N.E. Tyurin

SOME ASPECTS OF SPIN PHYSICS AT RHIC
(Talk presented at PHENIX project meeting.
Vladimir, Russia, November 9-11, 1995)

Introduction

Spin physics is becoming a very popular topic during last few years. Now it is generally accepted that spin plays an important role in particle and high energy physics [1-3]. It provides crucial information on such fundamental issues as

- hadron wave functions
- interplay of large and short distance dynamics
- chiral symmetry breaking and confinement.

To proceed in our understanding of the field we should answer the questions:

- How the constituents’ interactions depend on spin?
- What is a picture of the proton structure, in particular, its spin structure?

Spin experiments at RHIC are planned to provide systematic studies of the above issues. Spin program has been approved for both machine and detectors and RHIC operation before year 2000 is a realistic goal. All that cause great interest and enthusiasm of the physics community. The subject was extensively discussed in June, 1995 and could be found in distributed set of transparencies entitled “Review of the RHIC Spin Physics Program”.

In this talk we consider some aspects [1,4] which have not received much attention in the above mentioned review. In particular, we discuss spin properties of QCD, basic experimental results which continue to be an engine of this topic, physics to be done at RHIC with particular emphasis on asymmetries in inclusive hadron production.
Spin Properties of QCD

The QCD Lagrangian has the form

\[ L_{QCD} = \bar{\psi}(x)(i\gamma^\mu D_\mu - \hat{m})\psi(x) - \frac{1}{4}\text{tr}(G_{\mu\nu}G^{\mu\nu}), \]  

(1)

\[ D_\mu = \partial_\mu - ig\frac{\lambda^a}{2}G^a_\mu, \quad \hat{m} = \text{diag}(m_u, m_d, m_s). \]

\( G^a_{\mu\nu} \) is the gluon field strength tensor, \( \lambda^a \) are the generators of the \( SU(3) \) color group. It describes interactions between quarks and gluons — the hadron constituents. Contrary to QED, this Lagrangian describes self-interaction of the massless color gluons. The theory is nonlinear over the gauge fields \( G^a_\mu \), and the coupling constant is large. Fortunately because of asymptotic freedom [5] the running coupling constant \( \alpha_s(Q^2) \) becomes small at the scale \( Q^2 > \Lambda_{QCD}^2 \). The parameter \( (\Lambda_{QCD})^{-1} \) determines the scale of short distances. Thus one introduces perturbative and non-perturbative “phases” of QCD.

The current quark masses in \( L_{QCD} \) are small. In the limit \( m_q \to 0 \) \( L_{QCD} \) is invariant under the chiral group \( SU(3)_L \times SU(3)_R \). Chiral invariance and vector nature of QCD impose important constraints on spin observables. In the chiral limit \( m_q \to 0 \) the QCD interactions are the same for the left and right quarks

\[ \bar{\psi}\hat{D}\psi = \bar{\psi}_L\hat{D}\psi_L + \bar{\psi}_R\hat{D}\psi_R, \]
\[ \psi_L = \frac{1}{2}(1 - \gamma_5)\psi, \quad \psi_R = \frac{1}{2}(1 + \gamma_5)\psi, \]
\[ \gamma_5 \psi_{L,R} = \mp \psi_{L,R}. \]

For massless quarks chirality and helicity coincide

\[ \psi_{1/2} = \psi_R, \quad \psi_{-1/2} = \psi_L. \]

The quark helicity conservation is the most characteristic feature of perturbative theory with vector coupling.

Because of a small mass in \( L_{QCD} \)

\[ \psi_{\pm 1/2} = \psi_R + 0\left(\frac{m}{\sqrt{s}}\right). \]
In hard interactions polarization has to be vanishingly small

\[ P_q \propto \frac{\alpha_s m_q}{\sqrt{s}}, \tag{2} \]

where \( \alpha_s \) and \( m_q \) are small and \( \sqrt{s} \sim p_\perp \) is large.

In fact the chiral group \( SU(3)_L \times SU(3)_R \) is not realized in the hadron spectrum and chirality is not a symmetry of QCD. It is broken by the vacuum state \( \langle \bar{\psi}\psi \rangle \neq 0 \). This is a non-perturbative effect.

