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SPIN-FLIP EFFECTS IN THE POMERON EXCHANGE

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Observation of large spin effects in different high energy reactions [1] has aroused a considerable interest in spin physics investigations. Standard perturbative QCD methods cannot explain the observed spin effects because QCD leads to a power suppression of the spin-flip amplitude at large momenta transfer [2]. Here we are interested in small momenta transfer. It is obvious that the perturbative theory cannot be used in this region.

The high energy hadron interaction at fixed momenta transfer can be investigated on the basis of different model approaches [3]. Some of them lead to the spin effects which do not disappear in the $s\to\infty$ limit in different processes, including elastic scattering [4,5]. This means that the pomeron has a spin-flip amplitude.

In what follows we shall investigate this problem on the basis of a QCD model which takes into account some nonperturbative properties of the theory and show that different effects like a gluon ladder, quark loops, $q\bar{q}$ sea contributions may lead to the spin-flip amplitude growing as s. Some aspects of this problem were discussed previously in papers [6-8].

In the case of elastic scattering the leading contribution to the amplitude as $s\to\infty$, t-fixed, comes from the vacuum t-channel exchange (pomeron) which is usually associated in QCD with the two-gluon-object exchange [9]. We did not want to discuss here the large-distance effects connected with the hadron structure for simplicity. We shall investigate the quark-quark scattering that plays an important role in high energy processes at small t. This conclusion can be drawn from good agreement with experiment of an additive quark model, for example.

Let us suppose that the main contribution to the qq scattering amplitude in the investigated region comes from the two-gluon ladder diagrams. Diagrams of this type without gluon corrections in the quark lines can be represented in the form (fig.1), where the amplitude of the gluon-gluon interaction includes the pure gluon ladder together with the quark loops.

In our model we suppose as in [10] that nonperturbative effects are important in the region $s\to\infty$ and small $|t|$. The following representation for the quark and gluon propagators for the space-like momenta (without the colour indices) are used:

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

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

The form of the gluon propagator is conformed to the Fermy-Feynman gauge. 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 propagators become perturbative at large momenta. The connection between the nonperturbative part of the gluon propagator and gluon condensate is written in /10/. Discussion of the gauge-invariance problem in this case can be found in /11/.

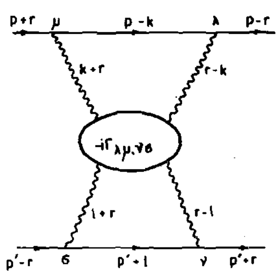

Fig.1. Exchange of a two-gluon object between quarks.

In what follows we shall calculate only the imaginary part of diagrams because the pomeron is approximately purely imaginary. Some gluon and quark propagators in these calculations are on the mass shell. In this case we suppose for them the usual pole behaviour. As a result, we have for the diagram of fig.1:

$$\mathrm{Im}T=\frac{g^4}{(2\pi)^4}\int d^4k d^4l \quad \delta[(p-k)^2-m^2]\delta[(p'+l)^2-m^2]F[-(k+r)^2]$$
$$F[-(k-r)^2]F[-(l+r)^2]F[-(l-r)^2]\mathrm{Im}\Gamma_{\lambda\mu,\nu\sigma}\; N^{\lambda\mu,\nu\sigma}, \tag{1}$$

where m is the constituent quark mass,

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

Performing integration over the light-cone variables

$$k=(xp_+,k_-,\vec{k}_\perp)\,,\qquad l=(yp_+,l_-,\vec{l}_\perp)\,, \tag{2}$$

we obtain:

$$\mathrm{Im}T=\frac{g^4}{s(2\pi)^6}\int_{\alpha/s}^{1-\beta/s}dx\int dk_\perp dl_\perp\; G(x,k_\perp,l_\perp,r_\perp)$$
$$\int d(p_+l_-)\;\mathrm{Im}\Gamma_{\lambda\mu,\nu\sigma}\;N^{\lambda\mu,\nu\sigma}.$$

