Single Spin Effects in Collisions of Hadrons and Heavy Ions at High Energy

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Abstract

Experimental data on transverse single-spin asymmetry, hyperon polarization and vector meson alignment in h+h, h+A and A+A-collisions have been analyzed. A new mechanism for the origin of single spin effects is proposed, which takes into account the interaction of massive constituent quarks via their chromomagnetic moment with an effective inhomogeneous chromomagnetic field of strings, produced after the initial color exchange. Quark spin precession in the color field is taken into account, which can be the reason for an oscillation of the single spin observables as a function of Feynman $x_F$ and its energy dependence. The model predictions are compared with the experimental data, in particular with the heavy ion collision data. The data are consistent with a large negative anomalous chromomagnetic moment of the constituent quarks which is predicted in the instanton model.

It is assumed in the model, that each quark or antiquark, which is not a constituent of the observed hadron $C$ in the reaction $A \uparrow +B \rightarrow C + X$ contributes, with some probability, to the effective color field, which acts on the hadron $C$ quarks. As is shown in [1], a string arises between the receding quark and antiquark, which has a longitudinal chromoelectric field $E^a$ and a circular chromomagnetic field $B^a$. The field $B^a$ spreads around the string like an ordinary magnetic field surrounds a conductor with a current:

$$B^{(2)}_\varphi = -2\alpha_s r/\rho^3 \exp(-r^2/\rho^2),$$

where $r$ is a distance from the string axis, $\rho = 1.25R_c = 2.08$ GeV$^{-1}$, and $R_c$ is the confinement radius, the index (2) in $B^{(2)}_\varphi$ means a color, and $\varphi$ is the azimuthal angle.

This inhomogeneous field $B^a$ acts on a color magnetic moment $\mu = sgq_s/2M_Q$ of the quark $Q$, where $q_s = \sqrt{4\pi\alpha_s}$ is the color coupling constant, $g$ is the color gyromagnetic number, $M_Q$ is the constituent quark (valon) mass. The Stern-Gerlach-like force given by

$$f_x = \mu_x \partial B^a_x/\partial x + \mu_y \partial B^a_y/\partial x,$$

can be the reason of the large single spin asymmetry (SSA) [2].

We assume a Larmore precession [3] of the mean quark spin $\xi$ in the color field $B^a$, which depends on the quark energy $E_Q$:

$$d\xi/dt = a[\xi B^a],$$

$$a = q_s(g - 2 + 2M_Q/E_Q)/2M_Q.$$
At high quark energies \( E_Q \gg 2M_Q/|g-2| \) the quark spin precession frequency \( \Omega_s = aB \)

\( kS = aB/v \) is almost energy independent due to the high \( |g-2| \) value and the energy-dependent term in (4) can be considered as a correction and estimated experimentally.

The Stern-Gerlach-like force (2) produces an additional transverse momentum:

\[
\delta p_x \approx \frac{gu[1 - \cos(kS)]}{2pkS(g - 2 + 2M_Q/E_Q)},
\]

where \( kS = aB/v \) is the precession angle, \( ds = v dt \), \( v \) is the quark velocity, and \( S \) is a quark path length in the string field. We assume that \( kS = \omega_A x_A \) in the hadron \( A \) fragmentation region, or \( kS = \omega_B x_B \) in the hadron \( B \) fragmentation region, where \( \omega_A \) and \( \omega_B \) are dimensionless values and the scaling variables are defined as \( x_A = (x_R + x_F)/2 \) and \( x_B = (x_R - x_F)/2 \).

The analyzing power is related with the additional \( p_T \) by eq. (6), (M.Ryskin, [2]):

\[
A_N \approx \delta p_x \partial/\partial p_T \ln(d^3\sigma/d^3p).
\]

The final expression for the SSA or hadron polarization in \( pp \), \( pA \) or \( AA \) collisions is:

\[
A_N = C(\sqrt{s})V(E_{cm})F(p_T, A)[G(\omega_A y_A) - \sigma(\theta^{cm})G(\omega_B y_B)];
\]

\[
G(\omega \cdot y) = [1 - \cos(\omega \cdot y)]/(\omega \cdot y);
\]

\[
\sigma(\theta^{cm}) = \xi \sin \theta^{cm} + \varepsilon \; ; \; F(p_T, A) = 1 - \exp\{- (p_T/p_T^{\min})^3\}(1 - \eta \ln A);
\]

\[
y_A = x_A - (E_0/\sqrt{s} + f_A)[1 + \cos \theta^{cm}] + a_0[1 - \cos \theta^{cm}];
\]

\[
y_B = x_B - (E_0/\sqrt{s} + f_B)[1 - \cos \theta^{cm}] + a_0[1 + \cos \theta^{cm}];
\]

\[
C(\sqrt{s}) = C_0/(1 - E_R/\sqrt{s}).
\]

The Heaviside step function \( V(E_{cm}) \approx \pm \Theta(E_{cm} - E_{cm}^{\min}) \) takes into account the threshold behavior of the SSA as a function of hadron \( C \) c.m. energy [5]. The eqs. (7) - (12) describe not only the SSA, but also the hyperon polarization in the unpolarized hadron collisions. The model has 8 phenomenological parameters in the case of identical particle collisions (\( \omega_A = \omega_B, f_A = f_B, \varepsilon = 1, \xi = 0 \)) and 12 parameters in a general case.

