ISSUES OF SPIN PHYSICS AT RHIC

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Abstract

Some novel aspects of spin studies at RHIC are summarized along with the persistent problems. Among them are those which emphasize the role of angular orbital momentum in the spin structure of the constituent quarks.
**Introduction.** The systematic spin studies program at RHIC have several well defined goals and among them:

- study the spin structure of the nucleon, 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 depends on spin degrees of freedom;
- understand chiral symmetry breaking and helicity non-conservation on the quark and hadron levels;
- study the overall nucleon structure and long range dynamics.

These goals are closely interrelated in the hadron sector and the experiments are to be interpreted in terms of hadron spin structure convoluted with the constituent interaction dynamics.

The analysis of DIS data in the framework of perturbative QCD provides information on longitudinal polarized parton densities $\Delta q(x)$.

The study of the transverse spin structure of the nucleon $\delta q(x)$ is equally actual problem. In deep inelastic scattering the transverse spin densities contribute only as higher-twist terms.

In hadronic interactions there could be significant spin effects in soft processes where there is no helicity conservation rule because the chiral $SU(3)_L \times SU(3)_R$ symmetry of the QCD Lagrangian is spontaneously broken at small $Q$. However, the analyzing power at low transverse momentum is small and decreases with energy. On the other hand, the analyzing power increases at high transverse momentum; but this is just where we should have $A = 0$ because of the helicity conservation due to the chiral invariance of perturbative QCD. New ideas and new experimental data are both needed to understand the dynamics of these unexpected one-spin effects.

**Single-spin asymmetries in inclusive processes.** The study of spin effects in inclusive processes probe the incoherent dynamics of hadronic interactions. The hard production process is described in perturbative QCD as a convolution integral of parton cross-sections with the light–cone parton densities. The study of spin effects in inclusive processes will yield information on the contribution of valence, sea quarks and gluons to the spin of the hadron:

$$1/2 = 1/2\Delta \Sigma + L_q + \Gamma + L_g$$

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

The primary goal of spin measurements with hadronic final states should be a study of onset of perturbative QCD regime. In the spin measurements in inclusive process $A + B \rightarrow C + X$ with polarized hadron $A$ this is based on the higher–twist origin of one–spin transverse asymmetries [2, 3]. The contribution of higher twists should be small at high energies where interactions at small distances $O(1/Q)$ 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 E143 data obtained at SLAC. If it is the case, the observed significant one-spin asymmetries in hadronic processes are to be associated with the 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.

$$A_N \sim \sum_{ab\rightarrow cd} \int d\xi_A d\xi_B \frac{dz}{z} \delta f_{a/A}(\xi_A) f_{b/B}(\xi_B) \hat{a}_N \hat{c}_D / c D_{C/c}(z)$$

(2)

then we should expect vanishing one-spin transverse asymmetries

$$A_N = 0.$$ 

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

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

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

(3)

where $F_{\lambda}$ are the helicity amplitudes of exclusive processes. When the helicity conservation in QCD for exclusive processes is valid at hadron level \[8\]

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

(4)

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.

Possible sources of the one-spin asymmetries are: higher twist effects \[3\], correlation of $k_{\perp}$ and spin in structure \[6\] and fragmentation \[7, 8\] functions, rotation of valence quarks inside a hadron \[9\] and the coherent rotation of the quark matter inside the constituent quarks \[10\].

The main points of the mechanism proposed in \[10\] are:

- asymmetry reflects the internal spin structure of the constituent quarks and is proportional 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 initial hadron.

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 can be probed (Fig. 1). The observed $p_{\perp}$-behavior of asymmetries in inclusive processes confirms these predictions \[11\]. 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, event at short
distances, could be filled with 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.

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

\[ p_\uparrow + p \rightarrow \pi, \gamma, \text{jet} + X \]  

(5)

As an example we consider charged pion production. The predicted values of \(A_N\) are different for the different mechanisms. In particular, the model \[10\] predicts the energy independent values about 30% at \(p_\perp > \Lambda_\chi(\simeq 1 - 2 \text{ GeV/c})\), i.e.

\[ A^{\pi\pm}_N \sim \text{const.} p_\perp^0 \simeq \pm 30\% \]

at high \(p_\perp\). Note that the corresponding asymmetry in the neutral pion production has small values due to isotopic relations. The similar values of asymmetry predicts the model \[9\], but the \(p_\perp\)-dependence of asymmetry should be significantly different; however, it is not specified in the model. As it has been noted higher twists effects at RHIC energies and high \(p_\perp\) will not provide significant contribution to asymmetry \(A_N\). Phenomenology of these effects has not been developed yet and predictions could vary from a few to tens percents. However, higher twists provide decreasing asymmetries at high \(p_\perp\)

\[ A^{\pi\pm}_N \sim M/p_\perp \]

and could be easily recognized then. The same is true for the predictions of the mechanisms discussed in \[8\].

