Instantons and Single Spin Asymmetries

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Abstract

A new mechanism for single spin asymmetries in strong interaction is proposed. It is based on instanton–induced nonperturbative chromomagnetic quark–gluon interaction. We estimate the contribution of this interaction to single spin asymmetry in quark–quark scattering. It is shown, that interference between quark spin–flip amplitude induced by instantons and spin–nonflip amplitude, which is related to nonperturbative two gluon exchange, gives a large value for a single spin asymmetry. Due to strong increasing of the instanton–induced spin–flip amplitude with energy, this asymmetry does not vanish at high energies.

1 Introduction

In the recent years the interest in polarized hadron–hadron and lepton–hadron interactions at high energies has grown enormously. This interest stems from sensational result of the measurement by the EMC(CERN) Collaboration [1] in polarized DIS of a part of proton spin carried by quarks. It has been shown that its value is very small. As a result, the "spin crisis" of a naive perturbative QCD picture of spin–dependent lepton–hadron cross sections (see review [2]) arose.

However, it should be mentioned that a number of anomalous polarized phenomena in hadron–hadron interaction have been found before the EMC result [3]. One of the very interesting results was connected with very large single spin asymmetries at high energy which was observed by the E–704 Collaboration [4] in the inclusive π mesons production in the reactions $pp \to \pi X$, $\bar{p}p \to \pi X$ by using transverse polarized proton and antiproton beams. To clarify the mechanism of the single spin asymmetries, the same experiment at more large energies has been included into the programs of the RHIC–Spin Collaboration at Brookhaven [5] and HERA–$\vec{N}$ project at DESY [6].

It is very important to have the predictions of the single spin asymmetries based on QCD. As it is well–known, the quark-quark scattering amplitude should contain a large spin–flip part to produce a substantial quark single spin asymmetry. The perturbative QCD predicts a decreasing of spin-flip effects with energy, therefore pQCD fails to describe the data [3] that show approximately energy independence of single spin asymmetries.

Recently, a new approach to the theory of polarized effects based upon nonperturbative QCD was proposed [7] (see also some applications of the instanton model to polarized DIS in[8]). In this approach the origin of the large polarized effects is the interaction of quarks with strong vacuum fluctuations of the gluon fields, so-called instantons [9].

In the recent paper [10] it was shown that instantons lead to a new type of the nonperturbative interaction, so–called chromomagnetic quark–gluon interaction. In [11] it was demonstrated that the contribution of this interaction to spin–dependent $g_1(x,Q^2)$ structure function is large and allow us to explain a most part of observed violation of the Ellis–Jaffe sum rule.

The fundamental feature of nonperturbative chromomagnetic quark–gluon interaction is its anomalous dependence on quark helicities. So, this interaction leads to the quark helicity flip, just as a usual perturbative quark–gluon vertex conserves the quark helicity. Therefore this nonperturbative interaction can be used as fundamental QCD mechanism to explain very large single spin asymmetries observed in hadron–hadron interaction.

The main goal of this article is to calculate the contribution of spin–flip chromomagnetic quark–gluon interaction induced by instantons to quark single spin asymmetries.

2 Quark–Gluon Chromomagnetic Interaction and Quark Single Spin Asymmetry

We will consider the case when the momentum transfer between quarks is small [1] $p_\perp^2 \ll S$, where $S=(p_1+p_2)^2$, $t=(p_1'-p_1)^2=-p_\perp^2$. In this case the main contribution to quark–quark scattering amplitude gives Landshoff–Nachtmann (LN) pomeron which is based on the exchange of a pair of nonperturbative gluons [12] (Fig.1a).

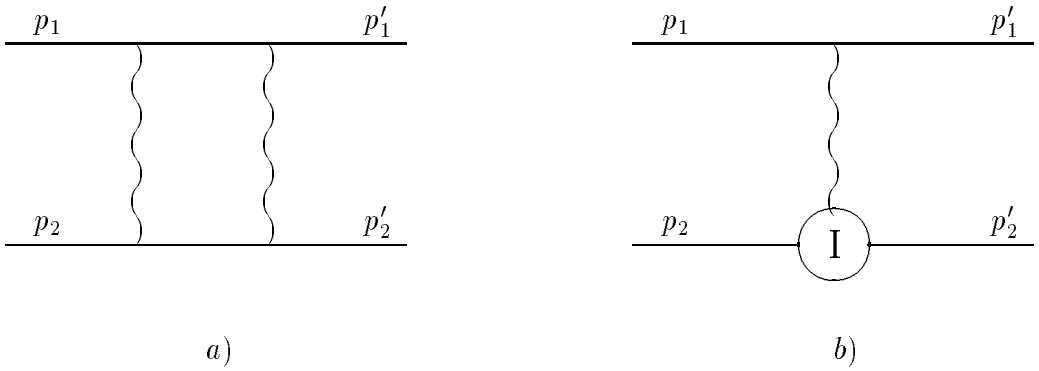

Figure 1: *The contribution to the quark–quark scattering amplitude: a) the contribution from nonperturbative double gluon exchange; b) the contribution from chromomagnetic quark–gluon interaction induced by instantons. The label I denotes instanton.*

In the framework of this model the nonperturbative gluon propagator reads

$$g^2 D(p_\perp^2) = -\beta_0 a e^{-p_\perp^2/\mu_0^2}, \tag{1}$$

where $a=(4\pi^3)^{0.1}/\mu_0$, $\beta_0 \approx 2GeV^{-1}$, and $\mu_0 \approx 1.1GeV$.