Due to the quark spin precession (3)-(4) the effective value of \( E_0 \) is given by

\[
E_0 \approx 2M_Q[1 + \frac{2}{2 - g}],
\]

where it is assumed that the constituent quark mass for \( u \)- and \( d \)-quarks is the same: \( M_u = M_D = 0.35 \) GeV. The relation (13) and the estimated values of the \( E_0 = 1.640 \pm 0.040 \) GeV \( (\pi^+) \) and \( E_0 = 2.02 \pm 0.21 \) GeV \( (\pi^-) \) allow to extract the quark anomalous chromomagnetic moment for \( u \)- and \( d \)-quarks: \( \mu_u = -0.74 \pm 0.03 \) (stat) and \( \mu_D = -0.53^{+0.10}_{-0.07} \) (stat). These values of \( \mu_a \) are compatible with the instanton model prediction [4].

The hyperon polarization arises due to the Stern-Gerlach-like forces, which separate the spin up and down quark states by adding a transverse momentum to the left or to the right in the scattering plane. The eq. (7) predicts an oscillation of \( A_N \) or \( P_N \) with the frequency \( \omega_A (\omega_B) \) as a function of \( y_A(y_B) \) and its energy dependence, eq. (12).

The following figures show examples of the oscillation of the SSA or hadron polarization in a wide range of energies and other kinematical variables. The curves in the figures show
the fit result using the model function (7) discussed above. A direct evidence of the proton $A_N$ oscillation as a function of $p_T$ (Fig. 1) is obtained in the FODS-2 (IHEP) experiment using the 40 GeV/c polarized proton beam [6]. Recently the $A_N$ oscillation with a smaller magnitude was observed in the BRAHMS (BNL) experiment at $\sqrt{s} = 200$ GeV [7]. The frequency $\omega_A$ is $-10.7 \pm 1.0$ for $\sqrt{s} = 8.77$ GeV and $-64 \pm 14$ for $\sqrt{s} = 200$ GeV. The rise of the $\omega_A$ is expected in the model due to additional sea quarks-spectators produced at high energy.

The transverse $\Lambda$ polarization in Au+Au-collisions is measured at $\sqrt{s} = 4.86$ GeV (Fig. 2) [8]. The fit gives positive $\omega_A = +18.61 \pm 0.54$, as expected in the model. Recently very interesting data on the global hyperon polarization in Au+Au collisions were reported by the STAR experiment [9]. These data show examples of polarization oscillation with negative and very high frequency $\omega_A$. This is exactly what is expected in the model due many spectator quarks $N_Q \propto A^{1/3} \exp(-w/\sqrt{s})$, whose number is proportional to the number of nucleons inside the tube of a transverse radius about the confinement radius, where $w = 236 \pm 16$ GeV. At high reaction energy many new spectator quarks and antiquarks are produced by each nucleon that increases the field $B$. The $\Lambda$-hyperon data fit gives $\omega_A = -374 \pm 51$ for 200 GeV (Fig. 3) and $\omega_A = -58 \pm 38$ for 62 GeV. The $\bar{\Lambda}$-hyperon data fit gives $\omega_A = -648 \pm 46$ and $\omega_A = -359 \pm 15$ for 200 GeV (Fig. 4) and
62 GeV, respectively.

The quark counting rule (QCR, Fig. 5) is designed to explain the dependence of the $\omega_A$ frequency on hadron quantum numbers, reaction energy and a projectile atomic weight. The quark counting rule for the $\omega_A$ assumes that each projectile spectator quark contributes to the quark precession frequency with a weight $\nu = \lambda$ and each antiquark with a unity weight. For the target quarks or antiquarks an additional factor $−\tau$ should be used. The factor $R_Q = (M_S/M_Q)\mu_Q^S/\mu_A$ takes into account the fact that the $\omega_A$ is proportional to $(g − 2)Q/M_Q$. The model QCR parameters are obtained from a global fit of 26 reactions: $\omega_0 = -3.23 \pm 0.30; \lambda = -0.106 \pm 0.018; \tau = -0.016 \pm 0.027; R_U = 1.60 \pm 0.24; R_D = 1.95 \pm 0.41; R_S = 1; R_C = 0.78 \pm 0.29$.

Conclusion: A new mechanism is proposed which explains the origin of the transverse single spin asymmetries and the hyperon polarization. The origin of the single spin effects can be related with the Stern-Gerlach-like forces between chromomagnetic moment of the massive constituent quark and the effective color field created by the quarks-spectators.

The $A_N$ and $P_N$ oscillation due to the quark spin precession in the effective color field is predicted and confirmed for proton, $\Lambda$, $\bar{\Lambda}$, $J/\psi$, $K^*$ (892), $\Xi^0$ and $\Xi^-$ production in the inclusive reactions. The polarization oscillation is the main signature of the model.

The estimated color anomalous magnetic moment is $-0.74 \pm 0.03$ and $-0.53^{+0.10}_{−0.07}$ for $u$ and $d$ quark, respectively, in agreement with the instanton model prediction $\mu_a = -0.744$.

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