Single-spin physics: experimental trends and their origin

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Abstract. The review of experimental trends in the physics of single-spin processes and their origin in the framework of an effective color field model is presented. A global analysis of polarization data for a large set of different reactions in \( h-h \), \( h-A \), \( A-A \) and lepton-\( A \) collisions is performed. In particular, the single-spin asymmetry, the polarization of hyperons and antihyperons are analyzed. The analysis revealed many common trends in the behavior of the experimental data, depending on the kinematic variables, the quark structure of hadrons and the mass of the colliding ions. The origin of large single-spin effects can be attributed to the influence of force such as the Stern-Gerlach-like one in a chromomagnetic field and to the Thomas precession in chromoelectric component of the Effective Color Field (ECF). Precession of the spin of the quarks in a chromomagnetic field is a major cause of the oscillation of the polarization as a function of kinematic variables. Focusing of quarks in the ECF leads to the resonant energy dependence of the single-spin observables. The predictions of large single-spin effects for the different reactions are presented, in particular, the expected oscillations of SSA and polarization, as well as change their sign at RHIC energies due to the growth of ECF with increasing reaction energy or the atomic weight of the ions. The Quark Counting Rules determine the sign and magnitude of the ECF.

1. Introduction
The report focuses on the global analysis of single-spin physics data. In total, the analysis includes 68 inclusive reactions for the \( h-h \), \( h-A \), \( A-A \) and lepton-\( A \) interactions. The observables are the single-spin asymmetry of hadrons, as well as the polarization of hyperons and vector mesons. In the single-spin processes we only know the spin state of one particle in the initial or final state. The observed polarization effects are much higher than the pQCD estimates. Many models have been proposed to explain the large single-spin effects, but they are unable to describe the experimental trends of the totality of available data.

The global analysis of single-spin data allows to reveal general regularities and data trends, which are otherwise not seen. To reveal and explain these regularities and the data trends in the framework of common mechanism, the Effective Color Field model is developed.

The data base for single-spin inclusive reactions is created in a unified format. It contains now data for 68 different reactions with more then 2100 data points and continue to grow.

As a result of the global analysis, many interesting phenomena have been found and they are explained below within the framework of semi-classical mechanism of the Effective Color Field model. The details of the ECF model can be found in [1].
2. SSA and hadron polarization origin

Global analysis is based on the semi-classical mechanism for single-spin phenomena. The basic assumptions of the model are as follows: Effective Color Field (ECF, chromomagnetic and chromoelectric) is a superposition of string fields generated by moving quarks and antiquarks, after an initial exchange of color and the production of additional (anti)quarks. Constituent quark \( Q \), which is part of the observed hadron, interacts with non-uniform color field through its chromomagnetic moment \( \mu^a_Q \) and its color charge \( g_S \). We consider the inclusive reactions

\[
\begin{align*}
A^\uparrow + B &\rightarrow C + X, \\
A + B &\rightarrow C^\uparrow + X,
\end{align*}
\]

where \( A \) and \( B \) are the colliding particles, and for the detected hadron \( C \) the single-spin asymmetry (SSA) in (1) or its polarization \( P_N \) in (2) is measured.

Microscopic Stern-Gerlach effect in a chromomagnetic field and the spin precession of a quark (Thomas precession) in a chromoelectric field leads to a large SSA. The ECF is considered as an external one with respect to the quark \( Q \) in the observed hadron \( C \). Precession of the quark in the ECF is an additional phenomenon, which leads to the specific dependence of the SSA or the polarization (such as an oscillation), depending on the kinematic variables (\( x_F, p_T \) or the scaling variables \( x_{A(B)} = (x_R \pm x_F)/2 \)). Based on the work [2] one can assume the following

\[
\begin{align*}
\omega_0^A &= \omega_0^S (2 + 2\lambda - 3\tau \lambda).
\end{align*}
\]

\[\text{Figure 1.} \quad \text{Schematic picture of a color flux tube or QCD string between quark and antiquark. The longitudinal lines show the chromoelectric field direction, while the circular curves show the chromomagnetic field direction.}\]

