Global polarization of QGP in non-central heavy ion collisions at high energies

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Abstract.
Due to the presence of a large orbital angular momentum of the parton system produced at the early stage of non-central heavy-ion collisions, quarks and anti-quarks are shown to be polarized in the direction opposite to the reaction plane which is determined by the impact-parameter and the beam momentum. The global quark polarization via elastic scattering was first calculated in an effective static potential model, then using QCD at finite temperature with the hard-thermal-loop re-summed gluon propagator. The measurable consequences are discussed. Global hyperon polarization from the hadronization of polarized quarks are predicted independent of the hadronization scenarios. It has also been shown that the global polarization of quarks and anti-quarks leads also to spin alignment of vector mesons. Dedicated measurements at RHIC are underway and some of the preliminary results are obtained. In this presentation, the basic idea and main results of global quark polarization are presented. The direct consequences such as global hyperon polarization and spin alignment are summarized.

1. Introduction
We all know that spin is a basic degree of freedom of the elementary particles. Spin effects in high energy reactions usually provide us with useful information on the reaction mechanism and often give us surprises. Such effects have been studied intensively in high energy lepton-hadron, hadron-hadron, and hadron-nucleus collisions and lead to an active field of High Energy Spin Physics. In contrast, less study has been made in this direction in high energy heavy-ion collisions. One of the reasons might be that it would be very difficult or even impossible to polarize a heavy ion beam. Recent studies [1-3] have shown that hadrons can be polarized w.r.t. the reaction plane in high energy AA collisions with unpolarized beams. This is one of the places where we can study spin effects without a polarized beam and I hope that my talk can serve as an example which shows you, by looking at the spin degree of freedom, one can obtain some interesting information on the reaction mechanisms, even in heavy ion collision.
2. Global orbital angular momentum and shear flow

We consider two colliding nuclei with the projectile of beam momentum $\vec{p}_{in}$ moving in the direction of the $z$ axis, as illustrated in Fig. 1. The impact parameter $\vec{b}$ is taken as $\hat{x}$-direction. The normal $\vec{n}_b \propto \vec{p}_{in} \times \vec{b}$ of the reaction plane is taken as $\hat{y}$. For a non-central $AA$ collision, the dense matter system in the overlapped region will carry a global orbital angular momentum $L_y$ in the direction $-\hat{y}$. The magnitude of $L_y$ is estimated using a hard spherical distribution for nucleus and is given in Fig. 2a. We see that $-L_y$ is indeed huge and is of the order of $10^5$ at most $b$’s.

![Figure 1. Illustration of non-central AA collision with impact parameter $\vec{b}$. The global angular momentum of the produced matter is along $-\hat{y}$, opposite to the reaction plane.](image)

![Figure 2. a (left), The global orbital angular momentum $L_y$ of the overlapping system in a non-central AA collision at RHIC energy as a function of the impact parameter $b$; b (right), The average orbital angular momentum of two neighboring partons separated by $\Delta x = 1$fm as a function of $x/(R_A - b/2)$ for different values of $b/R_A$.](image)

Assuming that a partonic system is formed immediately after the initial collision, interactions among the produced partons will lead to the formation of a quark-gluon plasma (QGP) with both transverse (in $x$-$y$ plane) and longitudinal collective motion. The existence of the global orbital angular momentum of the system discussed above implies a finite transverse (along $\hat{x}$) gradient of the longitudinal flow velocity.

