Spin asymmetries in diffractive high-energy reactions.

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Abstract

The analysis of some effects caused by the spin–dependent pomeron couplings is presented. It is shown that the structure of pomeron–proton and quark–pomeron couplings can be tested in future polarized experiments on elastic $pp$ reactions and diffractive $Q\bar{Q}$ production.

Extensive polarized programs are proposed at HERA, RHIC and LHC accelerators (see e.g. [1, 2, 3]). Among different processes which can be studied there are the diffractive and elastic high energy reactions predominated by the pomeron exchange. The study of the pomeron properties is a very popular problem now because of the observation of events with a large rapidity gap at CERN [4] and DESY [5]. These events may be caused by the diffractive reactions that can be investigated by using the QCD–models for the pomeron.

For the diffractive scattering of polarized particles, the question about the spin structure of the pomeron appears. This problem is very important for the following reasons:

• There are many observations of spin effects at high energies and fixed momenta transfer [6].

• Some model approaches predict nonzero spin effects in the $s \to \infty, |t|/s \to 0$ limit (see [7, 8] e.g.).

• Attempts to extract the spin-flip amplitude from the experimental data [9] show that the ratio of spin-flip and spin-non-flip amplitudes can be not small and independent of energy.

Just in all of these cases the pomeron exchange should contribute. So, there is a possibility that the pomeron has a complicated spin structure.

The high-energy two-particle amplitude determined by the pomeron exchange can be written in the form

$$T(s, t) = iP(s, t)V_{\mu}^{h_1 h_2 P} \otimes V^{h_2 h_3 P}_{\mu}.$$  \hspace{1cm} (1)

Here $P$ is a function caused by the pomeron, $V^{h_1 h_2 P}_{\mu}$ are the pomeron-hadron vertices. The calculation of this amplitude in the nonperturbative two-gluon exchange model [10] and in the BFKL model [11] shows that the pomeron couplings are simple in form (the standard coupling in what follows):

$$V_{h_1 h_2 P}^{\mu} = \beta_{h_1 h_2} \gamma_{\mu},$$  \hspace{1cm} (2)

In this case the spin-flip effects are suppressed as a power of $s$.

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The situation does change drastically when the large-distance loop contributions are considered that complicate the spin structure of the pomeron coupling. These effects can be determined by the hadron wave function for the pomeron-hadron couplings or by the gluon-loop $\alpha_s$ corrections for the quark-pomeron coupling. As a result, the spin asymmetries appear that have weak energy dependences as $s \to \infty$.

The main purpose of this report is to study the single transverse spin asymmetry in diffractive reactions. Note that the common perturbative QCD approach to the single–spin asymmetry was proposed in [12].

The single spin asymmetry depends strongly on the hadron properties. It is determined by the relation

$$ A_{\perp} = \frac{\sigma(\uparrow) - \sigma(\downarrow)}{\sigma(\uparrow) + \sigma(\downarrow)} = \frac{\Delta \sigma}{\sigma} \propto \Im (f^*_+ f_-) \frac{1}{|f^+|^2 + |f^-|^2}, $$

where $f_+$ and $f_-$ are spin-non-flip and spin-flip amplitudes, respectively. So, single spin asymmetry appears if both $f_+$ and $f_-$ are nonzero and there is a phase shift between these amplitudes. We shall discuss some consequences of the new spin-dependent form of the pomeron vertices in elastic scattering and diffractive $Q\bar{Q}$ production that can be studied in future polarized experiments at HERA, RHIC and LHC.

**Pomeron-proton vertex effects**

Pomeron-proton coupling is connected mainly with the proton structure at large distances. This coupling determines the single ($A_{\perp}$) and double ($A_{nn}$) transverse spin asymmetries at high energies and fixed momenta transfer.

The perturbative calculation of this coupling is rather difficult. Moreover, for a momentum transfer about few $GeV^2$ the nonperturbative contributions should be important. One of the models that takes into account these effects is the diquark model [13]. This model can be used to study the spin structure of the pomeron-proton coupling.

