Spin asymmetries at RHIC and nonperturbative aspects of hadron dynamics

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Abstract

Some nonperturbative aspects of spin studies at RHIC are discussed and the predictions for single- and two-spin asymmetries are given. Among them are those which emphasize the role of angular orbital momentum in the spin structure of the constituent quarks.
Introduction

The spin studies program at RHIC has several well defined goals and among them:

- study of the nucleon spin structure, i.e., how the proton’s spin state can be obtained from a superposition of Fock states with different numbers of constituents with nonzero spin;
- study how the dynamics of constituent interactions depend on spin;
- understanding the chiral symmetry breaking and helicity non-conservation on quark and hadron levels;
- study of the overall nucleon structure and long range dynamics.

These issues are closely interrelated at the hadron level and the results of the experimental measurements are to be interpreted in terms of hadron spin structure convoluted with the constituent interaction dynamics.

In this paper we discuss the respective physics potential of RHIC machine.

1 Single-spin asymmetries in inclusive processes

Studies of the spin effects in inclusive processes probe the spin dependence of the incoherent hadronic interaction dynamics. The cross–sections of the hard production processes are described in the perturbative QCD as a convolution integral of parton cross-sections with the light–cone parton densities.

These studies would yield information on the contribution of the spin and orbital angular momenta of quarks and gluons into the hadron helicity:

\[ 1/2 = 1/2\Delta \Sigma + L_q + \Gamma + L_g \]  

In the above sum all terms have clear physical interpretation, however besides the first one, they are gauge and frame dependent. Transparent discussions of the theoretical aspects of this sum rule are given in [1].

The primary goal of the single-spin measurements with hadronic final states would be a study where the onset of perturbative QCD regime occurs. In the spin measurements in inclusive process \( A + B \rightarrow C + X \) with polarized hadron \( A \) this is based on the assumption of the higher–twist origin of the one–spin transverse asymmetries [2, 3]. The contribution of higher twists should be small at high energies where the interactions at small distances \( l \sim 1/Q \) can be studied. There are some indications that such contributions are small even at not too high energies and \( Q^2 \) values. In particular, it follows from the recent data on the spin structure function \( g_2(x) \) obtained at SLAC. If it is the case, the observed significant one-spin asymmetries in hadronic processes are to be associated with manifestation of nonperturbative dynamics. However, the available energies are not high enough to make the unambiguous conclusion. Therefore, the measurements of one-spin asymmetries at RHIC energies are
crucial. For the production of hadrons with high $p_{\perp}$ the simple factorization is valid for the transversely polarized hadrons as well as for the longitudinally polarized ones [4], i.e.

$$A_N d\sigma \sim \sum_{ab \to cd} \int d\xi_A d\xi_B \frac{dz}{z} \delta f_{a/A}(\xi_A) f_{b/B}(\xi_B) \hat{a}_N d\sigma_{ab \to cd} C_{c/d}(z)$$

(2)

and we are expecting vanishing one–spin transverse asymmetries

$$A_N = 0.$$ 

since at the leading twist level $\hat{a}_N = 0$.

It can also be demonstrated expressing the asymmetry $A_N$ through the helicity amplitudes. Indeed, asymmetry $A_N$ results from the interference between helicity amplitudes which differ by one unit of helicity

$$A_N = 2 \sum_{X,\lambda_1,\lambda_2} \int d\Gamma_X \text{Im}[F_{\lambda_X;+\lambda_2} F^*_{\lambda_X;\lambda_1-\lambda_2}] \frac{\sum_{X,\lambda_1,\lambda_2} \int d\Gamma_X |F_{\lambda_X;\lambda_1,\lambda_2}|^2}{\sum_{X,\lambda_1,\lambda_2} \int d\Gamma_X |F_{\lambda_X;\lambda_1,\lambda_2}|^2},$$

(3)

where $F_{\lambda}$ are the helicity amplitudes of exclusive processes. If the helicity conservation in QCD for exclusive processes is valid at hadron level [3]

$$\lambda_1 + \lambda_2 = \lambda_X$$

(4)

then it follows that $A_N = 0$ in the phase when chiral symmetry is not broken, i.e. in the limit of high $p_{\perp}$‘s. Note, that $\lambda_X = \sum_{i=1}^{n_X} \lambda_i$ and $n_X$ is the number of particles in the exclusive final state $X$. Essential point here is the assumption that at the short distances vacuum is a perturbative one. Thus, the study of $p_{\perp}$–dependence of one–spin asymmetries might be used as a way to reveal the transition from the non–perturbative phase ($A_N \neq 0$) to the perturbative phase ($A_N = 0$) of QCD. The very existence of such transition can not be taken for granted since the vacuum, even at short distances, could be filled with the fluctuations of gluon or quark fields [12].