The initial collective longitudinal momentum can be calculated as the total momentum difference between participant projectile and target nucleons. Since the measured total multiplicity in $AA$ collisions is proportional to the number of participant
nucleons, we can assume the same for the produced partons with a proportionality constant \( c(s) \) at a given center of mass energy \( \sqrt{s} \). Hence, the average collective longitudinal momentum per parton is given by,

\[
p_z(x, b; \sqrt{s}) = \frac{\sqrt{s}}{2c(s)} \frac{dN^P_{\text{part}}/dx - dN^T_{\text{part}}/dx}{dN^P_{\text{part}}/dx + dN^T_{\text{part}}/dx}.
\]

\( p_z(x, b; \sqrt{s}) \) is a monotonically increasing function of \( x \). This can be seen more clearly by looking at the derivative \( dp_z/dx \), which is almost a constant for different \( x \). From \( dp_z/dx \), we can estimate the average longitudinal momentum difference \( \Delta p_z \) between two neighboring partons separated by a transverse interval. On the average, the relative orbital angular momentum for two partons separated by \( \Delta x \) in the transverse direction is given by \( l_y = -(\Delta x)^2 dp_z/dx \). E.g., for \( Au + Au \) at \( \sqrt{s} = 200 \text{ GeV} \), \( c(s) \approx 45 \), \( l_y \) for \( \Delta x = 1\text{fm} \) is shown in Fig. 2b. We see that \( l_y \) is in general of the order of 1 and is larger than the spin of a quark. This implies that the effect can indeed be very significant.

We emphasize that the results given in Fig. 2 correspond to the average over rapidity, and in principle, we should consider the distribution of such collective longitudinal momentum over rapidity. This kind of distribution has been discussed e.g. by Adil and Gyulassy in their study on jet tomography of twisted QGP, and can also be calculated e.g. using HIJING. If we take this distribution into account and consider that partons with slightly different rapidities can also interact with each other, we will still obtain a non-vanishing vorticity for the interacting parton system. Here, the final relevant quantity should be the local (both in transverse separation and in rapidity \( \eta \)) derivative of the longitudinal momentum distribution. The average results presented above can only serve as a guide for the magnitude of this effect. In the following, we will discuss the polarization effects caused by such local vorticity.

3. Global quark polarization w.r.t. the reaction plane

To see whether the local orbital angular momentum between the neighboring partons in a QGP can be converted to quark polarization via parton scattering, we consider quark scattering at fixed impact parameter. For definiteness, we consider a non-identical quark-quark scattering \( q_1(P_1, \lambda_1) + q_2(P_2, \lambda_2) \rightarrow q_1(P_3, \lambda_3) + q_2(P_4, \lambda_4) \), where \( P_i = (E_i, \vec{p}_i) \) and \( \lambda_i \) denote the 4-momentum and spin of the quark respectively. We start with the usual cross section in momentum space,

\[
d\sigma_{\lambda_3} = \frac{c_{qq}}{F} \frac{1}{4} \sum_{\lambda_1, \lambda_2, \lambda_4} \mathcal{M}(Q) \mathcal{M}^*(Q) (2\pi)^4 \delta(P_1 + P_2 - P_3 - P_4) \frac{d^3\vec{p}_3}{(2\pi)^3 2E_3} \frac{d^3\vec{p}_4}{(2\pi)^3 2E_4},
\]

where \( \mathcal{M}(Q) \) is the scattering amplitude in momentum space, \( Q = P_3 - P_1 = P_2 - P_4 \) is the 4-momentum transfer, \( c_{qq} = 2/9 \) and \( F \) are the color and flux factors, respectively. The cross section in impact parameter space is obtained by making a two dimensional Fourier transformation of the transferred transverse momentum \( \vec{q}_T \), i.e.,

\[
\frac{d\sigma_{\lambda_3}}{d^2\vec{x}_T} = \frac{c_{qq}}{16 F} \sum_{\lambda_1, \lambda_2, \lambda_4} \int \frac{d^2\vec{q}_T}{(2\pi)^2} \frac{d^2\vec{k}_T}{(2\pi)^2} e^{i(\vec{x}_T - \vec{q}_T) \cdot \vec{k}_T} \mathcal{M}(\vec{q}_T) \mathcal{M}^*(\vec{k}_T) \frac{\Lambda(M)}{\Lambda^*(M)},
\]
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where $\mathcal{M}(\vec{q}_T)$ and $\mathcal{M}(\vec{k}_T)$ are the scattering matrix elements in momentum space with 4-momentum transfer $Q = (0, \vec{q})$ and $K = (0, \vec{k})$ respectively, $\Lambda(\vec{q}_T) = \sqrt{(E_1 + E_2)[p + q_z]}$ is a kinematic factor. The differential cross section can be divided into a spin-independent and a spin dependent part, i.e.,