Perturbative QCD (pQCD) deals with perturbative vacuum invariant under the chiral transformations. Nonperturbative phase of QCD should provide the spontaneous breaking of chiral symmetry. The relevant scale is characterized by the parameter \( \Lambda_\chi \). The values of the parameters related to confinement and spontaneous breaking of chiral symmetry are \( \Lambda_{QCD} = 100 \div 300 \text{MeV} \) and \( \Lambda_\chi \simeq 1 \text{GeV} \) [6].

At small distances \( r < \Lambda_{QCD}^{-1} \) helicity is conserved due to chiral invariance. At \( r > \Lambda_{QCD}^{-1} \) there is no need for helicity conservation, but it appears that asymmetries in this range are close to zero. In the range between the two scales chiral symmetry is spontaneously broken and non-perturbative effects should be taken into account although \( \alpha_s \) is small at \( r < \Lambda_{QCD}^{-1} \).

How to deal with non-perturbative phenomena? To use the ideas of effective Lagrangians' approach which was worked out in details, for instance, Nambu-Jona-Lasinio model [7]. The chiral symmetry breaking results in particular in generation of quark masses and in appearance of quark condensates: \( m_q \propto -\Lambda_\chi^{-2} \langle \bar{\psi}\psi \rangle \). As a consequence it assumes some constraints on hadron structure. We return to this important issue in last part of this talk.

The basic tool for obtaining QCD predictions for hard processes is the factorization which separates long distance dynamics of the bound state system and short distance constituents' interaction.

The hadron wave function

\[ \psi^h(x_i, \vec{k}_{\perp i}, \lambda_i), \]

where \( x_i \) is light-cone momentum fraction of the i-th constituent (quark or gluon), \( \vec{k}_{\perp i} \) is its transverse momentum and \( \lambda_i \) — the helicity. It describes bound state of the constituents and may be decomposed over Fock basis

\[ |p \rangle = |qqq \rangle \psi_{qqq}^p + |qqqg \rangle \psi_{qqqg}^p + \ldots \]
For exclusive process $A + B \rightarrow C + D$ the hadron states with constituents additional to valence quarks are suppressed. The respective transition amplitude of a hadron [8]

$$
\Phi_{\lambda}^h(x_i, \lambda_i; Q) \propto \int_{k_{\perp i}^2 < Q^2} ^{k_{\perp i}^2} [d^2k_{\perp i}] \psi_{\lambda}^h(x_i, \vec{k}_{\perp i}, \lambda_i),
$$

(3)
corresponds to representation of the hadron as a set of collinear partons. Fig.1 shows the three valence quarks. As it was said the other states are suppressed by the powers of $(Q^2)^{-1}$.

According the factorization theorem the hadron amplitude $T$ can be presented in the form (Fig.2):

$$
T \propto \prod_{k=A,B,C,D} \Phi^k(x_i, \lambda_i, Q) \otimes T_H(x_i, \lambda_i; Q).
$$

This equation assumes integrations over momentum fractions for all four hadrons as well as sum over $\lambda_i$. All the quarks are in the $s$-state because of integration over $[d^2k_{\perp}]$ in eq.(3) and consequently the hadron helicity

$$
\lambda_h = \sum \lambda_i.
$$

The hard amplitude $T_H$ conserves the quark helicity and we get

$$
\lambda_A + \lambda_B = \lambda_C + \lambda_D.
$$

This equality leads to very important experimental consequences — vanishing of the one-spin asymmetries for hard exclusive processes:

$$
A_N = 0.
$$

For inclusive process $A + B \rightarrow C + X$ the key instruments are structure functions:

$$
f_{a/h}(x, \lambda, Q) \propto \sum_{n, \lambda_i} \int [dx][d^2k_{\perp}] \left| \psi_n^h(x_i, \vec{k}_{\perp i}, \lambda_i) \right|^2 \cdot \sum_{b=a} \delta(x_b - x).
$$

(4)
Contrary to exclusive reaction all of the Fock states with arbitrary numbers of quarks and gluons and values of orbital angular momentum contribute

\[ \lambda_h \neq \sum_i \lambda_i. \]

Therefore we should write

\[ \lambda_h = \lambda_q + \lambda_g + <L_z>_q + <L_z>_g. \]  (5)

This is the most general equation for a hadron helicity distributed among its constituents.

