Effects of Pomeron Coupling in Diffractive Reactions

S.V. Goloskokov

Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research.
Dubna 141980, Moscow region, Russia.

Abstract

The diffractive 2-jet production reactions in the proton-proton and lepton-proton processes are discussed. It is shown that they may be very suitable for studying the properties of the pomeron couplings with quarks and hadrons in future polarized experiments at HERA, especially for HERA-$\bar{N}$ project.
1 Introduction

Recently, the interest has increased in investigating polarized processes. To study the spin properties of the hadron interaction at high energies, the precise information about different spin asymmetries is important. For such experiments it is necessary to have high energy and high intensity polarized beams. The only project which is now being realized is the RHIC spin program [1]. Physics with a polarized beams is discussed now for the HERA accelerator (see [2]). An important part of this program is the HERA-\vec{N} project [3] with the fixed polarized target on the proton beam at HERA. At the ’phase I’ (with unpolarized proton beam) the HERA-\vec{N} experiment will allow one to study different single-spin asymmetries in the nucleon-nucleon reaction. When the polarized protons at HERA become available, the HERA-\vec{N} experiment at the ’phase II’ will permit one to study double-spin asymmetries. As a result, a great deal of information on the spin structure of QCD can be obtained.

The diffractive events with a large rapidity gap in deep inelastic lepton–proton scattering have recently been studied in the H1 and ZEUS experiments at HERA [4, 5]. The natural explanation of these events is based on the hard photon–pomeron interaction. This permits one to obtain new information about the structure of the pomeron and its couplings. So, the HERA accelerator is the best places to study the pomeron properties.

If the polarized program at HERA is realized, the diffractive effects with polarized particles can be investigated. Then, the question about the spin structure of the pomeron arises. This problem is very important for the following reasons:

- There are many observations of not small spin effects at high energies and fixed momentum transfer [4]. For example, the single-spin transverse asymmetry for |t| ≥ 1.5(GeV)^2 and \sqrt{s} = (19 – 24)GeV is about 10-20% [7] and may be independent of energy.

- Attempts to extract the spin-flip amplitude from experimental data [8] show that the ratio of spin-flip and spin-non-flip amplitudes can be about 0.1-0.3 at high energies.

- Some model approaches predict the same ratio of spin-flip and spin-non-flip amplitudes in the s → ∞, |t|/s → 0 limit (see [9, 10] e.g.).
Just in all these cases the pomeron exchange should give a contribution. Thus, the pomeron might have a complicated spin structure.

The pomeron is a colour–singlet vacuum $t$-channel exchange that can be regarded as a two-gluon state [11]. The pomeron contribution to the hadron high energy amplitude can be written as a product of two pomeron vertices $V_{\mu}^{hhP}$ multiplied by some function $P$ of the pomeron. As a result, the quark-proton high-energy amplitude looks like

$$T(s, t) = i P(s, t) V_{\mu}^{\mu}(t) \otimes V_{\mu}^{hhP}(t).$$

(1)

In the nonperturbative two-gluon exchange model [12] and the BFKL model [13] the pomeron couplings have a simple matrix structure:

$$V_{\mu}^{\mu} = \beta_{\mu}^{hhP} \gamma_{\mu},$$

(2)

which leads to spin-flip effects decreasing with energy as a power of $s$. We call this form the standard coupling.

The situation does change drastically when large-distance loop contributions are considered. As a result, the spin structure of the pomeron coupling becomes more complicated. 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.

Pomeron-proton coupling is mainly connected with the proton structure at large distances. The perturbative calculation of this coupling is difficult. Moreover, for a momentum transfer of about few $GeV^2$ the nonperturbative contributions are important. Some models can be used to study the spin structure of the pomeron-proton coupling. For example, the diquark model [14] takes effectively into account the nonperturbative contributions. It can leads to the spin–flip in the pomeron–proton vertex [15].

In models [9, 10] the spin-flip effects do not vanish as $s \to \infty$. It has been shown [3] that the pomeron–proton vertex is of the form

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

(3)

where $m$ is the proton mass, the amplitudes $A$ and $B$ are connected with the proton wave function. The model [3] predicts that the ratio

$$m^2 |A|/|B| \sim 0.2$$

(4)
at $|t| \geq 1 GeV^2$, which leads to the weak energy dependence of single and double spin transverse asymmetries which are about 10–15%. The discussion of this question can be found in [16].