\[\text{Figure 2.} \quad \text{Quark Counting Rules for the reaction } pp \rightarrow \Xi^0 \uparrow + X. \text{ The frequency } \omega_0^\Lambda \text{ at moderate energy } \sqrt{s} < 70 \text{ GeV follows from the quark flow diagram: } \omega_0^\Lambda = \omega_0^S (2 + 2\lambda - 3\tau \lambda).\]

picture of the field between the quark and antiquark: there is a longitudinal chromoelectric field \( E^a \) and a circular chromomagnetic field \( B^a \), as is shown in figure 1. Recently, Yu Gonchrov found an exact solution of the Yang-Mills theory with a circular chromomagnetic field [3]. Field dependence on the distance \( r \) from the axis of the string is described by equations (3) and (4) for a chromoelectric field \( E^a \) and a circular chromomagnetic field \( B^a \), respectively,

\[
\begin{align*}
E_Z^{(3)} &= -2\alpha_s \nu / \rho^2 \exp(-r^2 / \rho^2), \\
B_\varphi^{(2)} &= -2\alpha_s \nu / \rho^3 \exp(-r^2 / \rho^2),
\end{align*}
\]

where \( \nu \) is the number of quarks at the end strings, the effective radius of the string is \( \rho \) of order the radius of confinement, and \( \alpha_s = g^2 / 4\pi \approx 1 \), the running coupling constant. Constituent quarks has the chromomagnetic moment of \( \mu^a_Q \), which is directed along the spin of the quark.

On the quark moving in the QCD string or tube of color flow, acts the Stern-Gerlach-like force. Transverse components of the force are described by the equations

\[
\begin{align*}
f_x &= \mu^a_x \partial B^a_x / \partial x + \mu^a_y \partial B^a_y / \partial x, \\
f_y &= \mu^a_x \partial B^a_x / \partial y + \mu^a_y \partial B^a_y / \partial y.
\end{align*}
\]
Quark $Q$ of the observed hadron $C$, which gets an additional transverse momentum $\delta p_T$ as a result of the Stern-Gerlach-like force and experiences a spin precession, is called the probe one and it measures the integrals of fields $B^a$ and $E^a$.

Effective color field is a superposition of strings fields created by moving spectator quarks and antiquarks of the projectile and target, as well as those that were created during the interaction. Spectator quarks (remnant quarks) are all the quarks, which are not constituents of the detected hadron $C$. The ECF is described by the quark counting rules [1]. According to the rules of quark counting the effective number of strings ($\nu = \sum \nu_{A(B)}$) is a linear function of the number of spectator quarks and antiquarks of the incident hadron $A$ and the target $B$.

Let us consider an example of reaction shown in figure 2. In the case of the reaction $pp \to \Xi^0 + X$ the probe $s$ and $u$ quarks in a hyperon $\Xi^0$ feel field, generated by the incident quarks with the weight of $\nu_A = 1$, by the antiquarks with the weight $\nu_A = 1$, and by the target quarks with the weight of $\nu_B = -\tau \lambda$, respectively. As a result, $\nu = 2 + 2\lambda - 3\tau \lambda$, if we neglect the production of additional $q\bar{q}$ pairs, which is suppressed at low energy.

The phenomenological parameter $\lambda$ is a color factor [4], the theoretical value of which is given by equation (6) and is close to the experimental estimate of $\lambda = -0.1330 \pm 0.0014$, obtained for 68 reactions in the global analysis. This fact is a strong argument in favor of the Effective Color Field model. The parameter $\tau = 0.0548 \pm 0.0028$ has a positive sign, since the target quarks are moving in the opposite direction with respect to the projectile one in the c.m.s. reference frame.

\[
\lambda = -|\Psi_{qq'}(0)|^2/|\Psi_{qq'}(0)|^2 = 1 - \exp(1/8) \approx -0.1331. \tag{6}
\]

The quark spin precession is described by the eq. (7), similar to the BMT one [5],

\[
d\xi/dt = a[\xi B^a] + d[\xi E^a v], \tag{7}
\]

\[
a = g_s(g_Q^a - 2 + 2M_Q/E_Q)/2M_Q, \tag{8}
\]

\[
d = g_s(g_Q^a - 2E_Q/(E_Q + M_Q))/2M_Q, \tag{9}
\]

where the functions $a$ and $d$ depend on the probe quark mass $M_Q$, energy $E_Q$ and its color $g$-factor $g_Q^a$, as well as the color charge $g_s$.

