Anomalous nonperturbative quark-gluon chromomagnetic interaction and spin effects in high energy reactions

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Abstract

We discuss a new nonperturbative mechanism for spin effects in high energy reactions with hadrons. This mechanism is based on the existence of a large anomalous quark chromomagnetic moment (AQCM) induced by the nontrivial topological structure of QCD vacuum. As an example, we estimate the contribution of this interaction to the single spin asymmetry (SSA) in the inclusive pion production in the proton-proton scattering. We show that SSA induced by AQCM is large and its value is in qualitative agreement with experimental data.

The explanation of the large spin effects in high energy reactions with hadrons is one of the long-standing problems in QCD (see \cite{1, 2} and references therein). It is well known that QCD has a complicated structure of vacuum which leads to the phenomenon of spontaneous chiral symmetry breaking (SCSB) in strong interaction. The instanton liquid model of QCD vacuum \cite{3}, \cite{4} is one of the models in which the SCSB phenomenon arises in a very natural way due to the quark chirality-flip in the field of strong fluctuation of vacuum gluon fields called instantons. As the result, instantons lead to the anomalous quark-gluon chromomagnetic vertex with a large quark spin-flip \cite{5}.

Therefore, they can give an important contribution to the spin dependent cross sections.

In this Letter, we discuss the mechanism of spin effects based on the quark spin-flip by the nonperturbative contribution coming from AQCM. As an example, we present the estimation of the AQCM contribution to SSA in the inclusive pion production in the high energy proton-proton interaction \cite{2}.

The general quark-gluon vertex with the AQCM contribution is

\[ V_\mu(q^2)t^a = -g_\alpha t^a(\gamma_\mu + \frac{\mu_a F_2(q^2)}{2M_q} \sigma_{\mu\nu} q^\nu), \]

where the first term is the conventional pQCD quark-gluon vertex and the second term in our model comes from the nonperturbative sector of QCD. In Eq.1 the form factor \( F_2 \) describes the nonlocality of the interaction, \( \mu_a \) is AQCM, \( q^2 \) is the virtuality of the gluon and \( M_q \) is the dynamical quark mass.

Likewise, the important of SCSB phenomenon for quark spin-flip was also mentioned in the recent paper \cite{6} in the different aspect.

\textsuperscript{2}The details of calculation of the AQCM contribution to SSA at the quark level can be found in \cite{7}.
The form factor $F_2(q^2)$ suppresses the AQCM vertex at short distances when the respective virtuality is large. Within the instanton model \[3\] \[4\] it has the following form

$$F_2(q^2) = F_g(|q| \rho),$$

(2)

where

$$F_g(z) = \frac{4}{z^2} - 2K_2(z)$$

(3)

is the instanton form factor, $K_2(z)$ is the modified Bessel function and $\rho$ is the instanton size.

In this model AQCM is \[8\]

$$\mu_a = -\frac{3\pi(M_q \rho_c)^2}{4\alpha_s},$$

(4)

where $\rho_c$ is the average size of instantons in the QCD vacuum. The value $\mu_a$ of AQCM strongly depends on the dynamical quark mass $M_q$ generated by SCBS. In the mean field approximation (MFA) \[3\], $M_q = 170$ MeV and from Eq.4 $\mu^M_F A = -0.4$. In the Diakonov-Petrov model (DP) \[4\], $M_q = 350$ MeV and $\mu^D P = -1.6$. The strength of nonperturbative interaction in Eq.1 has the following dependence on $M_q$ and the strong coupling constant $g_s$

$$V_{\text{nonpert}} \sim \frac{M_q}{g_s},$$

(5)

which clearly shows the relation to the SCSB phenomenon induced by nonperturbative QCD dynamics.