If the structure functions eq.(4) are known the factorization allows one to calculate the cross-sections and asymmetries. As an illustration we give the two formulas (see fig.3) for the asymmetries in inclusive \( pp \to hX \) process:

\[
A_N\sigma(pp \to hX) = \sum_{a,b,c,d} \int dx_a dx_b \frac{dz}{z} \Delta_{L} f_{a/p}(x_a) \cdot f_{b/p}(x_b) \times \Delta_{L} f_{a/p}(x_a) \cdot f_{b/p}(x_b) \times a_N\sigma(ab \to cd) \cdot D_{h/c}(z), 
\]  (6)

\[
A_{LL}\sigma(pp \to hX) = \sum_{a,b,c,d} \int dx_a dx_b \frac{dz}{z} \Delta_{L} f_{a/p}(x_a) \Delta_{L} f_{b/p}(x_b) \times a_{LL}\sigma(ab \to cd) \cdot D_{h/c}(z), 
\]  (7)

where notations were earlier introduced or are obvious. Each factor \( f_{a/h} \) is related to a single incoming hadron. It makes useful the DIS data. Because of vanishing asymmetry in the hard subprocess

\[ a \propto \frac{\alpha_s m_q}{\sqrt{s'}} \sqrt{s'} \sim p_\perp, \]

the one-spin transverse asymmetry \( A_N \) at hadron level should also vanish. This is true even if the above simple factorization does not work. The conclusion is that perturbative QCD predicts \( A_N = 0 \).

Apart of that factorization provides a powerful and transparent approach based on \( L_{QCD} \) Eq.(1) to make calculations and predictions of the asymmetries to be then experimentally measured.

What are the limitations of such calculations? The approach assumes a parton picture of hadron consisting of free quarks and gluons. In fact
only interactions with $Q^2 > \Lambda_{QCD}^2$ resolve the partonic structure. The range $\Lambda_{QCD}^2 < Q^2 < \Lambda_{\chi}^2$ requires more care.

To rely on factorization predictions, for instance, under the study of two-spin asymmetries $A_{LL}$ and $A_{NN}$, one should ask the question: are we in the perturbative QCD sector? The best test is to measure $A_N$ and to prove that $A_N = 0$. It is a great challenge to find a “threshold” $p_{\perp}$ value where $pQCD$ and factorization could be well justified. In the case $A_N \neq 0$ one should estimate the potential sources of the observed asymmetry. The present day experiment shows that non-perturbative QCD effects are to be taken into account.

**Basic Experimental Results**

1. It is well known that single-spin effects [9] in general do not consent with $pQCD$. Fig.4 shows the asymmetry $A$ plotted against $p_{\perp}^2$ for polarized $pp$ elastic scattering at 24 and 28 GeV/c. The asymmetry $A$ grows up with $p_{\perp}^2$ contrary to what one could expect from the perturbation theory.

   The other important set of data [10] is related to $\Lambda$ — polarization in the inclusive production process $pp \to \Lambda X$. In fig.5 the polarization of $\Lambda$ hyperons produced by 400 GeV protons is plotted against $p_{\perp}$. Fig.6 shows the data at 12 GeV and 2000 GeV compared with the curve (dashed) which corresponds to 400 GeV data. We conclude that polarization of $\Lambda$ does not depend much on energy. It grows up and becomes constant at $p_{\perp} \simeq 1$GeV/c. It is $x$-dependent function.

   Analysis of the one-spin asymmetries data leads to conclusion on necessity of further experimental studies. If these effects persist at higher energies it will strongly indicate on non-perturbative origin of spin dynamics.

2. Measurements of polarized structure functions in DIS processes [11] revealed that quark contribution to the nucleon spin is small. The other possibilities could be contribution of gluons and account for orbital angular momentum. Then the only constraint is

$$\frac{1}{2} = \frac{1}{2} \Delta q + \Delta g + \langle L_z \rangle_q + \langle L_z \rangle_g, \quad \Delta q = \Delta u + \Delta d + \Delta s. \quad (8)$$

Knowing different terms in Eq.(8) allows one to approach the picture of
hadron structure and to clarify the role of non-perturbative effects. Experiment shows that
\[
(\Delta u + \Delta d + \Delta s)_p \simeq 1/3, \quad \Delta s \simeq -0.1 .
\] (9)
Therefore about 2/3 of the proton spin is to be attributed to orbital angular momentum and gluons. The role of \(s\)-quarks is important. Probably one should say in general that role of \(\bar{q}q\)-pairs in the proton structure is to be carefully traced.