It can be shown that in (1) the region $0<x<(1-c)$, c-fixed is

important /6/. In this region large momenta are going along the quark lines and the gluon-gluon amplitude is far from the asymptotic regime. So, it cannot contain the large variables s. For the gg amplitude we used the representation with all possible structure on the gluon indices. On the basis of this general representation for Γ we obtain the following behaviour for the qq spin-flip amplitude /6,8/:

$$\mathrm{Im}\Gamma_{\lambda\mu,\nu\sigma} < N^{\lambda\mu,\nu\sigma}>_{flip}\sim\; m\sqrt{|t|}\; s^2\; f(x,k_\perp,l_\perp,r_\perp). \tag{3}$$

Only the structures which are similar to the simplest 2-g exchange diagrams don't contribute to (3). As a result, we obtain the spin-flip amplitude growing as s. The analysis shows that this amplitude can be suppressed only logarithmically with respect to the spin-non-flip amplitude:

$$\frac{|T_{flip}|}{|T_{non-flip}|}\sim\frac{m\sqrt{|t|}}{a\,\ln s/s_0}. \tag{4}$$

Here a contains the constituent quark mass m and $|t|$ /12/. As a result, $a\sim|t|$ when $|t|\to\infty$ and the helicity is conserved in the case of large-angle scattering according to /2/. We can check (4) by analysing the diagrams of perturbative QCD /6/ (e.g. the ladder diagram with the gluon cross-beam).

Hence we show that in the α_s^3 order the behaviour:

$$T_{flip}\sim\; im\sqrt{|t|}\; s\alpha_s^3\;\phi(t) \tag{5}$$

for the spin-flip amplitude can be valid.

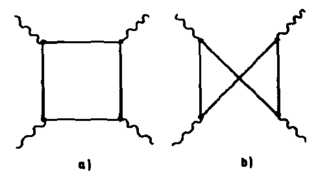

Fig.2. The quark loop contribution to the gluon-gluon amplitude:
a) -planar loop;
b) -nonplanar loop.

Now let us check (4) by calculating the quark loop contribution to the gluon-gluon amplitude /8/. We would like to recall that the quark-loops play a decisive role in the solution of the proton "spin crisis" problem [13]. It will be seen later that this contribution is very important in our case too.

The corresponding integral is of a form analogous to (1). The graphs (fig.2) contribute only to ImΓ. For the planar diagram (fig.2a) we have:

$$\mathrm{Im}\Gamma^{a}_{\lambda\mu,\nu\sigma} \sim \frac{g^4}{2(2\pi)^2} \int d^4q\ \delta[(k+q)^2-\sigma^2]\delta[(q+l)^2-\sigma^2]$$

$$\mathrm{Tr}\{[\hat{q}-\hat{r}+\sigma]\gamma_{\sigma}[\hat{q}+\hat{l}+\sigma]\gamma_{\nu}[\hat{q}+\hat{r}+\sigma]\gamma_{\lambda}[\hat{q}+\hat{k}+\sigma]\gamma_{\mu}\} \quad (6)$$

$$D[-(q-r)^2+\sigma^2]D[-(q+r)^2+\sigma^2].$$

Integration in (1,6) over k_-, l_-, q_-, y can be done with the help of δ-functions in the light-cone variables (2) and

$$q=(-zp_+,q_-,\vec{q}_\perp).$$

As a result, we obtain:

$$\mathrm{Im}T^a = \frac{c^a\ \alpha_s^4}{s(2\pi)^4}\int \frac{dxdz\ \theta(1-x)\theta(x-z)\theta(z-y)}{(1-x)(x-z)(z-y)} \int dk_\perp dl_\perp dq_\perp\ H\ S_{\lambda\mu,\nu\sigma}\ N^{\lambda\mu,\nu\sigma}, \quad (7)$$

where c_a is a colour factor,

$$H=\{F[-(k+r)^2]F[-(k-r)^2]F[-(l+r)^2]F[-(l-r)^2] D[-(q+r)^2+\sigma^2]D[-(q-r)^2+\sigma^2]\}\,|_{k_-,l_-,q_-,y}\ ; \quad (8)$$

$$S_{\lambda\mu,\nu\sigma}=\{\mathrm{Tr}\}|_{k_-,l_-,q_-,y}\ .$$

Here Tr is a trace from (6), the pole quantities k_-,l_-,q_-,y are determined by δ-functions. When the momenta transfer are sufficiently small $\Delta^2 = 4\ r^2 < 4\ m^2$, we find that $y \sim m^2/s$. At the pole points the arguments of quarks and gluons propagators