$$
\frac{d\sigma}{d^2\vec{x}_T} = \frac{d\sigma}{d^2\vec{x}_T} + \lambda_3 \frac{d\Delta\sigma}{d^2\vec{x}_T} \tag{4}
$$

Parity conservation demands that they have the following form,

$$
\frac{d\sigma}{d^2\vec{x}_T} = F(x_T, \sqrt{s}), \quad \frac{d\Delta\sigma}{d^2\vec{x}_T} = \vec{n} \cdot (\vec{x}_T \times \vec{p}) \Delta F(x_T, \sqrt{s}), \tag{5}
$$

where $\vec{n}$ is the polarization vector for $q_1$ in its rest frame. $F(x_T, \sqrt{s})$ and $\Delta F(x_T, \sqrt{s})$ are both functions of $x_T \equiv |\vec{x}_T|$ and the energy $\sqrt{s}$ of the quark-quark system. This is because, in an unpolarized reaction, the cross section should be independent of any transverse direction. For the spin-dependent part, the only scalar that we can construct from the vectors that we have at hand is $\vec{n} \cdot (\vec{p} \times \vec{x}_T)$.

We note that, $\vec{x}_T \times \vec{p}$ is nothing else but the relative orbital angular momentum of the $q_1 q_2$-system, i.e., $\vec{x}_T \times \vec{p} = \vec{l}$. We see from Eq.(5) that the cross section takes its maximum $\vec{n}$ is parallel to $\vec{l}$ or $-\vec{l}$ depending on whether $\Delta F$ is positive or negative. This corresponds to a polarization of quark in the direction $\vec{l}$ or $-\vec{l}$.

As discussed in last section, for $AA$ collisions with given reaction plane, the direction of the averaged $\vec{l}$ of the two scattered quarks is given. Since a given direction of $\vec{l}$ corresponds to a given direction of $\vec{x}_T$, this implies that there should be a preferred direction of $\vec{x}_T$ over others at a given direction of $\vec{l}$. The detailed distribution of $\vec{x}_T$ at given $\vec{l}$ depends on the collective longitudinal momentum distribution discussed above.

The polarization of the quark after one scattering is given by, $P_q = \Delta\sigma/\sigma$.

### 3.1. Results under small angle approximation

The calculations are in principle straightforward but in practice very much complicated. Hence, in Ref.[1], we have given an example by calculating them using a screened static potential model and in the “small angle approximation”. The results are given by,

$$
\left[ \frac{d\sigma}{d^2\vec{x}_T} \right]_{SM} = \frac{g^4 c_T}{2} \int \frac{d^2\vec{q}_T}{(2\pi)^2} \frac{d^2\vec{k}_T}{(2\pi)^2} \frac{e^{i(\vec{k}_T-\vec{q}_T) \cdot \vec{x}_T}}{(q^2_T + \mu_i^2)(k^2_T + \mu_D^2)} \tag{7}
$$

$$
\left[ \frac{d\Delta\sigma}{d^2\vec{x}_T} \right]_{SM} = -\frac{ig^4 c_T}{4} \int \frac{d^2\vec{q}_T}{(2\pi)^2} \frac{d^2\vec{k}_T}{(2\pi)^2} \frac{(\vec{k}_T - \vec{q}_T) \cdot (\vec{p} \times \vec{n}) e^{i(\vec{k}_T-\vec{q}_T) \cdot \vec{x}_T}}{p^2(q^2_T + \mu_i^2)(k^2_T + \mu_D^2)} \tag{8}
$$