For large quark energy $E_Q$ spin precession frequency (7) is proportional to the factor of $\Delta \mu_Q^a = (g_Q^a - 2)/2$, which is called the anomalous chromomagnetic moment of a quark. The instanton model predicts a large and negative $\Delta \mu_Q^a \approx -0.744$ due to spontaneous chiral symmetry breaking, as was shown by Kochelev and Diakonov [9,10]. Both parameters, $\Delta \mu_Q^a(q)$ and additional quark mass $\Delta M_Q(q) \approx 0.3$ GeV, converge to zero at $q \to \infty$. The second term in (7) is due to the Thomas precession in the chromoelectric field $E^a$.

As a result of the microscopic Stern-Gerlach effect probe quark $Q$ gets an additional spin-dependent transverse momentum $\delta p_x$ (equation 10), which leads to an azimuthal asymmetry $A_N$ or hadron polarization $P_N$. The value of $\delta p_x$ depends on the angle of spin precession of $\phi_A$ in the fragmentation region of hadron $A$,

\[
\delta p_x = \frac{g_Q^a g_{Q'}^a}{2p(g_Q^a - 2 + 2M_Q/E_Q)} \left[ \frac{1 - \cos(\phi_A)}{\phi_A} + \epsilon \phi_A \right], \tag{10}
\]

where the precession angle $\phi_A(B) = \omega_A(B) x_A(B)$ is a product of the scaling variable $x_A(B) = (x_R \pm x_F)/2$ and the oscillation frequency $\omega_A(B)$,

\[
\omega_A(B) = \frac{g_s \alpha_s \nu_{A(B)} S_0(g_Q^a - 2 + 2M_Q/E_Q)}{M_Q \rho^2}, \tag{11}
\]
where the parameter $S_0 = 1.3 \pm 0.4$ fm is the length of ECF, $\epsilon = -0.00447 \pm 0.00024$.

Equations (12) connect the $\delta p_x$ with observable $A_N$ or $P_N$, where $D \approx 5.78 \pm 0.12 \text{ GeV}^{-1}$ is an effective slope of the spectrum of produced hadrons as a function of $p_T$ [6]:

$$ A_N = -\delta p_x D, \quad D = -\frac{\partial}{\partial p_T} \ln(d^3 \sigma/dp). \quad (12) $$

2.1. Generalized equations for $A_N$ and $P_N$

Generalized formulas for the $A_N$ and $P_N$ are described by equations (13) to (17):

$$ A_N = C(\sqrt{s})V(x_F)F(p_T, A)[G(\phi_A) - \sigma G(\phi_B)]; \quad (13) $$

$$ G(\phi) = (1 - \cos \phi)/\phi + \epsilon \cdot \phi; \quad (14) $$

$$ C(\sqrt{s}) = v_0/(1 - E_R/\sqrt{s}), \quad (15) $$

$$ F(p_T, A) = (1 - \exp[-(p_T/p_T^0)^3])(1 - \alpha \ln A). \quad (16) $$

$$ V(x_F) \equiv \varepsilon_B^0 = \pm \Theta(x_F - x_0). \quad (17) $$

Here, the function $G(\phi_A(B))$ of the angle $\phi_A(B)$ takes into account the precession of the quark spin and the Stern-Gerlach-like force acting on it in the fragmentation region of the hadron $A(B)$. The equation (15) describes the effect of quark focusing in the ECF. The function $F(p_T, A)$ is a color form-factor, and $V(x_F)$ takes into account the polarization of $u$ and $d$ quarks in a proton. In total, there are 8 local parameters for each specific reaction: $\alpha$, $\sigma$, $E_0$, $E_R$, $f_0$, $a_0$, $x_0$, $p_T^0$. On average, every two out of the eight local parameters can be expressed in terms of global parameters and kinematic variables, which provides estimates of both global and local parameters [1]. There are 41 global parameters for 68 reactions used ($\epsilon$, $\lambda$, $\tau$, $\Delta M_Q$, $\Delta \mu^Q$, ...).