In this part of the report we shall discuss the predictions of the meson-cloud model \[7\] obtained in collaboration with O.Selyugin. This model effectively considers the proton structure at large distances. It leads to the following form of the pomeron-proton coupling

$$ V_{ppF}^\mu(p, r) = m p_\mu A(r) + \gamma_\mu B(r), $$

where $m$ is the proton mass and $r$ is the momentum transfer ($t = r^2$). Here $\gamma_\mu B(r)$ is a standard pomeron coupling like (2) that determines the spin-non-flip amplitude. The term $m p_\mu A(r)$ is caused by the meson-cloud effects. The coupling (4) leads to the spin-flip in the pomeron vertex that does not vanish in the $s \to \infty$ limit. Really, using the vertex (4) we can estimate the spin-non-flip and spin-flip effects from the pomeron-proton vertex

$$ |f_+(s, t)| \propto s |B(r)|; $$
$$ |f_-(s, t)| \propto m \sqrt{|t|} s |A(r)|. $$

(5)

So, both the amplitudes have the same energy dependence. The model predicts the following ratio for spin-flip and non-flip amplitudes

$$ \frac{m |f_-(s, t)|}{\sqrt{|t|} |f_+(s, t)|} \simeq \frac{m^2 |A(r)|}{|B(r)|} \simeq 0.05 \div 0.07 \quad \text{for} \quad |t| \sim 0.5 GeV^2 $$

(6)
that is consistent with estimations of ref. [9].

In the model [7] the amplitudes $A$ and $B$ have a phase shift caused by the soft pomeron rescattering effect. As a result, the single-spin asymmetry determined by the pomeron exchange

$$A_\perp \simeq \frac{2m\sqrt{|t|} \Im(AB^*)}{|B|^2}$$

appears. We omit here the $|A|^2$ term in the denominator because its contribution is rather small (6). The asymmetry (7) has a weak energy dependence.

The meson-cloud model [7] and the model of a rotating matter current [8] describe all known experimental data on elastic $pp$ scattering at fixed momenta transfer quantitatively and can predict the physical observables (cross-sections, asymmetries) at higher energies. The predictions of the model [7] for the differential cross section, transverse single spin and double spin asymmetries for the RHIC energy (LHS fixed target experiment energy) $\sqrt{s} = 120 GeV$ are shown in Figs 1-3. The model [8] predicts a similar absolute value for $A_\perp$ asymmetry but it is opposite in sign near the diffraction minimum. So, the future PP2PP experiment proposed at RHIC [3] can give an important information about the mechanism of spin–effect generation at the pomeron-proton vertex.

Moreover, the future PP2PP experiment at RHIC will give a possibility to measure the spin-dependent cross-section with parallel $\sigma(\uparrow\uparrow)$ and antiparallel $\sigma(\uparrow\downarrow)$ polarization in proton–proton scattering. It can be shown that in this case the energy dependence of the spin–flip and spin–non–flip amplitude can be measured. Really, using the standard notation for the $pp$ helicity amplitudes, let us suppose that the double-spin-flip amplitudes are small with respect to the spin–non–flip one $F_2(s, t) \sim F_4(s, t) \ll F_1(s, t)$ and spin-non-flip amplitudes are approximately equal $F_{++}(s, t) = F_1(s, t) \sim F_3(s, t)$. These usual restrictions are true for the models [7, 8]. In this case the observables are determined by two amplitudes $F_{++}(s, t)$ and $F_{+-}(s, t) = F_5(s, t)$ and we can find

$$|F_{+-}(s, t)|^2 \propto (\sigma(\uparrow\uparrow) - \sigma(\uparrow\downarrow)) \propto A_{nn}(\sigma(\uparrow\uparrow) + \sigma(\uparrow\downarrow))$$
$$|F_{++}(s, t)|^2 \propto \sigma(\downarrow\downarrow) \propto (1 - A_{nn})(\sigma(\uparrow\uparrow) + \sigma(\uparrow\downarrow)).$$

(8)