$$\tilde{a}^2 = a^2|_{k_-,l_-,q_-,y}$$

are the following:

$$-(\widetilde{k\pm r})^2=\{x^2m^2+[\vec{k}_\perp \pm(1-x)\vec{r}_\perp]^2\}/(1-x);\quad -(\widetilde{l\pm r})^2=(\vec{l}_\perp\pm\vec{r}_\perp)^2;$$
$$-(\widetilde{q\pm r})^2+\sigma^2=x/(x-z)\ [q_\perp^2+2\vec{q}_\perp(z/x\ \vec{k}_\perp\pm(x-z)/x\ \vec{r}_\perp)+h(x,z,k_\perp^2,r_\perp^2)]. \quad (9)$$

It can be shown that the integrals over $q_\perp^2$, $k_\perp^2$, $l_\perp^2$ have cut-offs at $q_\perp^2$, $k_\perp^2$, $l_\perp^2 \sim s$ /8/. The matrix elements of the product

$$N = S_{\lambda\mu,\nu\sigma}\ N^{\lambda\mu,\nu\sigma} \quad (10)$$

in (7) can be calculated on the basis of /6/. For the spin-flip amplitude we obtain:

$$N^a_{flip}= m\sqrt{|t|}\ s^2\ [a(x,z)\ q_\perp^2 +\Psi^a(x,z,q_\perp,k_\perp,r_\perp)], \quad (11)$$

where:

$$a(x,z)=-16[2z^2(1-x)-zx(1-2x)-x^3](z-y)/(x-z) \quad (12)$$

and Ψ^a is a linear function of $q_\perp$.

The analysis shows that the main contribution to integral (7) comes from the region with large $q_\perp^2$. It is easy to see that only the term, growing as $q_\perp^2$ in (11) is important in the leading logarithmic approximation. In this region we can use the perturbative quark propagators too. As a result we have:

$$T^a_{flip}= 2N_f\frac{m\sqrt{|t|}\ \alpha_s^4\ \pi\ s}{(2\pi)^4}\{\ln s/s_0\ \int d^2l_\perp\ F[-(\widetilde{l+r})^2]F[-(\widetilde{l-r})^2] \quad (13)$$
$$\int_y^1\frac{dx}{x^2\ (1-x)}\ \int d^2k_\perp\ F[-(\widetilde{k+r})^2]F[-(\widetilde{k-r})^2]I^a(x)+(\begin{smallmatrix}\text{non log}\\ \text{terms}\end{smallmatrix})\}.$$

Here

$$I^a(x) = c^a\int_y^x\frac{dz\ (x-z)}{(z-y)}\ a(x,z). \quad (14)$$

Summation runs over quark flavors, and the antiquark loops are taken into account in (13).

Similar calculations can be performed for the nonplanar graph (fig.2b). In this case the product N (10) has a term proportional to $q_\perp^2$ as in eq. (11):

$$N^b_{flip}= m\sqrt{|t|}\ s^2[b(x,z)q_\perp^2 +\Psi^b(x,z,q_\perp,k_\perp,r_\perp)]$$

with

$$b(x,z)=16[2z^2(1-x)-2zx(1-x)-x^3+2/3\ x^2].$$

Expression (13) is fulfilled for the leading logarithmic term of the nonplanar graph but instead of (14) we have:

$$I^b(x) = c^b\int_y^x dz\ b(x,z). \quad (15)$$

As a result, for the colour singlet exchange in the t-channel we obtain expression (13) for the total amplitude with

$$I(x)=\int_y^x dz\ [4/27\ a(x,z)(x-z)/(z-y)\ -1/54\ b(x,z)]=$$
$$=-16/27\ x^3[5/6\ -3x].$$

So, the integral over x in (13) is convergent near the lower limit, and we have no additional logarithmic factors from it. Thus, the large $q_\perp^2$ contribution in the quark-loop diagrams (fig.2) can lead to the following asymptotical behaviour for the spin-flip amplitude:

$$T_{flip} \sim i\alpha_s^4\, m\sqrt{|t|}\; s\ln s/s_0\; \phi(t). \tag{16}$$

We would like to note that an asymptotic similar to (16) can be obtained for the large $q_\perp^2$ contribution at the gluon ladder and corresponding ghost diagrams in the order α_s^4. All these $\ln s$ factors can compensate in the sum of diagrams. The check of this assumption will be done elsewhere.