Fragmentation mechanisms require measurements of the two-particle final states and are relevant for studies of transverse polarization of quarks inside polarized hadron. This problem will be discussed later.

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

\[ \delta A = \frac{1}{P_1} \frac{1}{\sqrt{N}}. \]  

(6)

For the values of RHIC luminosity \(L = 2 \cdot 10^{32} \text{cm}^{-2} \text{s}^{-1}\) and beam polarization \(P_1 = 70\%\) 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 \(p_L = 200\) GeV/c indicated that the observed symmetries could be of order of tens percents. In the \(\pi^0\) production asymmetries are expected to be smaller due to the isospin relation between cross sections valid in the parton model. The \(p_L = 200\) GeV/c is the maximal energy the asymmetries in these processes has been measured so far. The study of this reaction at RHIC energies is important as a clear test of perturbative QCD regime and nonperturbative dynamical models. In general, these studies are important for the understanding of the QCD vacuum and transitions between the perturbative and nonperturbative ones.

**Transverse spin densities and two–spin correlations in inclusive processes.** Extensive studies of the theoretical aspects of transverse spin structure of the nucleon were made in \[14\] and \[17, 18, 19\].
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.

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 a positive bound for \( \delta q(x) \) has been obtained [15]:
\[
|\delta q(x)| \leq q_+(x) \tag{7}
\]
and bound for \( \delta q(x) \) limiting its behavior at \( x \to 0 \) [16]:
\[
\delta q(x) \leq \log x/x. \tag{8}
\]

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

\[
p_\uparrow + p_\uparrow \rightarrow \mu^+ + \mu^- + X
\]

is most suitable for the determination of the quark transversity.

The corresponding two–spin asymmetry is directly related to the quark transversity distributions \( \delta q(x) \).

On the other hand, we would like to stress that the measurements of 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 \( p_L \)'s in the collisions of longitudinally polarized protons.

As it has been mention transversity for spin-1/2 nucleon gets no contribution from gluons contrary to helicity [17]. It leads to the following signal of the onset of perturbative QCD regime [22]

\[
A_{TT}/A_{LL} \ll 1 \tag{9}
\]
in the processes

\[
p + p \rightarrow 2 \text{jets} + X \\
p + p \rightarrow \pi + X \\
p + p \rightarrow Q\bar{Q} + X,
\]

but in the Drell-Yan processes of lepton pairs production the ratio \( A_{TT}/A_{LL} \) is sensible to the ratios \( \delta q/\Delta q \) and therefore

\[
A_{TT}/A_{LL} \sim 1. \tag{11}
\]

It has been stated [22] that the above results reflect the fundamental aspects of parton approach in QCD: helicity, twist and chirality selection rules.

Experimental sensitivity \( \delta A_{LL/TT} \) can be estimated according to the following formula:

\[
\delta A_{LL/TT} = \frac{1}{P_1P_2} \frac{1}{\sqrt{N}}. \tag{12}
\]
As in the case of single-spin asymmetry the measurements with accuracy of a few percents are feasible at RHIC up to $p_\perp$ about 30 GeV/c \cite{13}.

**Strangeness in the hadrons.** It is evident from deep-inelastic scattering data that strange quarks as well as gluons could play essential role in the spin structure of nucleon. DIS data shows that strange quarks are negatively polarized in polarized nucleon, $\Delta s \simeq -0.1$. Elastic $\nu p$-scattering also indicates that strange quarks are polarized and gives the value $\Delta s = -0.15 \pm 0.08$ \cite{23}. The presence and polarization of strange quarks inside a hadron should provide experimental signal in hadronic reactions.

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

$$y = \langle U|\bar s s|U\rangle/\langle U|\bar uu + \bar dd + \bar ss|U\rangle$$

(13)
can be estimated from different approaches as $y = 0.1 - 0.5$.

It was argued \cite{24} that the single spin asymmetry $A_N$ in the process $pp \rightarrow \varphi + X$ is connected with orbital momenta of strange quarks in the internal structure of constituent quarks. The estimate for asymmetry $A_N$ in $\varphi$-meson production at $p_\perp > \Lambda_\chi (\simeq 1 - 2$ GeV/c) is:

$$A_N(\varphi) \propto \langle P_Q\rangle \langle L_{\varphi\varphi}\rangle y \simeq 0.01 - 0.05.$$  

(14)

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

Another promising way to study the strange quark polarization inside a nucleon is in the measurement of the hyperon polarization in the polarized beam fragmentation region. A very significant polarization of $\Lambda$-hyperons has been discovered two decades ago \cite{25}. Since then measurements in different processes were performed and number of models was proposed for qualitative and quantitative description of these data \cite{26}. Among them the Lund model based on classical string mechanism of strange quark pair production \cite{27}, models based on spin–orbital interaction \cite{28} and multiple scattering of massive strange sea quarks in effective external field \cite{29} and also models for polarization of $\Lambda$ in diffractive processes with account for proton states with additional $\bar ss$ pairs such as $|uud\bar ss\rangle$ \cite{30, 31}.

