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SPIN EFFECTS IN QCD AT LARGE DISTANCES

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Great interest in the investigation of the spin role in high energy collisions aroused from the discovery of large spin effects in different reactions[1]. This problem is very important because the perturbative QCD leads to the quark helicity conservation[2]. In this case the spin-flip and nonflip amplitudes obey the condition:

$$\frac{|T_{flip}|}{|T_{non-flip}|} \sim \frac{m}{\sqrt{s}} . \qquad (1)$$

However, this result is not valid at small $|t|$ because the perturbative theory is not true here. The nonperturbative methods of QCD, e.g. QCD sum rules [3,4], are not developed for the objects dependent on several kinematic variables. So the study of small angle scattering can now be based on different model approaches[5,6]. Note that in some models developed for elastic scattering the spin effect appeared which did not disappear as $s \to \infty$ [7] (see also [8]). In this case the spin-flip amplitude for the t-channel exchange with vacuum quantum numbers must have a component growing with s. This paper is devoted to the investigation of this problem.

In QCD the vacuum exchange is associated with the exchange of a two-gluon object [9]. We would like to note that the quark-quark interaction is very important in high energy hadron reactions at low momenta transfer. This conclusion can be drawn from good agreement with the experiment of the additive quark model[10] and from the diffraction dissociation experimental data[11].

In [12] the qq spin-non-flip scattering was examined in the model with taking into account some nonperturbative properties of QCD. Here we shall investigate the spin effects in high energy quark-quark scattering at fixed $|t|$. It will be shown without using the perturbative theory that in the helicity-flip amplitude the terms growing as s appear. And we obtained for the ratio

$$\frac{|T^{qq}_{flip}|}{|T^{qq}_{non-flip}|} \sim \frac{m\sqrt{|t|}}{a^2 \ln s/s_0} , \qquad (2)$$

where the consistent quark mass m is approximately equal to the hadron mass, the dimension of the quantity a is m^2. The $\ln s$ term in the denominator (2) arises from the logarithmic suppression of the spin-flip amplitude. The ratio (2) turns into (1) at large $|t|$ because $a^2 \sim |t|$ when $|t| \to \infty$.

We shall check the existence of the terms growing as s in the spin-flip amplitude in some diagrams of the perturbative theory too.

In the **Appendix**, some spin-flip and spin-non-flip matrix elements in the symmetric system which is convenient for the calculations are written.

Let us investigate the leading asymptotic term of the quark-quark scattering amplitude. In calculation we shall use the following representations for the quark and gluon propagator for the space-like momenta (without the color indices)

$$\hat{G}^{q}(p) = i(\hat{p}+m)\,G(-p^2) \quad , \tag{3}$$

$$G^{g}_{\alpha\beta}(q) = -i g_{\alpha\beta}\, F(-q^2).$$

In the region we are interested in, the momenta p^2 and q^2 are small and we do not use any concrete form for the functions $F(-q^2)$ and $G(-p^2)$. We suppose only that these functions are decreasing as a power at large p^2 and q^2.

The form of the gluon propagator is conformed to the Fermi-Feinman gauge. This is convenient because the ghosts are absent in the investigated diagrams.

In what follows we shall calculate the imaginary part of the quark-quark amplitude in the region $s \to \infty$, t-fixed. For diagram, fig.1, we obtain:

$$Im\, T_1 = \frac{g^4}{(2\pi)^6}\int d^4k\, d^4\ell\; \delta[(p-k)^2-m^2]\;\delta[(p'+\ell)^2-m^2]\,F[-(k+r)^2]\times$$

$$\times F[-(k-r)^2]\,F[-(\ell+r)^2]\,F[-(\ell-r)^2]\,N^{\lambda\mu,\nu\sigma}\, Im\,\Gamma_{\lambda\mu,\nu\sigma}(k,\ell,r)\,. \tag{4}$$

Here $Im\,\Gamma_{\lambda\mu,\nu\sigma}$ is the imaginary part of the gg amplitude, m is the constituent quark mass

$$N^{\lambda\mu,\nu\sigma} = \bar{u}(p-r)\gamma^{\lambda}(\hat{p}-\hat{k}+m)\gamma^{\mu}u(p+r)\times\bar{u}(p'+r)\gamma^{\nu}(\hat{p}'+\hat{\ell}+m)\gamma^{\sigma}u(p'-r).$$