**The Structure Functions**

We introduce first distribution functions for quarks \(q_\lambda(x, Q^2) = f_{q/h}(x, \lambda; Q)\), antiquarks \(\bar{q}_\lambda(x, Q^2)\) and gluons \(G_\lambda(x, Q^2)\). Then spin dependent quark distributions are as follows:
\[
\Delta L q(x, Q^2) = q_{\rightarrow}(x, Q^2) - q_{\leftarrow}(x, Q^2) ,
\] (10)
for longitudinally polarized proton and
\[
\Delta_\perp q(x, Q^2) = q_{\uparrow}(x, Q^2) - q_{\downarrow}(x, Q^2) ,
\] (11)
for transversely polarized proton. For gluons
\[
\Delta G(x, Q^2) = G_{\rightarrow}(x, Q^2) - G_{\leftarrow}(x, Q^2) .
\] (12)

Averaged over spin structure function
\[
f_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2[q(x, Q^2) + \bar{q}(x, Q^2)] .
\] (13)

Sometimes it is represented as
\[
f_1 = f_1^q + f_1^\bar{q} .
\]
Spin structure function
\[
g_1(x, Q^2) = g_L(x, Q^2) = \frac{1}{2} \sum_q e_q^2(\Delta L q + \Delta L \bar{q})
\] (14)
measures quark helicity distribution in a longitudinally polarized nucleon. The function

$$h_1(x, Q^2) = g_\perp(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \left( \frac{m_q}{xM} \right) \cdot (\Delta_\perp q + \Delta_\perp \bar{q})$$  \hspace{1cm} (15)

measures the average transverse spin for quarks. In the simple parton model with noninteracting partons, i.e. when hadron is treated as a gas of free quarks, one should expect [12]

$$\Delta_\perp q = \Delta_L q.$$  

The second spin dependent structure function is determined as

$$g_2(x, Q^2) = h_1(x, Q^2) - g_1(x, Q^2)$$  \hspace{1cm} (16)

and is related to effects of quark-gluon interactions or to the higher twists.

The functions introduced satisfy to series of important constraints and relations (sum rules) [13]. They are often used as a tool for QCD tests. Up to now only the longitudinal spin-dependent structure functions of the nucleon were measured experimentally.

**Spin Physics at RHIC**

The topic was extensively reviewed during dedicated meeting at BNL [14]. This paragraph contains only some of the relevant directions (cf. [14, 4, 15]).

1. It is expected that enigma of the proton spin distribution between various constituents should be experimentally solved at RHIC by measuring the separate contributions of gluons, valence and sea quarks and angular momentum fraction.

We enlist below the reaction, fundamental subprocess (cf. fig3), the parameter to be measured and the function which will be extracted:
\[ \vec{p} + \vec{p} \rightarrow \gamma + X, \quad g + q \rightarrow \gamma + q, \quad A_{LL} \Rightarrow \Delta G \]
\[ \Delta G(x) \]
\[ \vec{p} + p \rightarrow W^+ + X, \quad u + \bar{d} \rightarrow W^+, \quad A_L \Rightarrow \Delta \bar{d}(x)/\bar{d}(x) \]
\[ \Delta u(x)/u(x) \]
\[ \vec{p} + p \rightarrow W^- + X, \quad \bar{u} + d \rightarrow W^-, \quad A_L \Rightarrow \Delta \bar{u}(x)/\bar{u}(x) \]
\[ \Delta d(x)/d(x) \]
\[ \vec{p} + \vec{p} \rightarrow \mu^+ \mu^- + X, \quad q + \bar{q} \rightarrow \mu^+ + \mu^-, \quad A_{LL} \Rightarrow \Delta \bar{q}(x) \]

We do not provide the equations for one- and two-spin asymmetries. The actual formulas certainly contain rather complicated integrations and should be analyzed with selection of appropriate kinematical limits.

2. Clarification of the Strangeness content of a nucleon (and sea) requires the study of hyperon production processes.

- \( p + p \rightarrow \Lambda + X \), where, as always, polarization of \( \Lambda \) is studied through its decay process.
- \( \vec{p} + p \rightarrow \vec{\Lambda} + X \), measurement of the parameter \( D_{LL} \) in the fragmentation region at large \( X_F \) values. The estimates provide significant values for \( D_{LL} \) close to 50%.
- \( \vec{p} + \vec{p} \rightarrow \vec{\Lambda} + X \), measurement of the three-spin correlation parameters \((l,l,l,0)\) would be important for the study of hyperon production dynamics and the strangeness content of the proton.

