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Spin Alignment of Vector Mesons in Non-central $A + A$ Collisions

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We discuss the consequence of global polarization of the produced quarks in non-central heavy-ion collisions on the spin alignment of vector mesons. We show that the alignment is quite different for different hadronization scenarios. These results can be tested directly by measuring the vector mesons' alignment through angular distributions of the decay products with respect to the reaction plane. Such angular distributions will give rise to azimuthal anisotropy v_2 of the decay products in the collision frame. Constraints provided by the data on the azimuthal anisotropy of hadron spectra at RHIC points to a quark recombination scenario of hadronization.

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 recently [1] to be polarized in the direction opposite to the reaction plan which is determined by the vector of impact-parameter and the beam momentum. Such global quark polarization should have many observable consequences such as left-right (with respect to the quarks' spin polarization) asymmetry in hadron spectra at large rapidity, global polarization of thermal photons, dileptons and final hadrons with spin. The left-right asymmetry of hadrons from the hadronization of such globally polarized quarks effectively gives rise to a "directed flow". However, it is difficult to disentangle it from the true directed flow due to interaction between produced matter and the spectator nucleons. Global hyperon polarization from the hadronization of polarized quarks are predicted [1] independently of the hadronization scenarios. Measurements of such global hyperon polarization are made possible by the self-analyzing power of the hyperon's parity-violating decay [2], which produces an angular distribution, $dN/d\cos\theta = 1 + \alpha P_H \cos\theta$, for its decay products with respect to the polarization direction. Here, α is a constant (*e.g.*, $\alpha = 0.642$ for $\Lambda \to p\pi^-$) and P_H is the hyperon's polarization. In practice, one needs to know not only the orientation but also the sign (or direction) of the reaction plane which can only be determined by the directed flow in each event class. If one sums over events with opposite reaction planes, the effect of the hyperon's polarization on the angular distribution of its decay products will cancel. While such measurements are underway, other consequences can and should be studied.

In this note, we discuss the spin alignment of vector mesons due to the global quark polarization in non-central $A + A$ collisions. Similarly as in Ref. [1], we consider two colliding nuclei with the projectile of beam momentum $\vec{p}$ moving in the direction of the z axis. The impact parameter $\vec{b}$ is taken as along $\hat{x}$, which is the transverse distance of the projectile from the target nucleus. The norm of the reaction plane is given by $\vec{n}_b \equiv \vec{p} \times \vec{b}/|\vec{p} \times \vec{b}|$ and is along $\hat{y}$. For a non-central collision, the dense matter produced in the overlapped region of the collision will carry a global angular momentum along the direction opposite to the reaction plane $(-\hat{y})$. Assuming that a partonic system is formed immediately following the initial collision, interactions among produced partons will lead to formation of a quark-gluon plasma (QGP) with both transverse (in x-y plane) and longitudinal collective motion. The global orbital angular momentum of the system will result in finite transverse (along $\hat{x}$) gradient of the longitudinal flow velocity. Given the range of interaction Δx, two colliding partons will have relative longitudinal momentum $\Delta p_z = \Delta x dp_z/dx$ with orbital angular momentum $L_y \sim -\Delta x \Delta p_z$ along the direction of $\vec{n}_b$. L_y is estimated [1] to be of the order of one for semi-central $Au + Au$ collisions at $\sqrt{s} = 200$ GeV and $\Delta x = 1$ fm.

Such local relative orbital angular momentum L_y will lead to global quark polarization via parton scattering in QGP due to spin-orbital coupling. The global quark polarization via elastic scattering was calculated in an effective static potential model and was found [1],

$$P_q = -\frac{\pi}{4} \frac{\mu \, p}{E(E + m_q)} \, , \tag{1}$$

where E and p are the energy and momentum of the initial quark in the c.m. frame of the parton scattering, μ is the Debye screening mass of the quark in medium, which specifies the average interaction range. The polarization can be enhanced by multiple scattering. Hence, we expect a significant global polarization of quarks and anti-quarks before hadronization. Such global polarization of quarks and anti-quarks will lead not only to the global hyperon polarization but also spin alignment of vector mesons.