[1] The generalization of this approach to the case of high transfer momentum in quark–quark scattering will be discussed elsewhere.

The double gluon exchange with the perturbative quark-gluon interaction does not lead to quark spin-flip and gives rise to helicity amplitudes [13] $\Phi_1 = \Phi_3 \approx M_{+,+;+,+}$. In the framework of LN model these amplitudes are [12]

$$\Phi_1 = \Phi_3 = i2\beta^2(p_\perp^2)S, \tag{2}$$

where $\beta^2(p_\perp^2) = \beta_0^2 exp(-p_\perp^2/2\mu_0^2)$.

The additional contribution to the quark–quark scattering amplitude is related to the non-perturbative chromomagnetic quark–gluon interaction induced by instantons [10] (see Fig.1b)

$$\Delta\mathcal{L}_{\mathcal{A}} = -i\mu_a \sum_q \frac{g}{2m_q^*}\bar{q}\sigma_{\mu\nu}t^a q G^a_{\mu\nu}, \tag{3}$$

where $m_q^* = 2\pi^2\rho_c^2 < 0 \mid \bar{q}q \mid 0 > /3$ is a quark mass in the instanton vacuum.

The value of the quark anomalous chromomagnetic moment in the liquid instanton model [14] is

$$\mu_a = -\frac{f\pi}{2\alpha_s}, \tag{4}$$

where $f = n_c\pi^2\rho_c^4$ is the so–called packing fraction of instantons in vacuum. The value of n_c is connected with the value of the gluon condensate by the formula

$$n_c =< 0 \mid \alpha_s G^a_{\mu\nu}G^a_{\mu\nu} \mid 0 > /16\pi \approx 7.5\ 10^{-4}\ GeV^4. \tag{5}$$

The following estimate for the value of the anomalous quark chromomagnetic moment has been obtained for $\rho_c = 1.6GeV^{-1}$ in [10]

$$\mu_a = -0.2. \tag{6}$$

The quark-gluon chromomagnetic interaction gives rise to $\Phi_5 = M_{++;+-}$ spin–flip amplitude and straightforward calculation leads to the result

$$\Phi_5 = \frac{4\mu_a p_\perp g^2 D(p_\perp^2)S}{9m_q^*}F(p_\perp^2\rho_c^2), \tag{7}$$

where F(z) is the instanton form factor (see for example [15])

$$F(z) = \frac{4}{z}(1 - \frac{z}{2}K_2(\sqrt{z})). \tag{8}$$

The single spin asymmetry on the quark level can be written in the following form

$$A = \frac{2Im(\Phi_5(\Phi_1 + \Phi_3))}{|\Phi_1|^2 + |\Phi_3|^2 + 4|\Phi_5|^2}, \tag{9}$$

where we have neglected the contribution which comes from double spin-flip amplitudes Φ_2 and Φ_4, that are connected with high order instanton contributions.

The result of the calculation of the quark single spin asymmetry is presented in Fig.2 The value of the asymmetry is rather large $A \approx 10\%$ at $p_\perp \approx 1GeV$. The magnitude of the asymmetry strongly depends on the value of the average size of instantons in QCD vacuum. For example, for slightly different value $\rho_c = 2GeV^{-1}$ [14], the final result for the asymmetry is approximately 1.5 of the original value. The above calculation, which was performed by using nonperturbative LN gluon propagator (1), is valid only at rather small value of transfer momentum $p_\perp \leq 1GeV$. At larger values of $p_\perp$ one should use a perturbative gluon propagator instead of nonperturbative one (1) and take into account the instanton contribution to spin-nonflip amplitude as well.

It should be mentioned also that due to the similar growth of both spin–flip amplitude induced by instantons (7) and of spin-nonflip amplitude with energy, the single spin asymmetry turns out to be energy–independent. This result is supported by the experimental data on single spin asymmetries [3] and is opposite to the prediction of perturbative QCD, $A \approx m_q/\sqrt{S}$ [16].

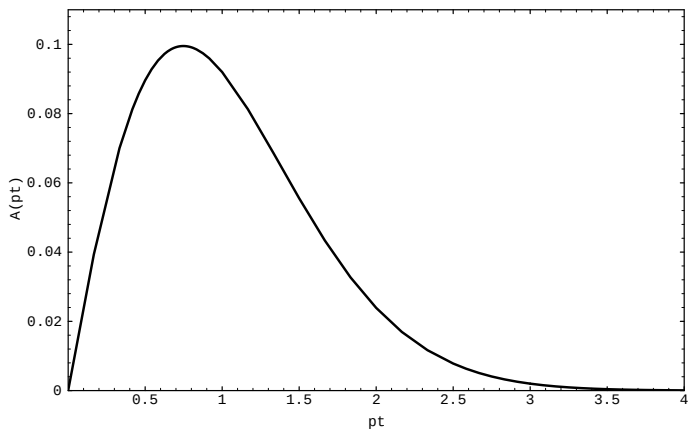

Figure 2: *The instanton contribution to the quark single spin asymmetry.*

3 Summary

In summary, the instanton–induced chromomagnetic quark–gluon interaction leads to a large quark single spin asymmetry at high energy. The magnitude of the single spin asymmetry is determined by the parameters of the instantons in the QCD vacuum. Therefore the investigation of the single spin asymmetries can give very important information on the structure of the QCD vacuum.

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