3. The transverse spin can not be measured in DIS because of the chiral invariance of electromagnetic current.

- \( p_\uparrow + p_\uparrow \rightarrow \mu^+ \mu^- + X \), \quad \( q + \bar{q} \rightarrow \mu^+ + \mu^- \), \quad \( A_{NN} \Rightarrow h_1(x) \)

The analysis based on operator product expansion shows that the function \( g_2(x,Q^2) \) in related to higher twists. Measuring the function \( h_1 \) (\( h_1 = g_1 ? \)) one could judge on the role of higher twists at high energies as well as non-perturbative effects in general.

- \( p_\uparrow + p_\uparrow \rightarrow Z^0 + X \), \quad \( q + \bar{q} \rightarrow Z^0 \rightarrow e^+ e^- \), \quad \( A_{NN} \Rightarrow \Delta \perp q(x) \)
\[ \Delta \perp \bar{q}(x) \]
\[ p_t^+ p \rightarrow h^\pm + X, \quad p_\perp \rightarrow h^\pm + X, \quad p_\perp \rightarrow \text{dependence of the asymmetry was not measured before. One may expect large } A_N \text{ at large } p_\perp \text{ values. Experimental conclusion on the prediction is an important test of } pQCD \text{ and the role of non-perturbative phenomena.} \]

4. Elastic scattering of polarized protons and measurements of parameters \( A_N \) and \( A_{NN} \) is needed to

- confirm AGS effect at higher energies;
- study spin structure of vacuum exchanges;
- discriminate the models accounting non-perturbative dynamics.

5. Effects beyond the Standard Model (compositeness, SUSY). Both \( A_L \) and \( A_N \) measurements are useful in the search for the compositeness.

- \( p + p \rightarrow \text{jet} + X, \quad A_L \) is to be rather large at \( p_\perp \approx 3 - 4 \text{ GeV} \).

Composite-ness should enlarge the expected polarization effects. This deviation would arise from the new interaction between quarks induced by their composite structure:

\[ L = L_{QCD} + \eta \frac{g^2}{\Lambda^2} \bar{q} A q \frac{A_q}{A_q}, \]

where \( \Lambda_c \) is the scale of the compositeness of the order of the binding energy for preons (1-2 TeV). The above said is also true for production of direct photons or lepton pairs.

The asymmetries appearing in the production of SUSY particles in the polarized hadron collisions will differ from the corresponding asymmetries arising in the production of ordinary particles. \( A_{LL} \) is a relevant spin parameter. For the processes where a pair of SUSY particles is produced, the subprocess asymmetry \( A_{LL} = -100\% \) for the case of massless squarks and gluinos because of the helicity conservation. As a result \( A_{LL} \) should be negative (and have larger values) contrary to the case of ordinary particles. So, one could expect in the jet production process appearance of events with specific behaviour of \( A_{LL} \).

**Inclusive Hadron Production**

Studies of one-spin transverse polarizations are of primarily importance because of
• the existing experimental results (versus $pQCD$);

• principal importance to clarify applicability of the "Born formulas" of $pQCD$ before going further to "the goals".

In this paragraph we discuss a possible origin of asymmetry on pion production:

$$p_\gamma + p \rightarrow \pi^{\pm,0} + X.$$  

We use the scheme [16] which incorporates perturbative and non-perturbative phases of QCD. It was already mentioned that non-perturbative sector of QCD should provide the two important phenomena: confinement and spontaneous breaking of chiral symmetry with the relevant scales $\Lambda_{QCD}$ and $\Lambda_{\chi}$. The chiral symmetry breaking results in generation of $m_q \sim M$ and appearance of quark condensates $\langle \bar{\psi}\psi \rangle \neq 0$.

A hadron is represented as a loosely bounded system of the valence constituent quarks and quark condensate surrounding this core. In this approach constituent quarks are extended objects. They are described by their size and quark matter distribution: $r_Q = \xi/m_Q$; $d_Q(b)$.

