Semiclassical mechanism for single-spin asymmetry in $^0$-production

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Abstract

The chiral quark model combined with unitarity and impact parameter picture provides simple semiclassical mechanism for generation of the single-spin asymmetry $A_N$ in the $^0$-production in the polarized proton collisions at RHIC. We derive its linear $x_F$-dependence in polarized proton fragmentation region along with the energy and transverse momentum independence at large $p_T$ values.
Introduction

Single-spin asymmetry (SSA) is a sensitive tool to probe QCD at small and large distances. Experimentally significant SSA was observed in various processes of elastic scattering and inclusive hadron production. Study of transverse single-spin asymmetries in deep-inelastic processes (DIS) observed a significant progress during last years; it has been shown that asymmetry can be related to a rescattering in the final-state interactions due to gluon exchange [1, 2] – coherent effect not suppressed in the Bjorken limit. Another step in this direction is the nonperturbative, instanton-induced mechanism of SSA generation [5, 6, 3, 7]. Instantons lead to appearance of the quark anomalous magnetic moment [5, 6] and soft rescattering can provide a source for a leading twist SSA in semi-inclusive DIS [7]. Moreover, as it was noted there it would also affect integrated parton distributions and may jeopardize QCD factorization. Pauli coupling have an important consequences opening possibility of transversity studies in DIS processes [7]. A unified picture of SSA generation in Drell-Yan processes which combines Sivers mechanism with account for the higher twists contributions was proposed recently in [4]. Thus the significant role of non-perturbative effects in the mechanism of SSA generation is becoming more and more evident nowadays.

The processes of hadron-hadron interactions are even more complicated than DIS and origin of SSA in these reactions is not fully clarified. Despite a great progress in theoretical studies devoted to this problem, the phenomenological success is rather limited; a comprehensive approach able to get description of the existing set of the experimental data on polarization, asymmetries, spin correlation parameters and cross-sections is still absent at the moment.

The most widespread approaches in the field of hadronic processes are based on the assumed extended factorization in QCD with account for the internal parton transverse momenta in structure functions [8, 9, 10] or in the fragmentation function [11, 12]. An account for the direct higher twists contributions to parton scattering subprocesses also can lead to a nonzero asymmetry [13, 14, 15].

However, as it was shown recently the Collins fragmentation mechanism is suppressed in hadronic pion production [16]. It was shown in this work that the Sivers effect gives dominating contribution to asymmetry and the second relevant contribution gives a convolution of transversity with Collins fragmentation while other contributions to asymmetry can be neglected. It can lead to a significant contribution to \( A_N \) for the quark Sivers mechanism at moderate \( P_T \) and to its decrease at higher transverse momenta. Note, that the asymmetry is predicted to be non-zero at \( x_F = 0 \) for the both quark and gluon Sivers mechanisms and the same is valid for the asymmetry \( A_N \) for the gluon Sivers mechanism at \( x_F < 0 \).

Decreasing dependence of SSA with \( P_T \) has not yet been observed experimentally, most experimental data are consistent with a flat transverse momentum
dependence at $p_T > 1$ GeV/c. Another important point regarding unpolarized inclusive cross-section of $^0\pi$-production was discussed in [17]: it is unclear are the above approaches able to describe unpolarized inclusive cross-section dependence on transverse momenta. It has also been shown in the above paper that the description of the inclusive cross-section for $^0\pi$-production, at the energies lower than the RHIC energies meets difficulties in the framework of the perturbative QCD. Role of higher twist contributions was studied in the recent analysis of pQCD scaling of inclusive cross-section at large $p_T$ and its experimental status was given in [18]. Deviation from the pQCD scaling is mostly noticeable in the forward region where the most significant asymmetry in the $^0\pi$ production in $pp \rightarrow ^0\pi X$ has also been observed by the STAR collaboration at RHIC [19] at $\sqrt{s} = 200$ GeV (in the fragmentation region of the polarized proton). At the same time $A_N = 0$ in the neutral pion production in the backward and midrapidity regions [20, 21]. SSA has also a zero value in the $pp \rightarrow pX$, while $A_N \neq 0$ in the $pp \rightarrow nX$ [22] in the polarized proton fragmentation region. The experimental features observed at RHIC represent a difficulty for the explanation in the above mentioned theoretical approaches, in particular, those based on Sivers mechanism (is at variance with zero asymmetry at $x_F = 0$) or account for the anomalous magnetic moment of quarks (is at variance with zero asymmetry in the process $p-p \rightarrow pX$). Of course, more experimental data are needed to perform a conclusive test of various theoretical predictions and those predictions should be more specified and elaborated for the observables at the hadronic level.