Carrying out the integrations over $\vec{q}_T$ and $\vec{k}_T$, we obtain that,

$$
\left[ \frac{d\sigma}{d^2\vec{x}_T} \right]_{SM} = 2\alpha_s^2 c_T \frac{1}{\Lambda^2} K_0^2(\mu_D x_T), \tag{9}
$$
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\[
\left[\frac{d\Delta\sigma}{d^2\vec{x}_T}\right]_{\text{SPM}} = \frac{\alpha_s^2 c_{T\mu_D}}{p^2} \frac{(\vec{p} \times \vec{n}) \cdot \vec{x}_T}{K_0(\mu_D x_T)K_1(\mu_D x_T)}, 
\]

where \( J_0 \) and \( K_0 \) are the Bessel and modified Bessel functions respectively. Carrying out the integrations in the half plane with \( x > 0 \) and we obtained that[1],

\[
P_q = -\pi \mu_D p/2E(E + m_q). \tag{11}
\]

The result is very encouraging since it shows a quite significant negative polarization of the quark after one scattering.

More accurate calculations should be made using QCD at finite temperature. The quark-quark scattering is described by a Hard-Thermal-Loop (HTL) re-summed gluon propagator [6],

\[
\Delta^{\mu\nu}(Q) = \frac{P_T^{\mu\nu}}{-Q^2 + \Pi_T} + \frac{P_L^{\mu\nu}}{-Q^2 + \Pi_L} + (\alpha - 1) \frac{Q^\mu Q^\nu}{Q^4},
\]

where \( Q \) is the gluon four momentum, \( \alpha \) is a gauge fixing parameter,

\[
P_L^{\mu\nu} = \frac{-1}{Q^2 q^2} (\omega Q^\mu - Q^2 U^\mu)(\omega Q^\nu - Q^2 U^\nu), \quad P_T^{\mu\nu} = \tilde{g}^{\mu\nu} + \frac{\tilde{Q}^{\mu} \tilde{Q}^{\nu}}{q^2}, \tag{13}
\]

\[
\Pi_L = \mu_D^2 \left[ 1 - \frac{x}{2} \ln \left( \frac{1 + x}{1 - x} \right) + i \frac{\pi}{2} x \right] (1 - x^2), \tag{14}
\]

\[
\Pi_T = \mu_D^2 \left[ \frac{x^2}{2} + \frac{x}{4} (1 - x^2) \ln \left( \frac{1 + x}{1 - x} \right) - i \frac{\pi}{4} x (1 - x^2) \right], \tag{15}
\]

where \( \omega = Q \cdot U \), \( \tilde{Q} = Q - \omega U \), \( q^2 = -\tilde{Q}^2 \), \( \tilde{g}_{\mu\nu} = g_{\mu\nu} - U_{\mu} U_{\nu} \), \( x = \omega/q \), \( \mu_D^2 = g^2(N_c + N_f/2)T^2/3 \) is the Debye screening mass, \( U \) and \( T \) are respectively the fluid velocity and temperature of heat bath. In this framework, we have,

\[
\mathcal{M}(\vec{q}_T) = \pi\lambda_3 (P_1 + Q) \gamma_\mu u_{\lambda_1}(P_1) \Delta^{\mu\nu}(Q) \pi\lambda_4 (P_2 - Q) \gamma_\nu u_{\lambda_2}(P_2), \tag{16}
\]

We work in the center of mass frame, and in Feynman gauge, so we have,

\[
\Delta^{\mu\nu}(Q) = \frac{g^{\mu\nu} - U^\mu U^\nu}{q^2} + \frac{U^\mu U^\nu}{q^2 + \mu_D^2}. \tag{17}
\]

The HTL gluon propagator needs to be regularized. We do this by introducing a non-perturbative magnetic mass \( \mu_m \approx 0.255\sqrt{N_c/2g^2T} \) into the transverse self-energy. For simplicity, we consider only the longitudinal momentum distribution of the partons in QGP and have, in c.m. frame, \( U^\mu = (1, 0, 0, 0) \).