The general form of the effective Lagrangian relevant for the description of the non-perturbative phase of QCD

$$L_{QCD} \rightarrow L_{eff} = L_\chi + L_I + L_c,$$

where $L_\chi$ is responsible for the spontaneous chiral symmetry breaking, $L_I$ — for the constituent quarks interaction, $L_c$ — for the confinement. Both $L_I$ and $L_c$ do not affect the internal structure of constituent quarks. The partonic structure of constituent quarks can be resolved in the processes with large $Q^2$ values.

The particular form for $L_\chi$ is NJL model with 6-quark interaction:

$$L_\chi = \bar{\psi}(i\gamma \cdot \hat{\partial} - \hat{m})\psi + \frac{1}{2} \sum_a G[(\bar{\psi}\lambda_a\psi)^2 + (\bar{\psi}i\lambda_a\gamma_5\psi)^2] + K[\det\bar{\psi}_i(1 - \gamma_5)\psi_j + \det\bar{\psi}_i(1 + \gamma_5)]. \quad (17)$$

Eq.(17) is a minimal effective Lagrangian which reflects some of the basic properties of non-perturbative QCD.

The constituent quark masses are:

$$m_U = m_u - 2G < 0|\bar{u}u|0> - 2K < 0|\bar{d}d|0> = < 0|\bar{s}s|0>.$$ \quad (18)
Massive quarks appear as quasiparticles: as current quarks and the surrounding clouds of $\bar{q}q$ — pairs which consist of a mixture of quarks of different flavors.

Quantum numbers of the constituent quarks are the same as the quantum numbers of current quarks due to conservation of the corresponding currents in QCD. Constituent quarks picture of a hadron is consistent with the results for the proton spin structure function $g_1(x)$ obtained in DIS. It is useful to note that

$$2 < U|\bar{s}s|U > / < U|\bar{u}u + \bar{d}d|U > \sim 0.15$$

$$< U|\bar{u}u|U > \gg < U|\bar{d}d|U >, < U|\bar{s}s|U > .$$

About the spin content of constituent quark. The axial anomaly leads to compensation of valence quark helicity by helicities of quarks from the cloud

$$< Q^i|A_{\mu s}^i|^Q > = \frac{1}{2} \left( \delta^i_j - \frac{2}{3} c \right) s_{\mu}^i. \quad (19)$$

Eq.(19) shows that constituent quark of any flavor contains a sea of polarized current quarks of all other flavors.

Significant part of constituent quark spin should be associated with the orbital angular momentum of quarks inside this constituent quark (cloud quarks should rotate coherently). What is the origin of this orbital angular momentum? One can use an analogy between hadron physics and superconductivity, where pairing correlations induce particle current around the anisotropy direction $\hat{l}$. Thus particle at the origin is surrounded by cloud of correlated particles that rotate around $\hat{l}$. In our case the axis of anisotropy is determined by the polarization vector of valence quark located at the origin of constituent quark. The orbital angular momentum $\vec{L}$ lies along $\hat{l}$ and its value is proportional to quark density $< Q|\bar{q}q|Q >$.

Thus, the spin of constituent quarks $J_U$ is determined by the following sum:

$$J_U = \frac{1}{2} = J_{uv} + J_{(\bar{q}q)} + < L_{(\bar{q}q)} > . \quad (20)$$

Estimation of the orbital momentum contribution with account for eq.(9) and $SU(6)$ model leads to conclusion

$$< L_{(\bar{q}q)} > \sim 1/3.$$
Orbital motion of quark matter inside constituent quark is the origin of the asymmetries in inclusive production at moderate and high transverse momenta. Such asymmetry will be significant at $p_\perp \geq \Lambda_\chi \simeq 1\text{GeV}$. At high $p_\perp$ values we will have a parton picture for constituent quark as a cluster of non-interacting quarks which however should naturally preserve their orbital momenta of the preceding non-perturbative phase of QCD.

Without going in the details the asymmetry for the process

$$h_1^\uparrow + h_2 \rightarrow h_3 + X$$

is taking the form

$$A_N(s, x, p_\perp) = \sin(P_Q < L_{\bar{q}q} >)d\sigma^\text{hard}/\{d\sigma^\text{hard} + d\sigma^\text{soft}\}. \quad (21)$$

The sign and value of the asymmetry are determined by the polarization $P_Q$ of the relevant constituent quark $Q$ inside the hadron $h_1$ and the mean orbital momenta of cloud quarks:

$$h_3 = \pi^+, \quad Q = U$$

$$h_3 = \pi^-, \quad Q = D.$$  

For instance, in $SU(6)$ model $P_U = 2/3$ and $P_D = -1/3$. Fig.7 represents the model predictions for the asymmetries in $p_\uparrow + p \rightarrow \pi^\pm + X$. $A_N$ has a weak energy dependence and gets significant values starting from $p_\perp \simeq 1\text{GeV}/c$. The observed $p_\perp$-behaviour of asymmetries in inclusive processes seems to confirm these conclusions. Fig.8 shows the asymmetry in $\pi^0$-production.