The alignment of a vector meson is described by the spin density matrix ρ or its element $\rho_{m,m'}$, where m and m' label the spin component along the quantization axis. The diagonal elements ρ_{11}, ρ_{00} and ρ_{-1-1} for the unit-trace matrix are the relative intensities of the meson spin component m to take the values 1, 0, and -1 respectively, which should be $1/3$ in the unpolarized case. Since vector mesons usually decay strongly into two pseudo-scalar mesons, it is difficult to measure all the elements of ρ. But some of them can be determined easily by measuring the angular distributions of the decay products. It can be shown that, in the rest frame of V, for the decay $V \to h + h'$, (where h and h' are two pseudo-scalar mesons), the angular distribution $W(\theta, \phi) \equiv dN/d\Omega$ of the decay products is given by [3]

$$
\begin{aligned}
W(\theta, \phi) = \ & \frac{3}{4\pi}\{\cos^2\theta\, \rho_{00} + \sin^2\theta\, (\rho_{11} + \rho_{-1-1})/2 \\
& - \sin 2\theta(\cos\phi \mathrm{Re}\rho_{10} - \sin\phi \mathrm{Im}\rho_{10})/\sqrt{2} \\
& + \sin 2\theta(\cos\phi \mathrm{Re}\rho_{-10} + \sin\phi \mathrm{Im}\rho_{-10})/\sqrt{2} \\
& - \sin^2\theta[\cos(2\phi)\mathrm{Re}\rho_{1-1} - \sin(2\phi)\mathrm{Im}\rho_{1-1}]\}.
\end{aligned}
\tag{2}
$$

Here θ is the polar angle between the direction of motion of h and the quantization axis, ϕ is the azimuthal angle. By integrating over ϕ, we obtain,

$$
W(\theta) = \frac{3}{4}[(1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta].
\tag{3}
$$

Similarly, by integrating over θ, we obtain,

$$
W(\phi) = \frac{1}{2\pi}[1 - 2\cos(2\phi)\mathrm{Re}\rho_{1-1} + 2\sin(2\phi)\mathrm{Im}\rho_{1-1}].
\tag{4}
$$

We see that a deviation of ρ_{00} from $1/3$ will lead to a non-uniform θ-distribution of the decay product. By measuring $W(\theta)$, we can determine ρ_{00}. Other elements, ρ_{10} and ρ_{1-1}, can be studied by further measuring $W(\theta, \phi)$. In fact, such measurements have already been carried out in lepton induced reactions and hadron-hadron collisions [4–13, 16–18].

Unlike the polarization of hyperons, the spin-alignment of vector mesons, ρ_{00}^V, does not know the direction of the reaction plane since it only depends on $\cos^2\theta$ [see Eq. (3)]. Therefore, one cannot measure the sign of the quark polarization through spin-alignment of vector mesons. On the other hand, one does not need to determine the direction of the reaction plane to measure the spin alignment which is directly related to the magnitude of the quark polarization along the orientation of the reaction plane.

We now assume that quarks and anti-quarks in the QGP are polarized as described in [1] and calculate the spin alignment of V by considering the following three different hadronization scenarios: (1) recombination of the polarized quarks and anti-quarks; (2) recombination of the polarized quarks (anti-quarks) with unpolarized anti-quarks (quarks); (3) fragmentation of polarized quarks (or anti-quarks).

The picture envisaged here is the following. In a non-central $A + A$ collision, a QGP is formed and the quarks and anti-quarks in the QGP are polarized. Besides them, there are also quarks and anti-quarks created in the accompanying processes such as the hard scattering of the partons and the subsequent parton cascade etc. These quarks and anti-quarks are characterized by higher transverse momenta and are unpolarized. Hence, there are different possibilities for hadrons to be produced. First, they can be produced via the recombination of the quarks and anti-quarks in QGP, this corresponds to the hadronization scenario (1). Second, they can also be formed via the recombination of the quarks/anti-quarks in QGP with those from the accompanying processes. In

this case, we have the recombination of polarized quarks (anti-quarks) with unpolarized anti-quarks (quarks), and this corresponds to the hadronization scenario (2). Finally, they can also be produced via the fragmentation of a fast quark/anti-quark from the QGP. This corresponds to the scenario (3). Clearly, the three different hadronization scenarios should contribute to different kinematic regions. While the first scenario should play the dominant role in the low p_T and central rapidity region, the second and third should play the important roles for the intermediate p_T and forward rapidity regions respectively.