The measurements of one–spin transverse asymmetries in this case will be important probe of the chiral structure of the effective QCD Lagrangian.

It should be mentioned that available experimental data are at some variance with PQCD predictions: the data do not at least show up tendency to converge to the vanishing single-spin asymmetries in inclusive and elastic hadron productions. Indeed, in the soft hadronic interactions significant single-spin effects could be expected since the helicity conservation rule does not work in the interactions at large distances because the chiral $SU(3)_L \times SU(3)_R$ symmetry of the QCD Lagrangian is spontaneously broken. However, the asymmetries at low transverse momentum are small. On the other hand, these asymmetries increase at higher transverse momentum; but this is just where we should expect $A_N = 0$.

Several mechanisms have been proposed for the explanation of the observed single-spin effects. Possible sources of the observed one–spin asymmetries could be: higher twist effects [3], correlation of $k_{\perp}$ and spin in structure [3] and fragmentation [4, 8] functions, rotation of valence quarks inside a hadron [3] and the coherent rotation of the quark matter inside the constituent quarks [10].

The main points of the mechanism proposed in [10] are:
• asymmetry in the pion production reflects the internal spin structure of the constituent quarks, i.e. it arises due to the orbital angular momentum of current quarks inside the constituent quark;

• sign of asymmetry and its value are proportional to polarization of the constituent quark inside the polarized nucleon.

The model predicts significant one-spin asymmetries at high $p_\perp$ values. The significant asymmetries appear to show up beyond $p_\perp > \Lambda_\chi(\simeq 1 - 2 \text{ GeV}/c)$, i.e. the scale where internal structure of a constituent quark could be probed (Fig. 1).

The observed $p_\perp$-behavior of asymmetries in inclusive processes confirms these predictions and indicates that the transverse size $\Delta b$ of the region where the asymmetries originate from is significantly less than the hadron size $\Delta b_H$ and is of the order of the magnitude of the size of constituent quark, i.e.

$$ \Delta b \sim 1/m_Q. $$

The relevant processes for the study of above problems are the following:

$$ p^\uparrow + p \rightarrow \pi, \gamma, \text{jet} + X \tag{5} $$

As an example we consider charged pion production. The model [10] predicts

$$ A_N(s, x, p_\perp) = \frac{\sin[\mathcal{P}_q(x)(L_{qq})]W^h_+(s, \xi)}{[W^+_+(s, \xi) + W^h_+(s, \xi)]}, \tag{6} $$

where the functions $W^{s,h}_+$ are determined by the interactions at large and small distances.

The asymmetries have energy independent values about 30% at $p_\perp > \Lambda_\chi(\simeq 1 - 2 \text{ GeV}/c)$ and $x \simeq 0.5$:

$$ A_\pi^{\pm} \simeq \pm 30\%. $$

Note, that the corresponding asymmetry in the neutral pion production has value about $5 - 6\%$ in the same kinematical region.

As it has been noted higher twists at RHIC energies and high $p_\perp$'s would not provide significant contribution to asymmetry $A_N$. Phenomenology of such contributions has not been developed yet and predictions could vary from a few to tens percents. However, higher twists provide a decreasing single-spin asymmetry at high $p_\perp$

$$ A_\pi^{\pm} \sim M/p_\perp. $$

The same is true for the predictions of the mechanisms discussed in [3].

Experimental error in asymmetry $A_N$ is given by the events number $N$ and the beam polarization $P_1$:

$$ \delta A = \frac{1}{P_1 \sqrt{N}}. \tag{7} $$

For the values of RHIC luminosity $L = 2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ and beam polarization $P_1 = 70\%$ the experimental measurements of single-spin asymmetry in pion production with accuracy of a few percents are feasible up to $p_\perp$ about 30 GeV/c [13]. It would be important to study
the processes of the charged pion production since the available data at \( p_L = 200 \text{ GeV/c} \) indicated that the observed symmetries could be of order of tens percents.

The \( p_L = 200 \text{ GeV/c} \) is the maximal energy the asymmetries in these processes has been measured so far. The study of this reaction at RHIC energies could provide a clear test of perturbative QCD regime and nonperturbative models. In general, these studies are important for understanding of the QCD vacuum and transitions between the perturbative and nonperturbative phases.

In the \( \pi^0 \) production the asymmetries are expected to be smaller due to the isospin substraction between \( \pi^\pm \) cross sections.