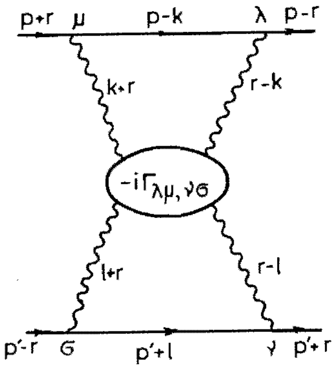

Fig.1.
Exchange of a two-gluon-object between quarks

The integration in (4) can be done in the light-cone variables/2/

$$p = (p_+, p_-, 0_\perp)\;;\quad p_+ = p_0 + p_z\;;\quad p_- = p_0 - p_z\;;$$

$$k = (x p_+, k_-, k_\perp)\;;\quad \ell = (y p_+, \ell_-, \ell_\perp)\;;$$

$$\int d^4k\, d^4\ell = \frac{1}{4}\int dx\, dy\, d(p_+k_-)\, d(p_+\ell_-)\, dk_\perp\, d\ell_\perp\,.$$

Integrating over dy and $d(p_+k_-)$ we have

$$Im\, T_1 = \frac{g^4}{4s(2\pi)^6}\int\limits_{\alpha/s}^{1-\beta/s}\frac{dx\, dk_\perp\, d\ell_\perp}{(1-x)}\,F_+^{(1)}F_-^{(1)}F_+^{(2)}F_-^{(2)}\times \tag{5}$$

$$\times\int d(p_+\ell_-)\, N^{\lambda\mu,\nu\sigma}\, Im\,\Gamma_{\lambda\mu,\nu\sigma}\Big|_{\tilde{y},\,\widetilde{(p_+k_-)}}\,,$$

where

$$\tilde{y} = \frac{m^2+\ell_\perp^2}{s}\;;\quad \widetilde{(p_+k_-)} = m^2 + r_\perp^2 - \frac{m^2+k_\perp^2}{(1-x)}\;;$$

$$F_\pm^{(1)} \simeq F\Big(\frac{1}{(1-x)}\big[x^2m^2 + (k_\perp \pm (1-x)r_\perp)^2\big]\Big);$$

$$F_\pm^{(2)} \simeq F\big((\ell_\perp \pm r_\perp)^2\big).$$

The region near the upper x -limit does not contribute to the integral (5) because the functions $F_+^{(1)}$, $F_-^{(1)}$ are decreasing. So we shall consider the region

$$0 < x < (1-c), \quad c\text{-fixed}, \tag{6}$$

in which the gluon-gluon amplitude is far from the asymptotic regime. Really all the gluon momenta squares are negative and small. The kinematic variables of Γ are not very large too:

$$\tilde{t} = t,$$

$$\tilde{s} = (\kappa-\ell)^2 \simeq x[(\widetilde{p_+ k_-}) - (\widetilde{p_+ \ell_-})] - (k_\perp - \ell_\perp)^2,$$

where $(\widetilde{p_+ k_-})$ is determined in (5), variable $(p_+ \ell_-)$ can have poles at $x=0$ and $x=1$ (see (17)). But in the region (6) $\tilde{s} \ll s$.

Let us investigate (5) in the general form. We must find the terms growing as s^2 in the numerator of (5) in order to obtain the behaviour $\sim s$ in $\mathrm{Jm}\, T_1$.

In what follows we shall calculate the amplitude with spin flip in the upper quark line. The matrix elements with the positive helicities in the lower quark line can be calculated with the help of Eq.(A.I)

$$N_1^{\nu\sigma} = \bar{U}^{(+)}(p'+r)\gamma^\nu(\hat{p}'+\hat{\ell}+m)\gamma^\sigma U^{(+)}(p'-r) \simeq 4p'^\nu p'^\sigma + \\ +2(p'^\nu \ell^\sigma + \ell^\nu p'^\sigma) + 2i\varepsilon^{\nu\sigma\delta\rho}\ell_\delta p'_\rho. \tag{7}$$