Keeping in mind the experimental and theoretical situation in the field of SSA studies we show in this note that the gross features of SSA measurements at RHIC and FNAL (linear increase of asymmetry with $x_F$ and flat transverse momentum dependence at $p_T > 1$ GeV/c) can be explained and qualitatively described in the framework of the simple semiclassical mechanism based on the further development of the specific chiral quark model [23] and results of its adaptation for the treatment of the polarized and unpolarized inclusive cross-sections [24]. The data of STAR collaboration [19] for the unpolarized inclusive cross-section can simultaneously be described. This mechanism is consistent with other new experimental facts found at RHIC.

1 Semiclassical mechanism of SSA generation

It might happen that the SSA originates from the nonperturbative sector of QCD and is related to the mechanism of spontaneous chiral symmetry breaking (SB) in QCD [25], which leads to generation of quark masses and appearance of quark condensates. This mechanism describes transition of current into constituent quarks, which are the quasiparticles with masses comparable to a hadron mass scale. The
other well known direct result of SB is appearance of the Goldstone bosons. Thus constituent quarks and Goldstone bosons are the effective degrees of freedom in the chiral quark model.

Thus we consider a hadron as an extended object consisting of the valence constituent quarks located in the central core which is embedded into a quark condensate. Collective excitations of the condensate are the Goldstone bosons and the constituent quarks interact via exchange of Goldstone bosons; this interaction is mainly due to a pion field and of the spin–flip nature [26].

At the first stage of hadron interaction common effective self-consistent field appears. This field is generated by $\bar{Q}Q$ pairs and pions interacting with quarks. The time of generation of the effective field $t_{\text{eff}}$

$$t_{\text{eff}} = t_{\text{int}};$$

where $t_{\text{int}}$ is the total interaction time. This assumption on the almost instantaneous generation of the effective field has some support in the very short thermalization time revealed in heavy-ion collisions at RHIC [27].

Valence constituent quarks are scattered simultaneously (due to strong coupling with Goldstone bosons) and in a quasi-independent way by this effective strong field. Such ideas were used in the model [23] which has been applied to description of elastic scattering and hadron production [24, 28].

In the initial state of the reaction $pp^* \rightarrow 0X$ the proton is polarized and can be represented in the simple SU(6) model as following:

$$p^* = \frac{5}{3}U^* + \frac{1}{3}U^*_\# + \frac{1}{3}D^* + \frac{2}{3}D^*_\#:$$

(1)

We will exploit the common feature of chiral quark models: the constituent quark $Q^*$ with transverse spin in up-direction can fluctuate into Goldstone boson and another constituent quark $Q^0_{\#}$ with opposite spin direction, i.e. perform a spin-flip transition [29]:

$$Q^* \rightarrow G B + Q^0_{\#}:$$

(2)

The $^0$-fluctuations of quarks do not change the quark flavor and assuming they have equal probabilities in the processes:

$$U^*_{\#} \rightarrow U^*_{\#}^0 + U^*_{\#}^0; \text{ and } D^*_{\#} \rightarrow D^*_{\#}^0 + D^*_{\#}^0;$$

(3)

the production of $^0$ by the polarized proton $p^*$ in this simple SU(6) picture can be regarded as a result of the fluctuation of the constituent quark $Q^*$ ($Q = U$ or $D$) in the effective field into the system $^0 + Q^0_{\#}$ (Fig. 1).

The contributions to the cross-sections difference of the quarks polarized in opposite directions compensate each other (as it will be clear in what follows),
Figure 1: Schematical view of $^{0}$-production in polarized proton-proton interaction.

and it is not the case for the $^{0}$-production in the unpolarized case. Therefore the asymmetry $A_N$ should obey the inequality $A_N(0) \leq 1/3$.