Under the “small angle approximation”, we obtain that,

\[
\frac{d\sigma}{d^2\vec{x}_T} = \frac{g^4 c_{qq}}{8} \int \frac{d^2\vec{q}_T}{(2\pi)^2} \frac{d^2k_T}{(2\pi)^2} e^{i(\vec{k}_T - \vec{q}_T) \cdot \vec{x}_T} \left( \frac{1}{q_T^2 + \mu_m^2} + \frac{1}{q_T^2 + \mu_D^2} \right) \left( \frac{1}{k_T^2 + \mu_m^2} + \frac{1}{k_T^2 + \mu_D^2} \right), \tag{18}
\]

\[
\frac{d\Delta\sigma}{d^2\vec{x}_T} = -\frac{i g^4 c_{qq}}{16} \int \frac{d^2\vec{q}_T}{(2\pi)^2} \frac{d^2k_T}{(2\pi)^2} e^{i(\vec{k}_T - \vec{q}_T) \cdot \vec{x}_T} \left( \frac{1}{q_T^2 + \mu_m^2} + \frac{1}{q_T^2 + \mu_D^2} \right) \left( \frac{1}{k_T^2 + \mu_m^2} + \frac{1}{k_T^2 + \mu_D^2} \right), \tag{19}
\]

We see that the difference between the results obtained with HTL propagator and those in the static potential model is the additional contributions from the magnetic part.
3.2. Numerical results

The expressions for the cross sections without “small angle approximation” are quite complicated. I will not present them here. Interested readers are referred to [3]. We have carried out the integrations numerically and obtained the preliminary results as shown in Fig. 3a. For comparison, we show the results together with those obtained under the small angle approximation in Fig. 3b.

![Figure 3. a (left), Preliminary results for the quark polarization \(-P_q\) as a function of \(\sqrt{s}/T\) obtained using HTL gluon propagator. b (right), Comparison with the results obtained under small angle approximation (dashed line) and that obtained using static potential model under small angle approximation (dotted line).](image)

The results in Fig. 3 show that the polarization is quite different for different \(\sqrt{s}/T\). It is very small both in the high energy and low energy limit. However, it can be as high as 20% at moderate \(\sqrt{s}/T\). At RHIC, we can only give a rough estimation of the ratio \(\sqrt{s}/T \sim \Delta p_{\perp}/T\) which should be between 0.1 and 2. We see that in this range the polarization can be quite significant but can also be only of a few percent.

From Fig. 3b, we see also that, at RHIC energy, small angle approximation is not a good approximation[1]. We have to rely on the numerical results obtained using HTL gluon propagator without small angle approximation. More detailed study including transverse flow of the partons are also underway.

4. The measurable consequences

The global polarization of quarks and anti-quarks in QGP should have many measurable consequences for the hadrons after hadronization. The most direct ones are the polarizations of the spin non-zero hadrons. Data[8-10] from LEP on \(e^+e^- \rightarrow Z \rightarrow h+X\) tell us that polarization of the quark or anti-quark can indeed be transferred to final hadrons via hadronization. We now present the results for hyperons and vector mesons from the global quark polarization discussed above in the following.
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4.1. Hyperon polarization

For hyperons produced via recombination $qqq \rightarrow H$, we obtain,

\[ P_H = P_q \]
\[ P_\Lambda = P_s; \quad P_\Sigma = (4P_q - P_s - 3P_s^2)/(3 - 4P_qP_s + P_q^2); \]
\[ P_\Xi = (4P_s - P_q - 3P_q^2)/(3 - 4P_qP_s + P_q^2); \]

(20)

(21)

We see in particular that $P_H = P_q$ for all the $H = \Lambda, \Sigma$ and $\Xi$ if $P_s = P_q$.