The energy dependence of $F_{++}(s, t)$ and $F_{+-}(s, t)$ amplitudes coincide with (3) for the $V_{ppF}$ vertex [4]. So, we shall have the same energy dependence of $(\sigma(\uparrow\uparrow) - \sigma(\uparrow\downarrow))$ and $\sigma(\downarrow\downarrow)$ for the spin–dependent pomeron–proton vertex and the ratio of these quantities will be practically energy– independent (Fig.4). Otherwise, we shall find the rapid decrease of the ratio

$$(\sigma(\uparrow\uparrow) - \sigma(\uparrow\downarrow))/\sigma(\downarrow\downarrow) \propto 1/s$$

with growing $s$ (see Fig.4) caused by the standard energy dependence of the spin–flip amplitude. The low-energy experimental point for the ratio $(\sigma(\uparrow\uparrow) - \sigma(\uparrow\downarrow))/\sigma(\downarrow\downarrow)$ from [14] is shown in Fig.4 too. This point does not contradict the weak energy dependence of this ratio predicted by the model [4]. The energy dependence of the cross sections $\sigma(\uparrow\uparrow)$ and $\sigma(\downarrow\downarrow)$ can be studied experimentally at RHIC. As a result, the direct information about the spin–flip effects in the pomeron–proton coupling should be obtained.
Quark-pomeron vertex effects

The standard quark–pomeron coupling (2) is determined by the contributions where two gluons from the pomeron interact with a single quark in the hadron. The nonplanar graphs in which gluons from the pomeron interact with different quarks in the loop, as a rule, do not exceed 10 percent as compared to the planar–diagram contributions at fixed momenta transfer (see e.g. [15]). The large–distance gluon–loop corrections to the quark–pomeron coupling have been studied in [16]. It is shown that they lead to new spin structures of the quark–pomeron vertex. The perturbative calculations [16] give the following form for this vertex:

\[ V_{\mu}^{\gamma}(k, r) = \gamma_{\mu}u_0 + 2m_Q k_{\mu} u_1 + 2k_{\mu} \gamma_5 + iM_Q u_4 \gamma_{\mu} r_\alpha, \]  

(9)

where \( k \) is the quark momentum, \( r \) is the momentum transfer and \( M_Q \) is the quark mass. So, in addition to the \( \gamma_{\mu} \) term, the new structures immediately appear from the loop diagrams. The functions \( u_1(r) \) are proportional to \( \alpha_s \). It has been shown [17] that these functions can reach \( 30 \div 40\% \) of the standard pomeron term \( u_0(r) \) for \( |r|^2 \approx \text{Few GeV}^2 \). Note that the spin structure of the quark-pomeron coupling (9) is drastically different from the standard one (2). Really, the terms \( u_1(r) - u_4(r) \) lead to the spin-flip at the quark-pomeron vertex in contrast with the term \( u_0(r) \gamma_{\mu} \).

This new complicated form of the pomeron–quark coupling (9) should modify various spin asymmetries in high–energy diffractive reactions [18, 19]. It has been shown that a simplest way to test the quark–pomeron coupling is to study the single pomeron two–jet production in lepton–proton and proton–proton reactions.

The double spin longitudinal asymmetries has been investigated in [19]. It has been shown that these asymmetries in hadron–hadron and lepton–hadron reactions do not depend practically on the pomeron–proton coupling structure. They are sensitive to the form of quark–pomeron coupling, especially to the terms \( u_0(r) \) and \( u_3(r) \) in (9).

Here we shall analyse the single–spin transverse asymmetry in diffractive \( Q\bar{Q} \) production. In the diffractive jet production at small \( x_p \) (fraction of the initial proton momentum carried off by the pomeron) the main contribution is determined by the region where the quarks in the loop are not far of the mass shell. In this case we can use here the same "soft pomeron" [20] as for the elastic reactions. As a result, in the asymmetry of diffractive \( Q\bar{Q} \) production the same single-spin hadron asymmetry (7) determined by the "soft pomeron" as in the case of elastic scattering should appear. In our further estimations we shall use the magnitude \( A_\perp^h = 0.1 \) that is consistent with the experiment and the model results.

The cross sections \( \sigma \) and \( \Delta \sigma \) determined in (3) can be written in the form

\[ \frac{d\sigma(\Delta \sigma)}{dx_p dt dk_{\perp}^2} = \{1, A_\perp^h\} \frac{\beta^4 |F_p(t)|^2 \alpha_s}{128\pi^2 x_p^2} \int_{4k_{\perp}/sx_p}^{1} \frac{dyg(y)}{\sqrt{1 - 4k_{\perp}^2/syx_p}} \frac{N_{\sigma(\Delta \sigma)}(x_p, k_{\perp}^2, u_i, |t|)}{(k_{\perp}^2 + M_Q^2)^2}. \]  

(10)