The SSA for the process of transversely polarized quark scattering on an unpolarized quark, $q^\uparrow(p_1) + q(p_2) \rightarrow q(p_1') + q(p_2')$, is defined as

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow},$$

(6)

where $\uparrow\downarrow$ denote the initial quark spin orientation perpendicular to the scattering plane. On the other hand, the value of SSA can be expressed in terms of the helicity amplitudes:

$$A_N = -\frac{2Im[(\Phi_1 + \Phi_2 + \Phi_3 - \Phi_4)\Phi_5^*]}{[\Phi_1]^2 + [\Phi_2]^2 + [\Phi_3]^2 + [\Phi_4]^2 + 4[\Phi_5]^2].$$

(7)

$$\Phi_1 = M_{++;++}, \quad \Phi_2 = M_{;++;--}, \quad \Phi_3 = M_{+--;+}, \quad \Phi_4 = M_{+--;+}, \quad \Phi_5 = M_{++;++},$$

(8)

where the symbols + or − denote the helicity of a quark in the c.m. frame.

Importantly, the SSA for this process is very large and has a rather weak dependence on $M_q$. We would like...
to emphasize that $A_N$ in our approach does not depend on energy. This behavior is directly related to the spin one t-channel gluon exchange. This phenomenon is in agreement with experimental data. Another remarkable feature of our approach is a flat dependence of SSA on the transverse momentum. It comes from a rather soft power-like form factor in the quark-gluon vertex, Eq.3 and a small average size of an instanton, $\rho_c \approx 1/3$ fm [3]. Such a flat dependence has been observed by the STAR collaboration in the inclusive $\pi^0$ production in high energy proton-proton collision, right panel of Fig.2, and was not expected in the models based on the so-called TMD factorization [10]. Finally, the sign of the SSA is defined by the sign of AQCM and should be positive. This sign is very important for explanation of the signs of SSA observed for the inclusive production of $\pi^+$, $\pi^-$ and $\pi^0$ mesons in proton-proton and proton-antiproton high energy collisions. We can estimate asymmetry at the hadron level for the inclusive production of pions in the proton-proton scattering by using some simple assumptions. Let us consider only leading fragmentation of pions from the final quark. In this case, SSA for the different charge of pions is

$$A_{\pi^+} N(q_t) \approx \frac{\Delta q_t}{q} A_{\pi^0} q A_{\pi^-} N(q_t), \quad (9)$$

where $A_{\pi^\pm} N(q_t)$ is SSA at the quark level presented in the left panel in Fig.2, $\Delta q_t$ is the transverse polarization of the quark with the given flavor in the transversely polarized proton and $q$ is the number of the corresponding quark in the proton. Using the additional assumption $\Delta q_t \approx \Delta q$, where $\Delta q$ is the longitudinal polarization of the quark in the longitudinally polarized proton we have got

$$A_{\pi^\pm} N(q_t) \approx 0.383 A_{\pi^0} N(q_t), \quad A_{\pi^-} N(q_t) \approx -0.327 A_{\pi^0} N(q_t), \quad A_{\pi^0} N(q_t) \approx 0.146 A_{\pi^0} N(q_t), \quad (10)$$

where we used values $\Delta u = 0.766$ and $\Delta d = -0.327$ from [11]. Finally, one can verify that our estimation given by Eq.10 is in qualitative agreement with the available experimental data [9, 12, 13] for the large $x_F$ region.

In summary, we discussed the spin effects in high energy reactions induced by AQCM. This phenomenon appears from the anomalous strong spin-flip quark-gluon interaction induced by the topologically nontrivial configuration of the vacuum gluon fields called instantons. As an example, we estimated the contribution of AQCM to SSA in the

Figure 2: Left panel: the $q_t$ dependence of SSA for the different values of the dynamical quark mass and fixed value for the dynamical gluon mass $m_g = 0.75$ GeV. Right panel: STAR data for inclusive $\pi^0$ production [9].
inclusive production of the pions in the proton-proton scattering and showed that it
was large. Additional arguments for the importance of AQCM for spin effects in high
energy reactions can be found in [14] where its contribution to the elastic proton-proton
scattering at large momentum transfer was considered. We would like to mention that
the mechanism of spin effects based on AQCM is quite general and might happen in any
nonperturbative QCD model with SCSB. The attractive feature of the instanton model
is that within this model this phenomenon comes from rather small distances \( \rho_c \approx 0.3
fm\). As the result, it allows one to understand the origin of large observed spin effects at
large transverse momenta.

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