Asymmetry reflects internal structure of the constituent quarks and is proportional to the orbital angular momentum of current quarks inside the constituent quark. The significant asymmetries appear beyond $p_\perp \geq 1\text{GeV}/c$, i.e. the scale where the internal structure of constituent quark can be probed. The proposed mechanism is also appropriate for description of hyperon polarizations. It is worth noting here that this idea could be traced back to the model of rotating hadronic matter [17].

The proposed mechanism for generation of the asymmetry differs from the one when asymmetry appears at the level of fragmentation function [18]. In this connection we would like to mention here the ALEPH result on depolarization occurring during hadronization [19].

In conclusion we would like to underline that spin physics program which can be conducted at RHIC is potentially very rich. Polarization experiments
always in the past provided particle physics with unexpected new results and initiated searches for deeper understanding of the fundamental dynamics.

I am pleased to thank S.M. Troshin for useful discussions and suggestions under preparation of this talk.

References

[1] Troshin S.M., Tyurin N.E. Spin Phenomena in Particle Interactions. World Scientific, 1994.

[2] Troshin S.M., Tyurin N.E. // Particle World, 1993, V.3, p.165.

[3] Ramsey G.P. // Particle World, 1995, V.4, p.11.

[4] Nadolsky P.M., Troshin S.M., Tyurin N.E. // Int.J.Mod.Phys.A9, 1994, p.2505.

[5] Mueller A. Perturbative Quantum Chromodynamics. World Scientific, 1987.

[6] Manohar A., Georgi H. // Nucl.Phys.B234, 1984, p.139.

[7] Nambu Y., Jona-Lasinio G. // Phys.Rev., 1961, V.122, p.345.

[8] Brodsky S. and Lepage P. // Phys.Rev.D22, 1980, p.2157.

[9] Krisch A.D. Plenary talk at the 9th International Symposium on High Energy Spin Physics, Bonn, 1990.

[10] Heller K. Invited talk at the 7th International Symposium on High Energy Spin Physics, Protvino, 1986.

[11] Ashman J. et al. // Nucl.Phys.B328, 1989, p.1.

[12] Anselmino M., Leader E. // Phys.Lett.B293, 1992, p.216.

[13] Bjorken J.D. // Phys.Rev., 1966, V.148, p.1457.
    Burkhardt H., Cottingham W.H. // Ann.Phys., 1970, V.56, p.453.
    Ellis J., Jaffe R.L. // Phys.Rev.D9, 1974, p.3594.
    Wandzura W., Wilczek F. // Phys.Lett.B172, 1977, p.195.
Ralston J.P., Soper D.E.// Nucl.Phys.B152, 1979, p.109.
Artru X., Mekhfi M.//Z.Phys.C45, 1990, p.669.
Jaffe R.L., X.Ji.// Phys.Lett., 1991, V.67, p.552.

[14] Review of the RHIC Spin Physics Program. BNL, June, 1995.

[15] Troshin S.M., Krisch A.D. in “Acceleration of Polarized Protons to 120 GeV and 1 TeV at Fermilab”. UM HE 95-09, 1995.
Robinett R.W. HEP-PH-9506230.
Sivers D. // Phys.Rev.D51, 1995, p.4880.
Bunce G. et al. Particle World, 1992, V.3,p.1.

[16] Troshin
S.M., Tyurin N.E.// Phys.Rev.D52, 1995, p.3862; //Phys.Lett.B355, 1995, p.543.

[17] Chou T.T., Yang C.N.// Nucl.Phys.B107, 1976, p.1.

[18] Collins J., Heppelmann S.F., Ladinsky G.A.// Nucl.Phys.B420, 1994, p.565.

[19] ALEPH Collaboration, CERN Report PPE/95-156.
This figure "fig1-1.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9512235v1
This figure "fig1-2.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9512235v1
This figure "fig1-3.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9512235v1