Here \( g \) is the gluon structure function of the proton, \( k_{\perp} \) is the transverse momentum of jets, \( M_Q \) is the quark mass, \( N_{\sigma(\Delta \sigma)} \) is the trace over the quark loop, \( \beta \) is the pomeron coupling constant, \( F_p \) is the pomeron-proton form factor. All the information on the quark-pomeron vertex structure is concentrated in \( N_{\sigma} \) and \( N_{\Delta \sigma} \) functions.
It has been found that the main contributions to \( N^\sigma(N^\Delta\sigma) \) in the discussed region come mainly from \( u_0 \) and \( u_3 \) structures in (9). Moreover, the ratio \( N^\Delta\sigma/N^\sigma \simeq 0.5 \) and is independent of \( k_\perp^2 \) for the standard quark–pomeron vertex but the same ratio is the \( k_\perp^2 \) dependent for the pomeron coupling (9). Our predictions for single spin asymmetry for the proposed HERA-N experiment [1] can be found in [21, 22].

Here we would like to show our results for \( \sigma \) and single spin asymmetry (Figs. 5, 6) for the light–quark jet production at the RHIC energy (LHS fixed target experiment energy) \( \sqrt{s} = 120 GeV, x_p = 0.05 \) and \(|t| = 1GeV^2\). It is easy to see that the shape of asymmetry is different for the standard (2) and spin-dependent pomeron vertex (9). In the first case it is approximately constant, in the second it increases with \( k_\perp^2 \). So, this asymmetry can be used for the study of the quark–pomeron vertex structure.

The cross sections \( \sigma \) and \( \Delta\sigma \) integrated over \( k_\perp^2 \) of jets have been calculated too. It was found that the asymmetry determined from the integrated cross sections does not practically depend on the quark–pomeron vertex structure. It can be written in any case in the form

\[
A_1 = \frac{\int dk_\perp^2 \Delta\sigma}{\int dk_\perp^2 \sigma} \simeq 0.5 A_{\perp}^h
\]  

Thus, we can conclude that the integrated asymmetry (11) can be used for studying the hadron asymmetry \( A_{\perp}^h \) caused by the pomeron.

We have presented here the analysis of some effects of the spin–dependent pomeron couplings. It is found that the structure of these couplings can be tested in elastic \( pp \) reactions and diffractive \( Q\bar{Q} \) production.

The information about the pomeron–proton vertex structure can be obtained from:

- Single transverse spin asymmetry in elastic reactions and diffractive \( Q\bar{Q} \) production.
- Double–spin \( A_{nn} \) asymmetry in elastic reactions.
- Energy dependence of the ratio \((\sigma(\uparrow\uparrow) - \sigma(\uparrow\downarrow))/\sigma(\uparrow\downarrow)\) in elastic reactions.

The properties of quark–pomeron vertex can be studied from:

- \( k_\perp^2 \)–dependence of the single transverse spin asymmetry in two–jet production determined by the single–pomeron exchange in \( pp \) reactions.
- \( A_{ll} \) longitudinal spin asymmetry in diffractive \( Q\bar{Q} \) production in lepton–proton and proton–proton reactions.

Note that the spin–structure of the pomeron couplings are determined by the large–distance gluon-loop correction or by the effects of the hadron wave function. So, the important test of the spin structure of QCD at large distances can be carried out by the study of diffractive reactions in future polarized experiments at HERA, RHIC and LHC accelerators.

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Fig. 1 Predictions for differential cross section of $pp$ scattering.

Fig. 2 Predictions for single-spin transverse asymmetry of $pp$ scattering.
Fig. 3 Predictions for double-spin transverse asymmetry of $pp$ scattering.

Fig. 4 Model predictions for the ratio of spin-dependent cross section for $pp$ scattering: solid line - for spin-dependent pomeron vertex; dot-dashed line - for the standard energy behaviour of the spin-flip amplitude. Experimental point is taken from [14].
Fig. 5  Distribution of $\sigma$ over jets $k_{\perp}^2$ in diffractive light-quark production: solid line - for standard vertex; dot-dashed line - for spin-dependent quark-pomeron vertex.

Fig. 6  $k_{\perp}^2$ dependence of single-spin-asymmetry in diffractive light-quark production: solid line - for standard vertex; dot-dashed line - for spin-dependent quark-pomeron vertex.