To compensate quark spin flip $S$, an orbital angular momentum $L = S$ should be generated in the final state of reaction (2). The presence of this orbital momentum $L$ in its turn means shift in the impact parameter value of the Goldstone boson $^{0}$:

$$S \leftrightarrow L \leftrightarrow \mathcal{B}.$$  

Due to different strengths of interaction at the different impact distances, i.e.

$$p^+ \leftrightarrow Q^* \leftrightarrow ^0 + Q^* \leftrightarrow \mathcal{B};$$
$$p^- \leftrightarrow Q^{-} ! \leftrightarrow ^0 + Q^- ! \leftrightarrow \mathcal{B};$$

the processes of transition $Q^*$ and $Q^*$ to $^{0}$ will have different probabilities which leads eventually to nonzero asymmetry $A_N(0)$. Eqs. (4) clarify mechanism of the SSA generation: when shift in impact parameter is $\mathcal{B}$ the interaction is stronger than when the shift is $+ \mathcal{B}$, and the asymmetry $A_N(0)$ is positive. It is important to note here that the shift of $\mathcal{B}$ (the impact parameter of final pion) is equivalent to the shift of the impact parameter of the initial proton according to the relation between impact parameters in the multiparticle production [30]:

$$b = \sum_{i} x_i \mathcal{B}_i;$$

The variable $\mathcal{B}$ is conjugated to the transverse momentum of $^{0}$, but relations between functions depending on the impact parameters $\mathcal{B}_i$, which will be used further for the calculation of asymmetry, are nonlinear and therefore we are using the semiclassical correspondence between small and large values of transverse momentum and impact parameter:

$$\text{small } \mathcal{B}, \text{ large } p_T \text{ and } \text{large } \mathcal{B}, \text{ small } p_T :$$

$$\text{(6)}$$
We consider production of $^{0}\pi$ in the fragmentation region, i.e. at large $x_F$ and therefore use the approximate relation

$$b' \approx x_F B;$$

which results from Eq. (5) with an additional assumption on the small values of Feynman $x_F$ for other particles. In the symmetrical case of $pp$-interactions the model assumes equal mean multiplicities in the forward and backward hemispheres and small momentum transfer between two sides. In that sense the model is similar the approach of Chou and Yang [31].

We apply chiral quark semiclassical mechanism which takes into account unitarity in the direct channel to obtain qualitative conclusions on asymmetry dependence on the kinematical variables.

2 Asymmetry and inclusive cross-section

The main feature of the mechanism is an account of unitarity in the direct channel of reaction. The corresponding formulas for inclusive cross-sections of the process

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

where hadron $h_3$ in this particular case is $^{0}\pi$ meson and $h_1, h_2$ are protons, were obtained in [32] and have the following form

$$dI'_{#} = Z \int_0^1 dI # (s;b) = \frac{1}{144} \sum_{j=1}^{144} U (s;b)^2,$$

where $b$ is the impact parameter of the initial protons. Here the function $U (s;b)$ is the generalized reaction matrix (averaged over initial spin states) which is determined by the basic dynamics of elastic scattering. The elastic scattering amplitude in the impact parameter representation $F (s;b)$ is then given [33] by the relation:

$$F (s;b) = \sum_{j=1}^{144} U (s;b)^2.$$

This equation allows one to obey unitarity provided inequality $\text{Im} U (s;b) > 0$ is fulfilled. The functions $I'_{#}$ in Eq. (8) are related to the functions $U'_{#}$ – the multiparticle analogs of the function $U$ [32] in the polarized case. The kinematical variables $(x_F$ and $p_T$ for example) describe the state of the produced particle $h_3$. Arrows " and # denote transverse spin directions of the polarized proton $h_2$.

Asymmetry $A_N$ can be expressed in terms of the functions $I$ and $U$:

$$A_N (s; b) = \frac{R_1}{2} \int_0^1 dI # (s;b) = \frac{1}{144} \sum_{j=1}^{144} U (s;b)^2.$$

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where $I_0 = 1 = 2 (I^* + I^\dagger)$ and $I = (I^* - I^\dagger)$ and $I_0$ obey the sum rule

$$I_0 (s; b^2) \text{d}I = n (s; b) \text{Im} U (s; b);$$

here $n (s; b)$ stands for the mean multiplicity in the impact parameter representation.

