomes negligibly small at temperature equal to 140 MeV. Our result is similar to that found in Ref. [34] based solely on the hydrodynamic model and using the Cooper-Frye formula to convert the vorticity and shear of the fluid to particle spins at decreasing decoupling temperatures. The decreasing contribution of the thermal vorticity and shear to both Λ global and local spin polarizations with decreasing temperature is thus a generic feature of the expanding matter produced in relativistic heavy ion collisions, if the spin degrees of freedom remain in thermal equilibrium during the expansion. This result therefore suggests the importance of including in theoretical studies the dynamical evolution of the spin degrees of freedom and their freeze-out in the expanding hadronic matter when the predicted global and local Λ spin polarizations are compared with the experimental measurements. Such a study requires a hadronic transport model that takes into account explicitly the spin degrees of freedom of hadrons, as in Refs. [45–49] on the nucleon spin transport in heavy ion reactions at lower energies, which we plan to study in the future.

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