It can be shown that the main contribution to the amplitude (5) as $s \to \infty$ comes from the first term in (7)

$$N_1^{\nu\sigma} \simeq 4p'^\nu p'^\sigma. \tag{8}$$

Let us choose the gluon-gluon amplitude in (5) in the following general form:

$$\mathrm{Jm}\,\Gamma_{\lambda\mu,\nu\sigma} = g_{\lambda\nu}g_{\mu\sigma}\Gamma 1 + g_{\lambda\mu}g_{\nu\sigma}\Gamma 2 + g_{\nu\mu}g_{\sigma\lambda}\Gamma 3 + \\ + g_{\nu\sigma}a_\mu\tilde{a}_\lambda\Gamma 4 + g_{\lambda\mu}b_\sigma\tilde{b}_\nu\Gamma 5 + g_{\mu\sigma}c_\lambda\tilde{c}_\nu\Gamma 6 + \\ + g_{\mu\nu}d_\sigma\tilde{d}_\lambda\Gamma 7 + g_{\sigma\lambda}f_\mu\tilde{f}_\nu\Gamma 8 + g_{\lambda\nu}h_\mu\tilde{h}_\sigma\Gamma 9 + \\ + j_\lambda j'_\mu\tilde{j}_\nu\tilde{j}'_\sigma\Gamma 10 + \varepsilon_{\lambda\mu\nu\sigma}\Gamma 11. \tag{9}$$

Here the vectors $a - j$ are linear combinations of vectors κ, ℓ, r. The functions Γi have not large variable s in the region (6) because, as mentioned previously, Γ is far from the asymptotic behaviour here.

The term leading as $s \to \infty$ in the matrix element (5) looks as follows:

$$N = N^{\lambda\mu,\nu\sigma}\mathrm{Jm}\,\Gamma_{\lambda\mu,\nu\sigma} = 4\bar{U}(p-r)[\hat{p}'(\hat{p}-\hat{k})\hat{p}'(\Gamma 1 + \Gamma 3) + \\ + \gamma_\mu(\hat{p}-\hat{k}+m)\gamma^\mu(p'b)(p'\tilde{b})\Gamma 5 + (p'\tilde{c})\hat{c}(\hat{p}-\hat{k}+m)\hat{p}'\Gamma 6 + \\ + (p'd)\hat{\tilde{d}}(\hat{p}-\hat{k}+m)\hat{p}'\Gamma 7 + (p'\tilde{f})\hat{p}'(\hat{p}-\hat{k}+m)\hat{f}\,\Gamma 8 + \\ + (p'h)\hat{p}'(\hat{p}-\hat{k}+m)\hat{\tilde{h}}\,\Gamma 9 + (p'\tilde{j})(p'\tilde{j}')\hat{j}(\hat{p}-\hat{k}+m)\hat{j}'\Gamma 10]U(p+r). \tag{10}$$

It is not difficult to calculate the helicity amplitudes from (10). For example, we obtain for the first matrix structure in (10), using (A2.3):

$$\langle \hat{p}'(\hat{p}-\hat{k})\hat{p}' \rangle_{++} \simeq s^2(1-x), \\ \langle \hat{p}'(\hat{p}-\hat{k})\hat{p}' \rangle_{+-} \simeq m\Delta s(1-x). \tag{11}$$

Just this matrix structure is in the simplest quark-quark diagrams with the two gluon exchange in the t-channel. We see that for these diagrams helicity is conserved.

We have found another behaviour for the $\Gamma 5 - \Gamma 10$ structures. Here we show this for the $\Gamma 5$ -term. Taking into account the wave function equation we have

$$\langle \gamma_\mu(\hat{p}-\hat{k}+m)\gamma^\mu \rangle \simeq \langle \hat{p}+\hat{k} \rangle, \\ \langle \hat{p}+\hat{k} \rangle_{++} \simeq 2p^2 + 2(p\kappa) = a^2, \\ \langle \hat{p}+\hat{k} \rangle_{+-} \simeq m\Delta(1+x). \tag{12}$$