As it is widely known now, only part (less than one third in fact) of the proton spin is due to quark spins \cite{32, 33}. These results can be interpreted 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 in asymmetries in hadron production. The explicit mechanism has been discussed in \cite{34}. The main role belongs to the orbital angular momentum of $qq$–pairs inside the constituent quark while constituent quarks themselves have very slow (if at all) orbital motion and may be described approximately by $S$-state of the hadron wave function. The observed $p_\perp$–dependence of $\Lambda$–hyperon polarization in inclusive processes seems to confirm such conclusions, since it appears to show up beyond $p_\perp > \Lambda_\chi (\simeq 1 - 2$ GeV/c) i.e. the scale where internal structure of constituent quark can be probed (Fig. 2). The main results of the considered model:
- polarization of Λ–hyperons arises as a result of the internal structure of the constituent quark and its multiple scattering in the mean field. It is proportional to the orbital angular momentum of strange quarks initially confined in the constituent quark;

- sign of polarization and its value are proportional to polarization of the constituent quark gained due to the multiple scattering in the mean field.

It is predicted that the double spin correlation parameters should have a similar $p_\perp$-dependence:

$$D_{TT} \sim D_{LL} \sim 0$$

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

$$D_{TT} \sim D_{LL} \sim \text{const.} \, p_\perp^0$$

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

$$p_\uparrow + p \rightarrow \Lambda_\uparrow + X$$

and

$$p_\rightarrow + p \rightarrow \Lambda_\rightarrow + X.$$ 

These relations reflects the fact that the polarized strange quark is located inside the constituent quark of a small size.

It is the generic feature of this model: spin effects in inclusive processes are related to the internal structure of constituent quark. This fact could explain similarity in the behavior of different spin observables in inclusive processes, i.e. 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.

**Elastic scattering.** In perturbative QCD, there are several mechanisms that could give important contributions to fixed-angle elastic scattering. However, due to small cross-section studies of this exclusive process could be carried out in the region where nonperturbative effects are essential.

There are several models based on nonperturbative dynamics predicting significant nonzero analyzing power at fixed angles.

We quote the predictions of the already mentioned $U$–matrix chiral quark model [35].

In elastic scattering constituent quarks are scattered coherently by effective field. Spin effects here are not associated with internal structure of constituent quark as it is in the inclusive processes. Elastic scattering then probes dynamic of scattering of constituent quark as a whole in effective field and spin effects here reflect dynamics of constituent quark helicity flip in this effective field.

The analyzing power in $pp$ elastic scattering does not decrease with energy and and has a nonzero value at $s \rightarrow \infty$. The analyzing power at $\sqrt{s} = 0.5 \text{ TeV}$ and $-t = 10 \text{ (GeV/c)}^2$ in $pp$ elastic scattering is predicted to be 12%, while $A$ is predicted to be 7% at $-t = 5 \text{ (GeV/c)}^2$. 
Other nonperturbative models \cite{36, 37} also predict nonzero values for the analyzing power in RHIC energy range, while perturbative QCD (hard scattering model) predict vanishing values.

For estimation of the experimental sensitivity the following dependence of differential cross-section of $pp$-elastic scattering provided by the mentioned model for the fixed $t$ region ($-t \gg 1$, $-t/s \ll 1$) can be used:

$$\frac{d\sigma}{dt} \simeq \frac{R(s)}{\sqrt{-t}} \exp\left(-\frac{2\pi\xi}{M} \sqrt{-t}\right), \quad (15)$$

where $M = Nm_Q$, $N = 6$, $m_Q = 0.3$ GeV and $\xi = 1.7$, $R(s) \sim \frac{1}{M} \ln s$ is the interaction radius. Such dependence is in a very good agreement with the available experimental at $3 < -t < 12$ (GeV/c)$^2$ and $p_L > 400$ GeV/c.

The measurement of analyzing power $A$ in the elastic scattering process $p_\uparrow + p \rightarrow p + p$ at RHIC will allow:

- study of hadron structure at long distances as a bound state of the constituent quarks and role of confinement;
- study of the dynamics of constituent quark helicity flip interactions and the role of spontaneous breaking of chiral symmetry.

Estimates of experimental sensitivity show that the region of $-t \sim 10$ (GeV/c)$^2$ is experimentally accessible.

**Conclusion.** Spin measurements at RHIC with polarized proton beams would probe the fundamental couplings of the underlying Lagrangian and investigate the spin structure of the nucleon. A wide range of one- and two-spin asymmetries could be measured. As has often happened in the past, these spin measurements might bring unexpected new results; this would certainly stimulate the development of new theoretical ideas.

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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