The precession angle $\phi_A(B)$ measures the color field integral in the fragmentation region of hadron $A(B)$ and can be parametrized as $\phi_A(B) = \omega_A(B)y_A(B)$, where

$$ \omega_A(B) = \frac{g_s\alpha_s\nu_{A(B)}S_0(g_Q^2 - 2)}{M_Q^2\rho^2} \quad (18) $$

is the high quark energy limit of the $\omega_A(B)$. The variable $y_A(B)$ takes into account the quark motion inside proton and spin precession in the ECF:

$$ y_A = x_A - (E_0/\sqrt{s} + f_0)(1 + \cos \theta_{cm}) + a_0(1 - \cos \theta_{cm}), \quad (19) $$

$$ y_B = x_B - (E_0/\sqrt{s} + f_0)(1 - \cos \theta_{cm}) + a_0(1 + \cos \theta_{cm}), \quad (20) $$

where $a_0$, $f_0$ and $E_0$ are phenomenological parameters, and $\theta_{cm}$ is the detected hadron production angle.

2.2. Quark focusing in a circular chromomagnetic field

Focusing of quarks in the color circular chromomagnetic field $B^a$ is one of the characteristic features of the model and it leads to the resonant dependence of spin observables on the energy of the reaction $\sqrt{s}$ in c.m.s. The Lorentz focusing force $F = g_s[vB^a]P$ leads to a retention of probe quark in the color field and thus increases the polarization effects in the case of $E_R > 0$. For the case of opposite direction of the focusing field (with respect to the direction of motion of the probe quark), the effect of quark defocus takes place, with a decrease in the absolute values of observables $A_N$ and $P_N$, while $E_R < 0$.

The focusing effect is similar to the so-called Z-pinch, which is used in the Tokamak fusion reactor to keep the plasma away from the reactor walls. Also Z-pinch effect is used for a creation of plasma lens, which can focuses ions and high energy charged particles [7].
3. Data trends and model predictions

3.1. Examples of quark focusing and defocusing processes

An example of the quark focusing in the field $B^a$ is the reaction of $\pi^+$ production in $pp$ or $pA$ collisions. In the figure 3 is shown the dependence of $1/C(\sqrt{s})$ on $\sqrt{\sigma_0/s}$ in equation (13), where $\sqrt{\sigma_0} = 100 \text{ GeV}$. The focusing effect exists when the frequency $\omega_0^A$ is positive, which is true in the case of $\pi^+$ production at moderately high energies, $\sqrt{s} < 70 \text{ GeV}$. The value $E_R = 3.31 \pm 0.09 \text{ GeV}$ is also positive. The crosses in the figure 3 represent the estimates of $1/C(\sqrt{s})$ in the measurements in the energy range $4.9 \leq \sqrt{s} \leq 200 \text{ GeV}$ [8, 9, 10, 11, 12, 13, 14, 15, 16].

![Figure 3](image)

**Figure 3.** Example of a quark focusing in the reaction $p\uparrow p(A) \rightarrow \pi^+ + X$. The blue crosses represent estimates of the parameter $1/C$ in eq. (13) from different experiments [8, 9, 10, 11, 12, 13, 14, 15, 16].

An example of the defocusing of quarks in a chromomagnetic field $B^a$ is the reaction of $\Lambda$ production in $pp$ or $pA$ collisions. The defocusing effect exists for the frequency of $\omega_0^A < 0$, which holds for energies $\sqrt{s} < 70 \text{ GeV}$. The value $E_R = -2.95 \pm 0.30 \text{ GeV}$ in this case is negative. Blue crosses in figure 4 show the data for different energies [17, 18, 20, 21, 22, 23, 24, 25, 26, 27]. Note, that in the case of Au Au collisions the sign of $\omega_0^A$ is positive and there is a focusing effect. The relevant data are shown in figure 4 by circles [28, 29]. In contrast to the $pp(A)$ collisions, where the dominant contribution to the color field makes spectator $s$-antiquark, in the case of Au Au collisions the dominant contribution comes from valence quarks of many nucleons, which changes the sign and the magnitude of the effective color field. The value $E_R = 4.805 \pm 0.016 \text{ GeV}$ in this case is positive, as expected. It is interesting, that the $E_R$ value is very close to the reaction energy $\sqrt{s} = 4.86 \text{ GeV}$ in [28], that is the reason for a large $\Lambda$ polarization and a very small $1/C$ value, shown in figure 4.

