Single-spin asymmetry in pp and pA-collisions

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Abstract. Experimental data on the transverse single-spin asymmetry $A_N$ in the collisions of polarized protons with protons and nuclear targets are analyzed. The existing data are compared with predictions from the chromomagnetic polarization of quarks (CPQ) model for the processes of $\pi^\pm$, $K^\pm$, p and antiproton production in the inclusive reactions. The results of $A_N$ calculations for the above processes are presented in the following kinematic region: $8.77 \leq \sqrt{s} \leq 500 \text{ GeV}$, $0 \leq x_F \leq 0.83$, $0 \leq p_T \leq 9 \text{ GeV/c}$. Predictions of the CPQ model can be used for planning of experiments SPASCHARM(IHEP), SPD(JINR), STAR and PHENIX.

1. Introduction
Studies conducted over the past 35 years have shown that there are significant spin effects in the inclusive processes at energies from a few GeV to hundreds GeV in the c.m.s. In this paper the single-spin asymmetries (SSA), which are measured using a vertically polarised proton beam, are discussed. The observed spin effects tend to be about 10% while the QCD perturbation theory predicts effects of the order of 0.1%. Further experimental research and a global analysis of all available information on single-spin processes are needed to resolve the above contradiction.

2. Chromo-magnetic polarization of quarks model
The main assumptions of the chromo-magnetic polarization of quarks (CPQ) model are:
1) After an initial color charge exchange a longitudinal chromoelectric field $E^a$ and a circular transverse chromomagnetic field $B^a$ are generated.
2) Single-spin asymmetry is due to the Stern-Gerlach force acting on a quark in the inhomogeneous transverse circular chromomagnetic field.
3) Quark spin precession in the color field is taken into account.
4) Quark flow diagrams and quark counting rules describe the contributions of quarks and antiquarks to the effective color field. The contributions of quarks and antiquarks are linear functions of their numbers with weights determined by the color factors $C_F(qq)$ and $\bar{C}_F(q\bar{q})$.

The effective circular transverse chromomagnetic field $B^a$ is generated by relativistic spectator constituent quarks moving in the forward and backward directions in the c.m. of colliding nucleons (see figure 1). A probe quark from the observed hadron is deflected by the Stern-Gerlach force in the inhomogeneous chromomagnetic field to the left or right depending on the direction of its spin (up or down). Interaction of a chromomagnetic dipole moment of a constituent probe quark with the field $B^a$ leads to the observed single-spin asymmetries [1, 2, 3].
The quark spin precession in the color field changes the direction and magnitude of the Stern-Gerlach force and leads to an oscillation of $A_N(x_F)$ in a strong chromomagnetic field, and to an approximately linear dependence of $A_N(x_F)$ in a weak field. The quark spin precession frequency at high quark energy is proportional to the quark anomalous chromomagnetic moment $\Delta \mu_a^Q$, which is directed along the spin of the quark and has a large negative value [4, 5].

Model-dependent (the CPQ model) estimates of $\Delta \mu_a^Q$ for $u$, $d$, $s$, $c$ and $b$ quarks are obtained from a global analysis of the polarization data [1, 2, 3]. It is found that for the upper $u$ and $c$ quarks $\Delta \mu_a^Q = -0.471 \pm 0.007$, while for the lower $d$, $s$, $b$ quarks it is by a factor of $\sqrt{2}/3$ less within experimental uncertainties. The model parameters were estimated from a global analysis of the single-spin data for 80 different reactions with about 3000 data points [1, 2, 3].

The quark counting rules tell us that the integral of the color field along the quark trajectory is a linear function of the number of spectator quarks and antiquarks with different weights. The weight depends on the color factor $C_F$ of a quark pair, where one quark is a spectator and the other one is a probe quark from the observed hadron. It is found that $q\bar{q}$ pair is in a singlet state with the $C_F = 4/3$ and weight equal to 1. A $qq$ pair is in an antitriplet state with the $C_F = 2/3$ and weight $\lambda = -0.1338 \pm 0.0014$ found from the global polarization data fit [1, 2, 3]. The value of $\lambda$ can be expressed as a function of the ratio $R_F = C_F(q\bar{q})/C_F(qq)$: $\lambda = 1 - \exp(R_F^{3/2})$ since the square of the wave function for a pair of quarks is proportional to the factor $C_F^3$ [6].