We first consider the hadronization scenario (1) of constituent quark recombination in which both quarks and anti-quarks are polarized. This is likely the case for hadronization in the central rapidity region for low p_T hadrons. We take $-\vec{n}_b = -\hat{y}$ as the quantization axis, and obtain the spin density matrix for quarks ρ^q as,

$$\rho^q = \frac{1}{2} \begin{pmatrix} 1 + P_q & 0 \\ 0 & 1 - P_q \end{pmatrix}, \tag{5}$$

and similarly for anti-quarks $\rho^{\bar{q}}$. Since the system is thermalized, there should be no intrinsic correlation between the quark and anti-quark in QGP. Also, since our purpose is to study the effect of global quark polarization, we will not go to the detail of the recombination mechanism but, just as people usually do[14, 15], assume no particular correlation between the quark and the anti-quark that combine into a vector meson. Hence, we can calculate the spin density matrix of the vector meson V by making the direct product of ρ^q and $\rho^{\bar{q}}$. After transforming it to the coupled basis, we obtain the normalized spin density matrix ρ^V for vector mesons as,

$$\rho^V = \begin{pmatrix} \frac{(1+P_q)(1+P_{\bar{q}})}{3+P_q P_{\bar{q}}} & 0 & 0 \\ 0 & \frac{1-P_q P_{\bar{q}}}{3+P_q P_{\bar{q}}} & 0 \\ 0 & 0 & \frac{(1-P_q)(1-P_{\bar{q}})}{3+P_q P_{\bar{q}}}) \end{pmatrix}. \tag{6}$$

Hence, we obtain

$$\rho_{00}^{V(\text{rec})} = \frac{1 - P_q P_{\bar{q}}}{3 + P_q P_{\bar{q}}}, \tag{7}$$

and all the non-diagonal elements are zero. Assuming $P_u = P_d = P_{\bar{u}} = P_{\bar{d}} \equiv P_q$, and $P_s = P_{\bar{s}}$, we obtain the results for ρ and K^* mesons as,

$$\rho_{00}^{\rho(\text{rec})} = \frac{1 - P_q^2}{3 + P_q^2}, \tag{8}$$

$$\rho_{00}^{K^*(\text{rec})} = \frac{1 - P_q P_s}{3 + P_q P_s}, \tag{9}$$

We see that both ρ_{00}^{ρ} and $\rho_{00}^{K^*}$ are smaller than $1/3$ if they are produced via recombination of similarly polarized quarks and anti-quarks. The non-diagonal elements are zero if there is no correlation between the polarization of the quark and anti-quark.

The polarization of quark and anti-quark discussed in [1] is a low p_T phenomenon, since the polarizing interaction typically has a momentum scale of $p_0 = \mu L_0$, where $1/\mu$ is the interaction range and L_0 is the typical relative orbital angular momentum between two-colliding partons. When the initial p_T of a quark is much larger than p_0, the quark will not be polarized. But such a quark can still recombine with a polarized low p_T anti-quark to form a hadron, according to the hadronization scenario (2). The spin alignment for such formed vector mesons can be obtained by inserting $P_q = 0$ or $P_{\bar{q}} = 0$ into Eq. (7). We have then $\rho_{00}^V = 1/3$, even if one of the constituent quarks is polarized before recombination.