For those produced via the fragmentation $q \rightarrow H + X$, we compare with the longitudinal polarization of hyperons in $e^+e^- \rightarrow Z^0 \rightarrow q\bar{q} \rightarrow \Lambda + X$ which has been measured and can be explained by assuming that polarized hyperons contain the initial polarized leading quark in its SU(6) wave-function. Similar calculations lead to,

\[ P_H = n_sP_s/(n_s + 2f_s), \quad P_\Lambda = (4f_sP_q - n_sP_s)/3(2f_s + n_s), \]
\[ P_\Xi = (4n_sP_s - f_sP_q)/3(2n_s + f_s), \]

(22)

(23)

where $n_s$ and $f_s$ are the relative s-quark abundances to u and d in QGP and fragmentation. We see in particular that $P_H = P_q/3$ if $P_s = P_q$ and $f_s = n_s$.

In dependent of the hadronization mechanisms, we expect: (1) Hyperons and their anti-particles are similarly polarized; (2) Different hyperons are also similarly polarized. (3) The polarization vanishes in central collisions and increases with $b$ in semi-central collisions. (4) It should have a finite value for small $p_T$ and central rapidity but increase with rapidity and eventually decreases and vanishes at large rapidities.

4.2. Vector meson spin alignment

The polarization of a vector meson $V$ is described by the spin density matrix $\rho^V$ where the diagonal elements $\rho^V_{11}$, $\rho^V_{00}$ and $\rho^V_{-1-1}$ are the relative intensities for the spin component $m$ of $V$ to take 1, 0, and $-1$ respectively. $\rho^V_{00}$ can be determined by measuring the angular distributions of the decay products. Furthermore, unlike the polarization of hyperons, $\rho^V_{00}$ does not know the direction of the reaction plane. Therefore, one cannot measure the sign of the quark polarization through $\rho^V_{00}$. On the other hand, one does not need to determine the direction of the reaction plane to measure $\rho^V_{00}$.

For vector mesons produced in quark recombination mechanism, we obtain,

\[ \rho^V_{00} = (1 - P_q^2)/(3 + P_q^2), \quad \rho^V_{00}^{K^+(rec)} = (1 - P_qP_s)/(3 + P_qP_s). \]

(24)

We see in particular that $\rho^V_{00} < 1/3$ if $V$ is produced in this hadronization scenario.

For the fragmentation of a polarized quark $q \uparrow \rightarrow V + X$, we again compare with $e^+e^- \rightarrow Z^0 \rightarrow q\bar{q} \rightarrow V + X$, and obtain,

\[ \rho^0_{00}^{(frag)} = \frac{1 + \beta P_q^2}{3 - \beta P_q^2}, \quad \rho^0_{00}^{K^+(frag)} = \frac{f_s}{n_s + f_s} \frac{1 + \beta P_q^2}{3 - \beta P_q^2} + \frac{n_s}{n_s + f_s} \frac{1 + \beta P_q^2}{3 - \beta P_q^2}. \]

(25)

The parameter $\beta \approx 0.5$ was obtained by fitting the $e^+e^-$ data. We see that, in this case, $\rho^0_{00} > 1/3$. We also see that, in both hadronization scenarios, vector meson spin alignment is a $P_q^2$ effect. This has the advantage discussed at the beginning of this sub-section but also the shortage that it may be very small.
We are happy to know that dedicated efforts have been made in measuring such effects at RHIC. See e.g. [13,14].

5. Summary and outlook

In summary, we have shown that produced partons have large local relative orbital angular momentum in non-central AA collisions at high energies. Parton scattering with given relative orbital angular momentum can polarize quarks along the same direction due to spin-orbital interaction in QCD. Such global quark polarization has many measurable consequences and the measurements on such effects might open a new window to study the properties of QGP in high energy AA collisions.

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