In order to show the possibility of this compensation, we shall discuss here a simple model which takes into account the nonperturbative effects connected with a $q\bar{q}$ sea contribution. A brief discussion of this problem is done in /7/. One of the $q\bar{q}$ sea diagrams is shown in fig.3. There are some gluon exchanges between quark-antiquark pairs in

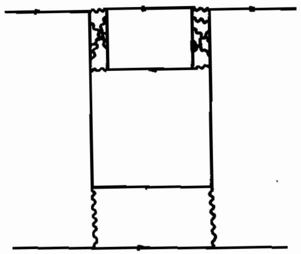

Fig.3 Quark-antiquark sea diagram.

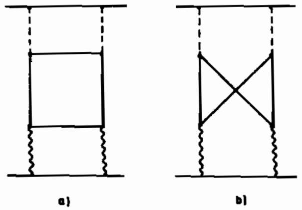

Fig.4. Effective diagram for $q\bar{q}$ sea contribution.

the t-channel. The confinement effects combine them together. These nonperturbative objects can be approximated by two meson states. As a result, we have effective diagrams (fig.4).Similar diagrams can be obtained from the low-energy effective meson lagrangians (see e.g./14/). In the case of $qq\pi$ coupling this lagrangian has a form (the isospin factor is not included):

$$L_{\pi qq} = ig_\pi \bar{\Psi}^a \gamma_5 \Psi^a \pi.$$

The scattering amplitude in this case can be written in form (7) with changing the coupling constants $g^4 \to g_\pi^4$ and propagators in (8):

$$F[-(k\pm r)^2] \to \frac{1}{(k\pm r)^2 - \mu_\pi^2}.$$

The leading logarithmic term of the spin-flip amplitude fig.4a,4b looks like (13) with $I_{a,b}$ functions determined in (14,15) where:

$$a(x,z) = -8x^3(z-y)/(x-z),$$

$$b(x,z) = 8x^3.$$

Taking into account that the colour factors for diagrams, fig.4a, 4b, are the same we find:

$$I_a = -I_b.$$

As a result, the leading logarithmic terms are cancelled for the sum of diagrams, and we have:

$$\mathrm{Im}T_{flip} \sim ig_\pi^4 \alpha_s^2\, m\sqrt{|t|}\; s\phi_\pi(t).$$

This energy dependence is similar to (5). In order to calculate function $\phi_\pi(t)$, we must use in (7) some model for the nonperturbative quark and gluon propagators.

We would like to note that the obtained integral representation for the $q\bar{q}$ sea contribution is in form equivalent to the corresponding amplitude in the meson-cloud model /5/ which describes the spin effects sufficiently well /15/. Thus, we hope that effective meson diagrams (fig.4) can play an important role in investigation of the spin structure of the pomeron.

So, we can conclude that in QCD at large distances the spin-flip amplitude growing as s can be obtained. It is possible that this behaviour is modified by some $\ln s$ factors. However, in the model which takes into account the $q\bar{q}$ sea contribution the leading logarithmic factors are cancelled. The obtained in the model spin-flip amplitudes (5,16) are not extremely small because they contain in the constituent quark mass as a dimensional parameter which is equal to the hadron mass in the order of magnitude.

Thus, we see here that different mechanisms can lead to a term growing as s in the spin-flip amplitude. So, the pomeron can have a complicated spin structure. The model analysis /4,5,15/ shows that this effect does not contradict the experimental data.

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Эффекты с переворотом спина
в померонном обмене

На основе КХД на больших расстояниях, с учетом некоторых непертурбативных свойств теории, изучена возможность переворота спина в померонном обмене. В случае высокоэнергетического qq рассеяния при фиксированных передачах импульса, показано, что возникает амплитуда с переворотом спина, растущая как S.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1989

Goloskokov S.V. E2-89-731

Spin-Flip Effects in the Pomeron
Exchange

On the basis of QCD at large distances with taking account of some nonperturbative properties of the theory, the possibility of spin-flip in the pomeron exchange is investigated. In the case of high energy qq scattering at small momenta transfer it is shown that the spin-flip amplitude growing as S can be obtained.

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

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