3. Comparison of the $A_N$ data and the CPQ model predictions
Below are presented the results of the $A_N$ measurements and the CPQ model predictions. Calculations of $A_N$ in unexplored areas are made for a fixed $p_T = 3$ GeV/c and $\sqrt{s} > 60$ GeV and for $p_T = 2$ GeV/c and $\sqrt{s} \leq 60$ GeV. The $A_N(x_F)$ is predicted for $\sqrt{s} = 500$ (1), 200 (2), 130 (3), 64.2 (4), 19.4 (5) and 8.77 (6) GeV, respectively, and is shown in the right panels.
The data for reaction $p^\uparrow + p(A) \rightarrow \pi^+ + X$ at $\sqrt{s} = 200$ (1a, 1b) and 64.2 (2) (BRAHMS [7, 8]), 19.4 (3) (E704 [9]) and 8.77 (4) GeV (FODS [10]) are shown in figure 2. These $A_N$ data possess the energy dependence that is consistent with the corresponding CPQ model curves. Predictions of $A_N(x_F)$ in figure 3 show an approximate scaling law for $\sqrt{s} \leq 60$ GeV (curves 4, 5 and 6). At higher energies this scaling is violated due to additional $q\bar{q}$ pair production that changes the number of spectator quarks and, as a result, changes the color field strength and its sign. The second reason for the $A_N(x_F)$ scaling violation is the quark spin precession, which changes the direction of the Stern-Gerlach force and leads to oscillation of $A_N(x_F)$ in a strong chromomagnetic field. The CPQ model predicts $A_N(x_F) < 0$ at $\sqrt{s} = 130$ GeV (curve 3).

The data for reaction $p^\uparrow + p(A) \rightarrow \pi^- + X$ [7, 8, 9, 10] are shown in figure 4. For $\pi^-$ production the SSA scaling is expected to be at $\sqrt{s} \leq 60$ GeV (see figure 5, curves 4, 5 and 6).

The $K^-$ SSA data [7, 8, 10, 12] are compared with the model calculations in figure 6. In a $K^-$ meson there is no valence quarks common to the polarized proton but the $A_N(x_F) > 0$ at 64.2 GeV [8]. The positive $A_N$ (solid squares) is explained by the dominating polarized $u$ quark scattering in an effective color field. The positive SSA of the $u$ quark, obtained in the scattering, is then inherited by a $K^-$ meson in the process of $u^\uparrow \rightarrow K^- + X$ fragmentation. Scaling law for $A_N(x_F)$ is held only at large $x_F > 0.6$ and $\sqrt{s} \leq 60$ GeV (see figure 7, curves 4, 5 and 6).
Positive SSA was also measured for the antiproton production at $\sqrt{s} = 200$ GeV [7] (not shown). This is due to the dominance of the process of $u^+ \rightarrow \bar{p} + X$ fragmentation, analogous to the case of $K^-$ meson production. The dependence on energy of the $A_N(x_F)$ for antiproton production is predicted to be weak in the region of $x_F > 0.6$ and $\sqrt{s} \leq 60$ GeV, in accordance with the CPQ model.

The proton production SSA data are shown in figure 8 [7, 8, 10, 11] and the CPQ model predictions in figure 9. A sizable SSA was measured in FODS experiment [10]. The oscillation of $A_N(x_F)$ (solid squares [10] and curve 3) at 8.77 GeV is due to the spin precession of a polarized $u$ quark. The scaling behavior is not expected for the $A_N(x_F)$ (see figure 9).

Figure 8. $A_N(x_F)$ data for reaction $p^+ + p(A) \rightarrow p + X$.

Figure 9. $A_N(x_F)$ predictions for reaction $p^+ + p \rightarrow p + X$.

4. Conclusion
1) A scaling law of $A_N(x_F)$ is expected for the production of $\pi^+$, $\pi^-$ and $K^+$ at $\sqrt{s} < 60$ GeV. The polarized valence quarks fragment into the observed hadrons for these reactions.
2) Generation of new $q\bar{q}$ pairs at $\sqrt{s} > 60$ GeV violates the scaling of $A_N(x_F)$ for the production of $\pi^+$, $\pi^-$ and $K^+$ mesons. The color field can change its sign and strength at high energies.
3) $A_N(x_F) > 0$ at large $x_F > 0.6$ and $\sqrt{s} < 60$ GeV for $K^-$ and $\bar{p}$, as in the case of $A_N(x_F)$ for $\pi^+$ production due to the dominance of polarized $u$-quark fragmentation to a hadron.
4) A sizable $A_N(x_F)$ and its oscillation is expected for the proton production due to the spin precession of polarized valence quarks in the effective chromomagnetic field.

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