For the vector b determined by the condition

$$b = \alpha K + \beta \ell + \gamma r$$

the following equation is valid

$$(p'b) \simeq \alpha (p'K) = \frac{\alpha S x}{2}. \tag{13}$$

As a result we obtain for the $\Gamma 5$ matrix elements:

$$\langle \dots \Gamma 5 \rangle_{++} \sim a^2 S^2 x^2 \Gamma 5, \tag{14}$$

$$\langle \dots \Gamma 5 \rangle_{+-} \sim m \Delta S^2 x^2 (1+x) \Gamma 5.$$

So there are the terms growing as S in both the spin-non-flip and spin-flip amplitudes. The matrix elements from other structures have a behaviour similar to (14). All helicity-flip matrix elements are proportional to x^2. But some helicity-non-flip matrix elements do not vanish at $x = 0$. As a result

$$\langle N \rangle_{++} \sim S^2 a^2 f_1 (x, \Delta), \tag{15}$$

$$\langle N \rangle_{+-} \sim m \Delta S^2 x^2 f_2 (x, \Delta).$$

Usually the function f_1 has the following form near $x \to 0$ /13/

$$f_1 (x, \Delta) \underset{x \to 0}{\sim} \frac{\ln^K S x}{x} \varphi_1 (\Delta).$$

The function f_2 must have a similar behaviour. The integration in (5) in this case near $x = 0$ leads to the following asymptotic behaviour for the helicity amplitudes

$$\langle \mathrm{Jm}\, T_1 \rangle_{++} \sim a^2 S (\ln S)^{K+1} \varphi_1 (\Delta), \tag{16a}$$

$$\langle \mathrm{Jm}\, T_1 \rangle_{+-} \sim m \Delta S (\ln S)^K \varphi_2 (\Delta). \tag{16b}$$

So we conclude that the contribution growing as S must take place in the helicity-flip amplitudes connected with the two-gluon-object exchange in the t-channel. They are suppressed with respect to the helicity-non-flip amplitudes.

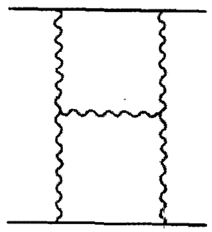

Fig. 2. Ladder diagram which contributes to the spin-flip amplitude.

Now we cannot perform some quantitative QCD calculations in this region. But we can demonstrate the appearance of similar terms by using the diagrams of perturbative QCD.

The simplest diagram of the fig.1 type with the complicated matrix structure (9) is the ladder diagram with the gluon cross-beam (fig.2). In this case we have

$$\int d(p_+ \ell_-)\, \mathrm{Jm}\, \Gamma^{(2)}_{\lambda\mu,\nu\sigma} = \frac{\pi g^2}{x} \Big\{ g_{\nu\lambda} g_{\mu\sigma} t^2 + g_{\nu\sigma} (d+r)_\mu (d-r)_\lambda +$$

$$+ g_{\mu\lambda} (u+r)_\sigma (u-r)_\nu - g_{\mu\sigma} \big[(t+2r)_\lambda (u-r)_\nu + (t+2r)_\nu (d-r)_\lambda \big] +$$

$$+ g_{\mu\nu} (u+r)_\sigma (d-r)_\lambda + g_{\sigma\lambda} (d+r)_\mu (u-r)_\nu - \tag{17}$$

$$- g_{\lambda\nu} \big[(d+r)_\mu (t-2r)_\sigma + (u+r)_\sigma (t-2r)_\mu \big] \Big\} \Big|_{(\widetilde{p_+ \ell_-})},$$

where

$$t = K + \ell\,; \quad d = 2\ell - K\,; \quad u = 2K - \ell\,;$$

$$(\widetilde{p_+ \ell_-}) = m^2 + r_\perp^2 - \frac{m^2 + K_\perp^2}{(1-x)} - \frac{(K_\perp - \ell_\perp)^2}{x}.$$

Using (8) and the matrix elements (A.3) we can calculate the main asymptotic term of this helicity-flip amplitude

$$\Big\langle \int d(p_+ \ell_-)\, \mathrm{Jm}\, \Gamma^{(2)}_{\lambda\mu,\nu\sigma} N^{\lambda\mu,\nu\sigma} \Big\rangle_{+-} \simeq \frac{\pi g^2}{x} \left(-8 m \Delta x^2 S^2 (1-x) \right). \tag{18}$$

The obtained integral for the amplitude $\langle T^{(2)} \rangle_{+-}$ has the form (5) without singularity at $x = 0$. In this case it has the asymptotic behaviour (16b) with $K = 0$. The helicity-non-flip amplitude /13/ has the form (16a).