## 2 Transverse spin densities and two–spin correlations in inclusive processes

The transverse quark spin density measures the difference of the quark momentum distributions in a transversely polarized nucleon when a quark is polarized parallel or antiparallel to the nucleon. This quantity \( \delta q(x) \), unlike the longitudinal quark spin density \( \Delta q(x) \), cannot be measured in deep inelastic scattering due to its different properties under chiral transformations. Extensive studies of the theoretical aspects of transverse spin structure of the nucleon were made in [14] and [17, 18, 19]. Quark transversity is a new observable for understanding the hadron wave function in terms of bare quarks. Gluons give no contribution to the transverse spin of the proton. It is promising to explore this new spin observable and compare it with the longitudinal spin densities.

Recently an upper bound for \( \delta q(x) \) [15]:

\[
|\delta q(x)| \leq q_+(x)
\]

and the bound for \( \delta q(x) \) limiting its behavior at \( x \to 0 \) [16]:

\[
\delta q(x) \leq \log x / x
\]

have been obtained.

Low-\( x \) behavior of the spin structure functions \( g_1(x) \) and \( h_1(x) \) has been considered [22] in the unitarized chiral quark model which combines ideas on the constituent quark structure of hadrons with a geometrical scattering picture and unitarity. A nondiffractive singular low-\( x \) dependence of \( g_1^p(x) \) and \( g_1^n(x) \) was obtained and a diffractive type smooth behaviour of \( h_1(x) \) is predicted at small \( x \). The quark densities \( q(x) \), \( \Delta q(x) \) and \( \delta q(x) \) at small \( x \simeq Q^2 / s \) have the following forms [22]:

\[
q(x) \sim \frac{1}{x} \ln^2(1/x),
\]

\[
\Delta q(x) \sim \frac{1}{\sqrt{x}} \ln(1/x)
\]

and

\[
\delta q(x) \sim x^{\alpha+1} \ln(1/x).
\]
It also follows that the unpolarized structure function $F_1$ and transversity $h_1$ will be the universal for the proton and neutron, i.e.:

$$F_1^p(x) = F_1^n(x) \sim \frac{1}{x} \ln^2(1/x).$$

(13)

and

$$h_1^p(x) = h_1^n(x) \sim \frac{\alpha - 1}{x^{\frac{\alpha - 1}{1 + \alpha}}} \ln(1/x).$$

(14)

It is also seen that $h_1(x)$ has a smooth behaviour at $x \to 0$, i.e. $h_1(x) \to 0$ in this limit ($\alpha > 1$).

So far the Drell–Yan process with transversely polarized protons in the initial state

$$p^\uparrow \cdot p^\uparrow \rightarrow \mu^+ + \mu^- + X$$

is most suitable for the determination of the quark transversity. The corresponding two–spin asymmetry is directly related to the quark transversity distributions $\delta q(x)$. The explicit low-$x$ forms Eqs. (11) and (12) allow one to analyze the asymmetries $A_{TT}$ and $A_{LL}$ in the central region of the low-mass Drell-Yan production. They appear to be small at $x_F \simeq 0$

$$A_{LL}^\parallel \simeq 0 \quad \text{and} \quad A_{TT}^\parallel \simeq 0$$

(15)

when invariant mass of the lepton pair $M_\ell^2 \ll s$ At the same time the ratio of the asymmetries $A_{TT}^\parallel$ and $A_{LL}^\parallel$ is also small in this kinematical region:

$$A_{TT}^\parallel/A_{LL}^\parallel \simeq 0.$$ 

(16)

This result agrees with the predictions made in [23]. Despite the small predicted asymmetries the experimental measurements in this kinematical region could be important.

The measurements of the two–spin longitudinal asymmetries will probe the gluon contribution $\Delta g(x)$ to the helicity of the nucleon. The relevant processes for that purpose are the direct $\gamma$, jets, $\chi_2$ and pion–production at high $p_\perp$’s in the collisions of longitudinally polarized protons. Estimation of the experimental sensitivity $\delta A_{LL}/TT$ shows that the measurements with accuracy of a few percents are feasiable at RHIC up to $p_\perp$ about 30 GeV/c.

3 Strangeness in the hadrons

It is evident from deep–inelastic scattering data that strange quarks alongside with gluons could play essential role in the spin structure of nucleon. DIS data show that strange quarks are negatively polarized in polarized nucleon, $\Delta s \simeq -0.1$. Elastic $\nu p$-scattering data as well provide the value $\Delta s = -0.15 \pm 0.08$ [24]. The presence and polarization of strange quarks inside a hadron should give an experimental signal in hadronic reactions as well.

We address now the asymmetry in the production of $\varphi$-meson consisting of strange quarks. It is worth to stress that in addition to $u$ and $d$ quarks the constituent quark ($U$, for example) contains pairs of strange quarks and the ratio of scalar density matrix elements

$$y = \langle U|\bar{s}s|U\rangle / \langle U|\bar{u}u + \bar{d}d + \bar{s}s|U\rangle$$

(17)
is estimated as \( y = 0.1 - 0.5 \).