Finally, we consider the hadronization scenario (3), $i.e.$, fragmentation of a polarized quark $q^{\uparrow} \rightarrow V + X$. This likely happens for quarks with large rapidities in the QGP and may play an important for hadrons in the forward rapidity region. The situation in this case is very much different from that in scenario (1) or (2). Here, the anti-quark that combines with the initial polarized quark is

created in the fragmentation process and may carry the information of the initial quark that induces this creation. This implies that the polarization of this anti-quark can be correlated to that of the initial quark. Since this is a non-perturbative process that cannot be calculated from pQCD, we do not know *a priori* whether such a correlation indeed exists. Fortunately, the situation here is very similar to $e^+e^- \to Z^0 \to q\bar{q} \to V + X$, where the initial q and $\bar{q}$ are longitudinally polarized so that we have the fragmentation process $\vec{q} \to V + X$. Therefore, we can compare it with the latter to extract some useful information.

The 00-element of the spin density matrix for the vector mesons in $e^+e^- \to Z^0 \to q\bar{q} \to V + X$ have been measured at LEP[13, 16–18]. The results show clearly that ρ_{00}^V is significantly larger than $1/3$ in the helicity frame of the vector meson (*i.e.* the quantization axis is taken as the polarization direction of the fragmenting quark) at large fractional momenta. A simple calculation [19] for ρ_{00}^V in $e^+e^- \to V + X$ has been carried out by building the direct product of the spin density matrix of the polarized leading quark (ρ_q) and that of the anti-quark created during the fragmentation process ($\rho_{\bar{q}}^{\text{frag}}$). In the helicity frame, ρ_q takes exactly the form as shown by Eq. (5). The most general form was taken for $\rho_{\bar{q}}^{\text{frag}}$. The calculation is exactly the same as that for quark recombination. It also leads to a result of ρ_{00}^V for the first rank V's similar to that shown by Eq. (7). The only difference is that we should replace $P_{\bar{q}}$ in Eq. (7) by $P_{\bar{q}}^{frag}$, which is the polarization of the anti-quark created in the fragmentation process. This result has been compared with the available data[13, 16–18]. It has been found out that, the available data can only be fitted if the anti-quark is taken as effectively polarized in the opposite direction as the leading quark, and the polarization is $P_{\bar{q}}^{\text{frag}} = -\beta P_q$, where $\beta \approx 0.5$ was obtained[19] by fitting the data[13, 16–18]. Hence, for the first rank V's,

$$\rho_{00}^{V(frag)} = \frac{1 + \beta P_q^2}{3 - \beta P_q^2}. \tag{10}$$

For V's other than the first rank hadrons, $\rho^V = 1/3$. These results can be considered as a parametrization of the LEP data[13, 16–18].

If the same model can be applied to the fragmentation of quarks (anti-quarks) polarized along the opposite direction of the reaction plane in heavy-ion collisions, then the anti-quarks (quarks) that are produced in the fragmentation and will combine with the leading quarks (anti-quarks) to form vector mesons is effectively polarized in the opposite direction as the initial quarks (anti-quarks) with the polarization $P_{\bar{q}}^{\text{frag}} = -\beta P_q$. One can then obtain a result for ρ_{00}^V in the same form as that shown by Eq. (10). The difference is that now the quantization axis is along the opposite direction of the reaction plane, which is transverse to the direction of longitudinal motion. Taking the fragmentation of different flavors of quarks and anti-quarks into account, we obtain, for the first rank V's,

$$\rho_{00}^{\rho \, (\text{frag})} = \frac{1 + \beta P_q^2}{3 - \beta P_q^2}, \tag{11}$$

$$\rho_{00}^{K^* (\text{frag})} = \frac{f_s}{n_s + f_s} \frac{1 + \beta P_q^2}{3 - \beta P_q^2} + \frac{n_s}{n_s + f_s} \frac{1 + \beta P_s^2}{3 - \beta P_s^2}, \tag{12}$$

where n_s and f_s are the strange quark abundances relative to up or down quarks in QGP and quark fragmentation, respectively. Therefore, in this case of quark fragmentation, ρ_{00} is always larger than $1/3$.