The contribution with the 4-g vertex which occurs at the same order in g^2 leads to the helicity conservation because it has only $\Gamma_1 - \Gamma_3$ structures.

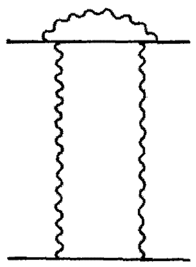

Fig.3. Planar diagram with gluon exchange in the upper quark line.

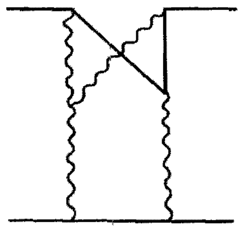

Fig.4. Nonplanar diagram with gluon exchange.

Let us now investigate diagrams of figs.3,4 which are not similar in form to fig.1. Calculations analogous to the previous ones leads to the following expressions for the helicity-flip amplitudes

$$\langle \mathrm{Jm}\, T^{(3)} \rangle_{+-} \simeq \frac{\alpha_s^3}{(2\pi)^2} \frac{1}{S} \int\limits_{\alpha/S}^{1-\beta/S} \frac{dx\, dk_\perp dl_\perp}{x(1-x)} F_+ F_- G_+ G_- N^{(3)}, \qquad (19)$$

where

$$G_\pm = G\left[(1-x)m^2 + \frac{1}{(1-x)}(k_\perp \pm (1-x) r_\perp)^2\right];$$

$$N^{(3)} = 8 m \Delta x^2 S^2 (1-x)$$

and

$$\langle \mathrm{Jm}\, T^{(4)} \rangle_{+-} \simeq \frac{\alpha_s^3}{(2\pi)^2} \frac{1}{S} \int\limits_{\alpha/S}^{1-\beta/S} \frac{dx\, dk_\perp dl_\perp}{x(1-x)} F^{(4)} G^{(4)} F_+ F_- N^{(4)}.$$

Here

$$F^{(4)} = F\left(\frac{1}{(1-x)}\left[x^2 m^2 + (k_\perp + r_\perp(1-x))^2\right]\right); \qquad (20)$$

$$G^{(4)} = G\left[\frac{(1-x)}{x}(l_\perp - k_\perp)^2 + (r_\perp + k_\perp - l_\perp)^2 + x m^2 - (1-x) r_\perp^2\right];$$

$$N^{(4)} = 4 m x (1-x) S^2 \left[2\Delta x + (l_x - \Delta)\right].$$

The functions F and G are determined in (3), $F_\pm$ coincide with functions $F_\pm^{(2)}$ in (5). An extra "1" in (20) comes from the colour factor.

The helicity-non-flip contributions from the diagrams (fig.3,4) were calculated in /13/

$$\langle \mathrm{Jm}\, T^{(3,4)} \rangle_{++} \sim a^2 S \ln S\, \varphi^{(3,4)}(\Delta).$$

Thus, the helicity-flip-amplitudes are suppressed logarithmically as above. This permits us to conclude that when integrals (5),(19),(20) are calculated in the main logarithmic approximation the obtained helicity-flip amplitudes will be lost.

There are other diagrams with the gluon corrections to the vertex functions. They lead to the contributions containing the anomalous magnetic moment of the quark μ_q. Simple calculations show that these contributions lead to the helicity-flip amplitude which is proportional to μ_q. It can be shown that the diagrams with gluons coupled with the lower quark line (the overturned diagrams 3,4) do not contribute to the investigated matrix elements because they lead to the helicity-flip in the lower quark line.

We do not show the colour factors here because their magnitudes are unimportant.

The analysis made in this paper shows us that the helicity-flip amplitudes not vanishing as $S \to \infty$ are connected with the gluon contributions. Really the amplitude T_{+-} growing as S appears in the case when the gluon line couples the valence quarks in the initial and final states. It contains the constituent quark mass as a dimensional parameter which is equal to the hadron mass in the order of magnitude. Thus we can conclude that the arising effect is not extremely small. The quantitative calculations cannot be done now. However, it is possible that the nonperturbative methods of QCD will permit us to perform similar calculations in future.