On the basis of the described mechanism we can postulate that the functions $I^* (s; b^2)$ and $I^\dagger (s; b^2)$ are related to the functions $\frac{1}{3} I_0 (s; b^2) \frac{1}{3} B$ and $\frac{1}{3} I_0 (s; b^2) \frac{1}{3} B$, respectively, i.e.

$$I (s; b^2) = \frac{1}{3} I_0 (s; b^2) \frac{1}{3} B \quad I (s; b^2) = \frac{1}{3} I_0 (s; b^2) \frac{1}{3} B = \frac{2}{3} \frac{I_0 (s; b^2)}{B};$$

(11)

We can connect $B$ with the radius of quark interaction $r_{Q}^{\text{flip}}$ responsible for the transition changing quark spin:

$$B' = r_{Q}^{\text{flip}};$$

Using the above relations and, in particular, (7), we can write the following expression for asymmetry $A_N$:

$$A_N (s; \cdot) \propto r_{Q}^{\text{flip}} \frac{R_1}{3} \frac{1}{\text{Im} U (s; b^2)} \frac{1}{\text{Im} U (s; b^2)};$$

(12)

where $I_0 (s; b^2) = \text{Im} U (s; b^2)$ and $I_0 (s; b^2) = \text{Im} U (s; b^2)$. In (12) we made replacement according to relation (7):

$$I_0 (s; b^2) = \frac{1}{\text{Im} U (s; b^2)} \frac{1}{\text{Im} U (s; b^2)} = \frac{2}{3} \frac{I_0 (s; b^2)}{B};$$

It is clear that $A_N (s; \cdot) [12]$ should be positive because $I_0 (s; b^2) < 0$.

The function $U (s; b)$ is chosen as a product of the averaged quark amplitudes in accordance with the quasi-independence of valence constituent quark scattering in the self-consistent mean field [23]. The generalized reaction matrix $U (s; b)$ (in a pure imaginary case, which we consider here for simplicity) is the following

$$U (s; b) = i \text{Im} (s; b) = i g (s) \exp (M b = \cdot);$$

(13)

where the function $g (s)$ power like increases at large values of $s$

$$g (s) \propto \frac{P s^N}{m_Q};$$

$M$ is the total mass of $N$ constituent quarks with mass $m_Q$ in the initial hadrons and parameter $\frac{1}{b}$ determines a universal scale for the quark interaction radius in the model, i.e. $r_{Q} = \frac{1}{m_Q}$. 7
To evaluate asymmetry dependence on $x_F$ and $p_T$ we use semiclassical correspondence between transverse momentum and impact parameter values. Performing integration by parts and choosing the region of small $p_T$ we select the large values of impact parameter and we obtain

$$A_N^0 (s; b) \propto \frac{R}{b > R (s)} \frac{\int_{b > R (s)} dxT(x; b)}{\int_{b > R (s)} dxT(x; b)}$$

(14)

where $R (s)$ is the hadron interaction radius, which serve as a scale separating large and small impact parameter regions. In the large impact parameter region: $U (s;b) \sim 1$ for $b > R (s)$ and therefore we have a small dynamically suppressed asymmetry $A_N^0 (s; b)$ in the region of small and moderate values of $p_T$, i.e. $p_T = x = R (s)$.

But at small values of $b$ the value of $U$-matrix is large, $U (s;b) \sim 1$, and we can neglect unity in the denominators of the integrands. Thus the ratio of two integrals (after integration by parts in nominator in Eq. (12)) is of order of unity, i.e. the energy and $p_T$-independent behavior of asymmetry $A_N^0 (s; b)$ takes place at the values of transverse momentum $p_T = x = R (s)$:

$$A_N^0 (s; b) \propto \frac{R}{b > R (s)} \frac{\int_{b > R (s)} dxT(x; b)}{\int_{b > R (s)} dxT(x; b)}$$

(15)

This flat transverse momentum dependence of asymmetry results from the similar rescattering effects for the different spin states, i.e. spin-flip and spin-nonflip interactions undergo similar absorption at short distances and the relative magnitude of this absorption does not depend on energy. It is one of the manifestations of the unitarity. The numeric value of polarization $A_N^0$ can be significant; there are

Figure 2: $x_F$ (left panel) and $p_T$ (right panel) dependencies of the asymmetry $A_N$ in the process $p + \bar{p} \rightarrow \pi^0 X$ at RHIC, experimental data from [19].