One can measure directly the angular distribution of vector mesons' decay products with respect to the reaction plane and therefore determine the spin-alignment of vector mesons in non-central heavy-ion collisions. Such measurements will elucidate the hadronization mechanisms in the different kinematic regions if ρ_{00} differs noticeably from $1/3$. Before such data become available, one can, however, find constraints on ρ_{00} from the measured azimuthal anisotropy of produced hadrons, since finite fraction of final hadrons come from vector meson decays and they have a particular angular distribution with respect to the reaction plane according to Eq. (3) if $\rho_{00} \neq 1/3$. Such an angular distribution will produce an azimuthal asymmetry with respect to the reaction plane. If one characterizes the asymmetry by the second coefficient v_2 of the Fourier transformation of the

angular distribution similarly as the elliptic flow study [20], $v_2 > 0$ for $\rho_{00} < 1/3$ and $v_2 < 0$ if $\rho_{00} > 1/3$.

Note that the angular distribution in Eq. (3) is in the rest frame of the decaying vector mesons. To calculate the azimuthal anisotropy of the decay products in the center of mass (c.m.) frame of $A + A$ collisions, one has to perform Lorentz transformation on the momentum distribution of the decay products from the rest frame of the vector mesons. Since quarks' polarizations should disappear at large p_T as we have argued earlier, the vector mesons' spin alignment should approach to $\rho_{00} = 1/3$ at large p_T. Therefore, we can assume the following ansatz for the p_T dependence of ρ_{00},

$$\rho_{00}(p_T) = \rho_{00}^0 + (\frac{1}{3} - \rho_{00}^0)\frac{2}{\pi}\tan^{-1}(\frac{p_T}{a_0}), \tag{13}$$

where ρ_{00}^0 is the value of the spin alignment at $p_T = 0$ and a_0 sets the p_T scale at which quark's polarization vanishes. We will use $a_0 = 0.5$ GeV/c to illustrate the effect of vector mesons' spin alignment on the v_2 of final hadrons.
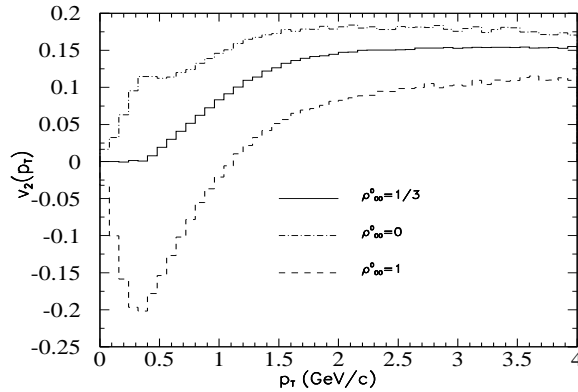

FIG. 1: Azimuthal anisotropy v_2 of pions from the decay of ρ vector mesons that have spin alignment according to Eq. (13) with $\rho_{00}^0 = 1/3$ (solid line), 0 (dot-dashed line) and 1 (dashed line).

Effects of vector resonances' decay on final pions' azimuthal asymmetry has been studied recently [21, 22] without spin alignment. We will follow the same procedure and assume that vector mesons at low p_T have an exponential distribution in $m_T = \sqrt{p_T^2 + m^2}$ with an effective temperature $T = 200$ MeV. The azimuthal anisotropy of ρ mesons is assumed to follow the scaling behavior of a recombination model [21, 22]

$$v_2^\rho = \frac{0.22}{1.0 + e^{-(p_T/2.0-0.35)/0.2}} - 0.06. \tag{14}$$

Shown in Fig. 1 are the azimuthal anisotropies of pions from ρ meson decays with three limiting cases of ρ-mesons' spin alignment. For $\rho_{00}^0 = 1/3$, ρ-mesons are not aligned, pion distribution in the rest frame of the ρ-meson is isotropic. Therefore, v_2 of pions (solid line) from the decay follows closely that of the ρ mesons. For one extreme case, $\rho_{00}^0 = 1$, the angular distribution of pions prefers the out-plane direction and therefore v_2 is negative at low p_T shown as dashed line. As the transverse momentum of the ρ-meson increases, the opening angle of pions from the decay in the c.m. frame of $A + A$ collisions becomes smaller. Eventually, v_2 of pions approaches that of ρ-meson (solid line) at high p_T. But it is always smaller than v_2 of the ρ-mesons. For another extreme case, $\rho_{00}^0 = 0$, the azimuthal anisotropy of pions (dot-dashed line) is positive and larger than that of the ρ-mesons for small p_T while it approaches to the ρ-mesons' v_2 at large p_T from above.