![Figure 4](image)

**Figure 4.** Quark defocusing. The blue crosses show the estimates of the $1/C$ in eq. (13) for the reaction $pp(A) \rightarrow \Lambda\uparrow + X$ [17-27]. The red circles shows the data for the reaction AuAu $\rightarrow \Lambda\uparrow + X$ [28-29].

3.2. Dependence of the frequency $\omega_0^A$ and ECF on $\sqrt{s}$ and atomic weights $A_1$ and $A_2$

The ECF and $w_0^A$ depend on the energy $\sqrt{s}$ and atomic weights $A_1$ and $A_2$ of the colliding hadrons or ions. In high energy $hh$-collisions, $\sqrt{s} > 70 \text{ GeV}$, a formation of new quarks and antiquarks intensifies the ECF.

In the case of ion collisions, the intensity of the color field is also high, since the quarks of many nucleons are involved in collisions and contribute to the ECF. The effective number of...
quarks $q_A$ and antiquarks $\bar{q}_A$ in the incident nucleus is equal to their number in the tube with a radius $R_a = r_0 A_a^{1/3}$, that is limited by the phenomenon of confinement:

$$q_A = 3(1 + f_N)A_{\text{eff}} \sim 3(1 + f_N)A^{1/3}, \quad \bar{q}_A = 3f_N A_{\text{eff}} \sim 3f_N A^{1/3}, \quad (21)$$

where the function $f_N$ accounts for the contribution of newly created pairs of $q\bar{q}$ to the ECF and the number of strings $\nu_A$. There is a suppression of the contribution of new quarks in $f_N$ and $\nu_A$ at high $p_T$ and $x_F$: a fast probe quark very quickly escapes the ECF and has no time to get a significant additional transverse momentum $\delta p_x$. The variable $A_{\text{eff}}$ is the effective number of nucleons in the incident nucleus $A$, which contribute to the color field [1]. The global parameters in (22) are $n_q = 4.52 \pm 0.32$, $p_N = 31 \pm 11$ GeV/c, $W = 270 \pm 12$ GeV, $r_0 = 1.2$ fm, $A_0 = 11.54 \pm 0.47$ and $n_1 = 1.18 \pm 0.05$ for $hh$ interactions, which should be replaced by $n_2 = 0.80 \pm 0.26$ for ion collisions. Compared to [1] parameters are updated.

3.3. The case of collision of two ions with atomic weights $A_1$ and $A_2$

In a more general case, the collision of two nuclei with different atomic weights of $A_1$ and $A_2$, a phenomenological parameter $W$ reduces by a factor $(A_1 A_2)^{1/6}$, which can be interpreted as a decrease in heat capacity of created quark-hadron matter. On the contrary, a fractal parameter $n$ increases by a factor $(A_1 A_2)^{1/6}$.

3.4. Scaling violation of $A_N(x_F)$ or $P_N(x_F)$ at $\sqrt{s} > 70$ GeV

At moderate energies $\sqrt{s} < 70$ GeV, the contribution of newly created (anti)quarks is too low and the ECF is almost independent off energy, which leads to an approximate scaling for the dependence of $A_N$ or $P_N$ off $x_F$ at $p_T > 0.7$ GeV/c. The scaling of $A_N(x_F)$ dependence is violated at energies $\sqrt{s} > 70$ GeV due to the contribution (22) to the ECF of newly produced (anti)quarks. This is illustrated in figure 5 by the behavior of $A_N(x_F)$ in the reaction of $\pi^+$ production in $pp$ collisions. Data from experiments E704 at 19 GeV [14] and BRAHMS at 62 and 200 GeV [15, 16] are shown as a function of $x_F$. The curves in figure 5 show the ECF model predictions with matching energies indicated in the figure. Note that at the energy $\sqrt{s} = 130$ GeV we expect a large negative $A_N$ for $x_F$ close to 0.3. Also, when the energy in the c.m.s. is 200 GeV we expect a large negative $A_N$ for $x_F$ close to 0.6. Such unusual behavior is associated with the change of the sign and magnitude of the color field and the corresponding change in frequency of precession of the probe quark in the ECF, which is a consequence of the production of a large number of quarks and antiquarks at energies $\sqrt{s} > 70$ GeV.