The author expresses his deep gratitude to V.G.Kadyshevsky, V.A.Matveev and A.N.Sissakian for the interest in the work and fruitful discussions.

Appendix

For caloulations of the matrix elements of the quark-quark scattering amplitudes

$$q(p_1) + q(p_2) \to q(p_3) + q(p_4)$$

the symmetric system is convenient in which the sum of the quark momenta before and after scattering is directed along the z -axis:

$$p = \tfrac{1}{2}(p_1+p_3) = (p_0, 0, 0, p_z);$$

$$p' = \tfrac{1}{2}(p_2+p_4) = (p_0, 0, 0, -p_z);$$

$$r = \tfrac{1}{2}(p_1-p_3) = \tfrac{1}{2}(p_2-p_4) = (0, r_x, 0, 0) = (0, -\tfrac{\Delta}{2}, 0, 0);$$

$$s \simeq 2(pp') \;;\; p^2 = p'^2 = m^2 + \Delta^2/4 .$$

where Δ is the momenta transfer.

We here write the main asymptotic terms of two helicity non-flip-matrix elements:

$$\bar{U}^{+}(p_4)\, \gamma_\mu\, U^{+}(p_2) \simeq 2p'_\mu$$
$$\bar{U}^{+}(p_4)\, \gamma_\mu \gamma_5\, U^{+}(p_2) \simeq 2p'_\mu . \qquad (A.1)$$

Let us introduce the following definition

$$\bar{U}^{S_3}(p_3)\, \hat{A}\, U^{S_1}(p_1) = \langle \hat{A} \rangle_{S_3 S_1} ,$$

where S_1 and S_3 are the quark helicities.

For the states without helicity flip we have

$$\langle \gamma_\mu \rangle_{++} \simeq 2p_\mu \;;\; \langle \gamma_\mu \gamma_5 \rangle_{++} \simeq 2p_\mu ; \qquad (A.2)$$
$$\langle 1 \rangle_{++} \simeq 2m .$$

The main asymptotio terms of the spin-flip matrix elements which are important in our oalculations look as follows

$$\langle \gamma_0 \rangle_{+-} \simeq \frac{2m\Delta}{\sqrt{s}} ;$$
$$\langle 1 \rangle_{+-} \simeq \Delta ; \qquad (A.3)$$

$$\langle i\varepsilon^{\alpha\beta\gamma\rho} a_\alpha p'_\beta r_\gamma \gamma_\rho \gamma_5 \rangle_{+-} \simeq -2m\, r_x (ap') ;$$

$$\langle i\sigma^{\lambda\mu} p'_\lambda r_\mu \rangle_{+-} \simeq -2(pp') r_x = -s\, r_x .$$

The matrix elements $\langle \gamma_z \rangle_{+-}$, $\langle \gamma_\perp \rangle_{+-}$, $\langle \gamma_0 \gamma_5 \rangle_{+-}$ and so on are suppressed as a power of s .

It is easy to see that the ratio

$$\frac{\langle \gamma_0 \rangle_{+-}}{\langle \gamma_0 \rangle_{++}} \sim \frac{m\Delta}{s}$$

is going to zero as $s \to \infty$ and the QCD quark-gluon vertex conserves the quark helicity.

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Спиновые эффекты в КХД на больших расстояниях

Без использования методов теории возмущений КХД исследовано кварк-кварковое рассеяние при высоких энергиях. Показано, что обмен 2g-состоянием в t-канале приводит к амплитуде с изменением спиральности, растущей как S, которая в качестве размерного параметра содержит массу составляющего кварка. Наличие таких членов в амплитуде с переворотом спина проверено на основе исследования диаграмм теории возмущений КХД.

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Spin Effects in QCD at Large Distances

The high-energy quark-quark scattering is investigated without using the QCD perturbative theory. It is shown that the two-gluon-object exchange in the t-channel leads to the helicity-flip amplitude growing as S which contains the constituent quark mass as a dimensional parameter. The existence of such terms in the spin-flip amplitude is checked in some diagrams of perturbative theory.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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