Since there are also directly produced pions, one needs to also include them in the estimate of the effect of ρ-mesons' spin alignment on the azimuthal anisotropy of the final pions. The ρ/π ratio is measured to be 0.183 in peripheral $Au + Au$ collisions at $\sqrt{s} = 200$ GeV about the same value as in $p + p$ at the same energy [24]. We simply assume the same value for the total number of ρ mesons. We also assume that v_2 for the directly produced pions is the same as ρ-mesons. Shown in
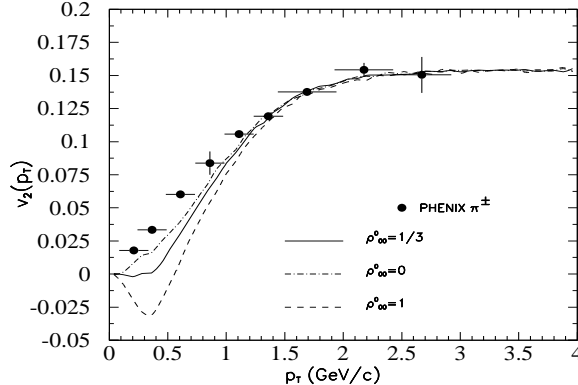
FIG. 2: Azimuthal anisotropy v_2 of final produced pions that include both directly produced and these from the decay of ρ vector mesons that have spin alignment according to Eq. (13) with $\rho_{00}^0 = 1/3$ (solid line), 0 (dot-dashed line) and 1 (dashed line). The multiplicity ratio $\rho/\pi = 0.183$ [24] is assumed. The data are for pions from PHENIX experiment [23].

Fig. 2 are $v_2(p_T)$ of the final produced pions with the above three limiting cases of ρ-mesons' spin alignment as compared to the experimental data [23] which are always above the assumed v_2 of the ρ-mesons (solid line) in the scaling model [21, 22]. The effect of vector mesons' spin alignment is not big due to the small value of ρ/π ratio. In addition to pions from ρ-meson decays, one also finds [21, 22] that pions from decays of other resonances such as Δ and ω also enhances pions' v_2 at low p_T. For a complete analysis, one should include decays of these resonances that might also have similar spin alignment. However, it is clear that the data favor the scenario of $\rho_{00}^0 < 1/3$ from parton recombination, even though the measured v_2 of pions does not provide stringent constraints on the value of ρ-mesons' spin alignment, which can be directly measured by the angular distribution of the decay products in the rest frame of vector mesons.

In summary, we calculated the spin density matrix for vector mesons produced in non-central $A + A$ collisions by taking into account the global polarization of quarks and anti-quarks in the overlapping region of the two colliding nuclei. We showed that the results for ρ_{00}^V depend very much on the hadronization mechanisms. Since mesons from the decay of aligned vector resonances have anisotropic angular distribution with respect to the reaction plane, they will contribute to the azimuthal anisotropy v_2 of the final produced meson spectra. Even though experimental data on pions' v_2 cannot provide stringent constraints on the value of ρ-mesons' spin alignment, they favor $\rho_{00}^0 < 1/3$ for the scenario of parton recombination in the central rapidity region. For the parton fragmentation scenario, $\rho_{00}^0 > 1/3$ and v_2 of the decay products is negative. In this case the spin-alignment tends to decrease the v_2 of the total produced mesons. Such scenario is more likely in the large rapidity region and can potentially explain why the measured v_2 drops sharply with rapidity.

It is also interesting to note that similar quark polarization effect could also happen in $p + p$ collisions as pointed out in Ref. [25] and could explain the measured hyperon polarization. Therefore, it should also be interesting to correlate hyperon's polarization to the reaction plane in $p+p$ collisions if one can similarly determine the reaction plane as in $A + A$ collisions. However, one must also take into account the spin of partons inside initial beam proton as one cannot neglect them in $p + p$ collisions.

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