Even more interesting behavior of $A_N$ depending on $x_F$ is shown in figure 6 for the energy $\sqrt{s} = 500$ GeV. We expect several maxima and minima due to the precession of the quark spin.

3.5. Polarization in ion collisions

Very intense color fields are expected in AuAu collisions, where the color field is proportional to the factor $f_N A^{1/3}$. The STAR data for the global $\Lambda$ polarization are shown in figure 7, depending on $p_T$. The large value of $P_N$ is predicted for the region of large $p_T > 2.7$ GeV/c, where correlation is expected between the reaction plane and the production plane. The data at energies 62 and 200 GeV in the c.m.s. confirm the unusual predictions of the model.

3.6. Polarization of antihyperons

Polarization of antihyperons, produced in nucleon-nucleus collisions, in most models is predicted zero. The experimental data obtained for several reactions show a nonzero polarization. The ECF model predicts a nonzero polarization, the origin of which is associated with the microscopic
Figure 5. Dependence $A_N(x_F)$ for the reaction $p^+p(A) \rightarrow \pi^+ + X$. The calculation of $A_N$ was performed for energies, indicated in the figure. The production angle is $4.1^\circ$ for 130 and 200 GeV.

Figure 6. Dependence $A_N(x_F)$ for the reaction $p^+p(A) \rightarrow \pi^+ + X$. The calculation of $A_N$ for 500 GeV is shown by a solid red curve. The production angle is $4.1^\circ$ for 500 and 200 GeV.

Figure 7. Dependence of global polarization $P_N(p_T)$ for the reaction AuAu $\rightarrow \Lambda + X$. The calculation of $P_N$ was performed for pseudorapidity of $\eta = 1$.

Figure 8. Dependence $P_N(p_T)$ for the reaction $pp(A) \rightarrow \bar{\Lambda} + X$. The calculation of $P_N$ for $\sqrt{s} = 7.31$ GeV is shown by a solid red curve.

Stem-Gerlach effect. For antihyperon, produced in the $pp$ or $pA$ collisions, the effective color field and the precession angle $\phi_A$ are large due to the large number of spectator quarks.

Polarization of $\bar{\Lambda}$, shown in figure 8, is an enigma, since it is different from the other antihyperon polarization. For $\bar{\Lambda}$ production in $pp$ or $pA$ collisions most of the data are at high energy, $\sqrt{s} > 27$ GeV, and $P_N$ is compatible with zero (diamonds in figure 8) [23, 24, 25, 26, 30]. The only non-zero data are from the E766 experiment, reported by J. Felix [31], have $\sqrt{s} = 7.31$ GeV (solid points). In the ECF model the large $P_N$ values are explained by the quark focusing effect with $E_R = 7.2 \pm 0.2$ GeV, which is close to the $\sqrt{s}$ value.
4. Summary
A semi-classical mechanism is proposed for single-spin phenomena, the main assumptions of which are stated below.

- Effective color field is a superposition of string fields, created by moving spectator quarks and antiquarks and described by quark counting rules.
- Microscopic Stern-Gerlach effect in a chromomagnetic field and Thomas precession in a chromoelectric field lead to the large SSA or to the polarization of hadrons.
- The dependence of the effective color fields on the energy of the reaction and the atomic weight of projectile, in conjunction with the phenomenon of precession of the quark, leading to an oscillatory behavior of $A_N$ and $P_N$, depending on the kinematic variables.
- Additional anti(quark) production at high energies, $\sqrt{s} > 70$ GeV, changes the dependence on kinematic variables: we expect the oscillation of $A_N$ and $P_N$ and violation of an approximate scaling for the $A_N(x_F)$ and $P_N(x_F)$.
- Focusing or defocusing of the quarks in the effective color field leads to the energy dependence of the resonant-type for the $A_N$ and $P_N$.

Acknowledgments
We would like to thank the organizing committee of SPIN2010 International Symposium for the invitation. This work is partially funded by RFBR Contract No. 09-02-00198.

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