no small factors in (15). In Eq. (15) $M$ is proportional to two nucleon masses, the value of parameter $\epsilon_{FIP}^1 = 0.1 \pm 0.2$ fm on the basis of the model estimate [23, 32]. The above qualitative features of asymmetry dependence on $x_F$, $p_T$ and energy are in a good agreement with the experimentally observed trends [19]. For example, Fig. 2 demonstrates that the linear $x_F$ dependence is in a good agreement with the experimental data of STAR Collaboration at RHIC [19] in the fragmentation region ($x_F < 0.4$) where the model should be applicable. Of course, the conclusion on the $p_T$–independence of polarization is a qualitative one and small deviations from such behavior cannot be excluded. The same dependencies are compared with the FNAL E704 data [34] (Fig.3). Those dependencies as it is clear from their derivations are valid in high-energy approximation and therefore have been compared with FNAL and RHIC data only. However, they are in qualitative agreement with the lower energy data also [35]. Similar mechanism

Figure 3: $x_F$ (left panel) and $p_T$ (right panel) dependencies of the asymmetry $A_N$ in the process $p^+ + p^-$ → $\pi^0 + X$ at FNAL, experimental data from [34].

should generate SSA in the production of charged pions. The relevant process for $^* +$–production in polarized $pp^*$ interactions

$$U^*! + D^*;$$

leads to a negative shift in the impact parameter and consequently to the positive asymmetry $A_N$, while the corresponding process for the $D^* +$–production

$$D^*! + U^*$$

leads to the positive shift in impact parameter and, respectively, to the negative asymmetry $A_N$. Asymmetry $A_N$ in the $\pi^0$–production in the fragmentation region of polarized proton should have linear $x_F$–dependence at $x_F > 0.4$ and flat $p_T$ dependence at large $p_T$. Those dependencies are similar to the ones depicted on Fig. 2 for $^0 +$–production.
The reversed mechanism (chiral quark spin filtering) was used for the explanation of the hyperon polarization \[36\]. Note that polarization of \( \equiv \) hyperon has the same generic dependence on \( x_F \) and \( p_T \).

To demonstrate the model self-consistency it should be noted that it is able to describe the unpolarized cross-section of \( \pi^0 \)-production also. In the fragmentation region it was shown \[24\] that at small \( p_T \) the poles in impact parameter plane at \( b = R(s) \) lead to the exponential \( p_T \)–dependence of inclusive cross-section. At high \( p_T \) the power-like dependence \( p_T^n \) with \( n = 6 \) should take place. It originates from the singularity at zero impact parameter \( b = 0 \). The exponent \( n \) does not depend on \( x_F \). Experimental data are in a good agreement with the \( p_T^6 \)–dependence of the unpolarized inclusive cross-section (Fig. 3). Recently a similar \( p_T^6 \)–dependence has been obtained for the soft contribution to quark-quark scattering induced by an anomalous chromomagnetic interaction due to instanton mechanism \[37\].

Thus, in the approach with effective degrees of freedom – constituent quarks and Goldstone bosons – differential cross-section at high transverse momenta has a generic power-like dependencies on \( p_T \) at large transverse momenta. The differential cross-section and the asymmetry \( A_N \) are in agreement with the experimental data at the highest available energy at RHIC and asymmetry is in agreement with FNAL data also.

**Conclusion**

The proposed semiclassical mechanism of SSA generation considers the effective degrees of freedom and takes into account collective aspects of QCD dynamics.
Together with unitarity, which is an essential part of this approach, it leads to linear dependence on $x_F$ and flat dependence of SSA on transverse momentum at large $p_T$ in the polarized proton fragmentation region. Such dependencies with the energy independent behavior of asymmetry at large transverse momenta are the direct phenomenological consequences of the proposed mechanism.

The chiral quark fluctuation mechanism in effective field with spin flip is relatively suppressed when compared to direct elastic scattering of quarks in effective field and therefore does not play a role in the reaction $pp \rightarrow pX$ in the fragmentation region, but it should not be suppressed in $pp \rightarrow nX$. These features really take place in the experimental data set: asymmetry $A_N$ is zero for proton production and deviates from zero for neutron production in the forward region.

We discussed here particle production in the fragmentation region of polarized proton. In the symmetrical case of $pp$-interactions the model leads to the equal mean multiplicities in the forward and backward hemispheres and very small momentum transfer is expected between the two sides. In the central and backward regions where correlations between impact parameter of the initial and impact parameters of the final particles are weak or completely degraded, the asymmetry cannot be generated due to this chiral quark semiclassical mechanism. The vanishing asymmetries in the central and backward regions observed experimentally provide the indirect evidences in favor of this mechanism.

Acknowledgement

We are grateful to S. Shimanskiy and A. Vasiliev for the interesting discussions.

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