It was argued \[25\] that the single spin asymmetry \( A_N \) in the process \( pp \rightarrow \varphi X \) is due to orbital momenta of strange quarks in the internal structure of constituent quarks. The estimation for the asymmetry \( A_N \) in \( \varphi \)-meson production at \( p_\perp > \Lambda_\chi (\simeq 1 - 2 \text{ GeV}/c) \) is:

\[
A_N(\varphi) \propto \langle P_{Q} \rangle \langle L_{(\bar{q}q)} \rangle y \simeq 0.01 - 0.05. \tag{18}
\]

Thus, a quite noticeable one-spin asymmetry at high \( p_\perp \) values in inclusive \( \varphi \)-meson production can be expected. The above estimate also shows that it is reasonable to make experimental measurements of the cross-section and asymmetry in inclusive \( \varphi \)-meson production to study strange content of constituent quark as a possible source of OZI-rule evasion.

As it now is known, only part (less than one third in fact) of the proton spin is due to quark spins \[26, 27\]. These results one can interpret in the effective QCD approach ascribing a substantial part of hadron spin to an orbital angular momentum of quark matter. This orbital angular momentum might be revealed when asymmetries in hadron production are measured. The main role belongs to the orbital angular momentum of \( \bar{q}q \)-pairs inside the constituent quark while constituent quarks themselves have very slow (if at all) orbital motion and the hadron wave function may be approximated by \( S \)-state of the constituent quark system. The observed \( p_\perp \)-dependence of \( \Lambda \)-hyperon polarization in inclusive processes seems to confirm such conclusions, since it appears to show up beyond \( p_\perp > \Lambda_\chi (\simeq 1 - 2 \text{ GeV}/c) \) i.e. the scale where internal structure of constituent quark can be probed (Fig. 2).

The main outcome of the considered model: polarization of \( \Lambda \)-hyperons arises as a result of the internal structure of the constituent quark and its multiple scattering in the same effective field. It is proportional to the orbital angular momentum of strange quarks which is initially resided inside the constituent quark. It is predicted in this model that the double spin correlation parameters should have a similar \( p_\perp \)-dependence:

\[
D_{TT} \sim D_{LL} \sim 0 \tag{19}
\]

at \( p_\perp < \Lambda_\chi (\simeq 1 - 2 \text{ GeV}/c) \) and

\[
D_{TT} \sim D_{LL} \sim \text{const.} \tag{20}
\]

at \( p_\perp > \Lambda_\chi \) in the polarized beam fragmentation region in the processes

\[
p_\uparrow + p \rightarrow \Lambda_\uparrow + X
\]

and

\[
p_\rightarrow + p \rightarrow \Lambda_\rightarrow + X.
\]

Eqs. \[19\), \[20\]] reflect the fact that the polarized strange quark is located inside the constituent quark of a smaller than a hadron size.

It is the generic feature of the above referenced model: spin effects in inclusive processes are related to the internal structure of constituent quark. This fact could explain similarity in the observed behaviour of different spin observables in inclusive processes, i.e. its rise with \( p_\perp \) at small and medium transverse momenta and then flattening at higher values of \( p_\perp \).

It would be interesting to check these predictions at RHIC energies as well as to measure for the first time triple spin correlation parameters in the processes of hyperon production with two polarized proton beams. It would help to understand the mechanism of hyperon polarization.
Conclusion

We have considered above the inclusive processes. Spin measurements at RHIC with single and both polarized proton beams would probe the fundamental couplings of the underlying Lagrangian and investigate the spin structure of the nucleon. A variety of one- and two-spin asymmetries could be measured. As it has often happened in the past, these spin measurements might bring unexpected new results; this would certainly stimulate the development of new theoretical ideas.

Among the spin studies the most exiting ones are those related to the nonperturbative effects. Asymmetries in fixed angle elastic scattering are predicted to have significant values by several models based on the nonperturbative dynamics [29, 30, 31]. One should also say that despite the obvious experimental difficulties in conducting elastic scattering experiments the data would be extremely desirable for the comprehensive spin physics program.

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Figure captions

Fig. 1. Asymmetry $A_N$ in the process $p_t + p \rightarrow \pi^+ + X$ (positive values) and in the process $p_t + p \rightarrow \pi^- + X$ (negative values) at $\sqrt{s} = 500$ GeV.

Fig. 2 The $p_\perp$–dependence of $\Lambda$–hyperon polarization in the process $pp \rightarrow \Lambda X$ at $p_L = 400$ GeV/c.
Fig. 1