The form of the quark-pomeron coupling $V_{qq\mathcal{P}}^\mu$ has been studied in [17]. It was shown that besides the standard pomeron vertex (2) determined by the diagrams, where gluons interact with one quark in the hadron [12], the large-distance gluon-loop effects should be important. The perturbative calculations [17] give the following form of this vertex:

$$V_{qq\mathcal{P}}^\mu(k, r) = \gamma^\mu u_0 + 2M_Q k^\mu u_1 + 2k^\mu k u_2 + iu_3 \epsilon^{\mu \alpha \beta \rho} k_\alpha r_\beta \gamma_\rho \gamma_5 + iM_Q u_4 \sigma^{\mu \alpha} r_\alpha,$$

(5)

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 $u_1(r) \sim u_4(r)$ are proportional to $\alpha_s$. These functions can reach $30 \div 40\%$ of the standard pomeron term $u_0(r)$ for $|r^2| \sim \text{Few GeV}^2$ [18].

The new form of the pomeron–quark coupling (5) should modify various spin asymmetries in high–energy diffractive reactions [19, 21, 20]. In this report we shall discuss the single and double spin asymmetries in polarized diffractive reactions, which may be studied in the future HERA-$\bar{N}$ project to test the spin structure of the pomeron couplings.

## 2 Spin Asymmetries

The single-spin asymmetry which can be studied at the 'phase I' of HERA-$\bar{N}$ experiment is determined by the relation

$$A_\perp = \frac{\Delta \sigma}{\sigma} = \frac{\sigma^{(\uparrow)} - \sigma^{(\downarrow)}}{\sigma^{(\uparrow)} + \sigma^{(\downarrow)}}.$$

(6)

We shall discuss here the single transverse spin asymmetry in the $p \uparrow p \rightarrow p + Q\bar{Q} + X$ process. This reaction is determined by the pomeron exchange between the proton and the produced $Q\bar{Q}$ pair at high energies and small $x_p$ ($x_p$ is a fraction of the initial proton momentum carried off by the pomeron). The distributions of the cross sections $\sigma$ and $\Delta \sigma$ over $p^2_\perp$ of jets can be written
in the form
\[
\frac{d\sigma(\Delta\sigma)}{dx_p dtdp^2} = \left\{1, A^h_1\right\} \frac{\beta^4|F_p(t)|^2\alpha_s}{128\pi s x_p^2} \int_{4p_{\perp}^2/x_p}^{1} \frac{dyg(y)}{\sqrt{1 - 4p_{\perp}^2/s y x_p}} \frac{N^{\sigma(\Delta\sigma)}(x_p, p^2_{\perp}, u_i, |t|)}{(p_{\perp}^2 + M_Q^2)^2}.
\]  

(7)

Here \( g \) is the gluon structure function of the proton, \( p_{\perp} \) is a transverse momentum of jets, \( M_Q \) is a quark mass, \( N^{\sigma(\Delta\sigma)} \) is a trace over the quark loop, \( \beta \) is a pomeron coupling constant, and \( F_p \) is a pomeron-proton form factor. In (7) the coefficient equal to unity appears in \( \sigma \) and the transverse hadron asymmetry \( A^h_1 \) at the pomeron-proton vertex appears in \( \Delta\sigma \). This asymmetry \( A^h_1 \) is determined by the interference between the amplitudes \( A \) and \( B \) in the pomeron–proton coupling (3).

\[
A^h_1 \simeq \frac{2m\sqrt{|t|\Im(AB^*)}}{|B|^2}.
\]  

(8)

We use a simple form of the gluon structure function
\[
g(y) = R(1 - y)^5/y, \quad R = 3.
\]  

(9)

In the diffractive–jet production the main contribution is determined by the region where the quarks in the loop are not far from the mass shell. So, we can assume that the asymmetry \( A^h_1 \) (7) can be determined by the soft pomeron, and it coincides with the elastic transverse hadron asymmetry. In our further estimations we use the magnitude \( A^h_1 = 0.1 \). Some details of calculations can be found in [21].

It has been found that both \( \sigma \) and \( \Delta\sigma \) have a similar dependence \( \sigma(\Delta\sigma) \propto 1/x_p^2 \) at small \( x_p \). This allows one to study asymmetry at small \( x_p \) where the pomeron exchange is predominated because of a high energy in the quark-pomeron system.

Our predictions for the asymmetry \( A_1 \) at \( \sqrt{s} = 40\text{GeV}, \ x_p = 0.05 \) and \( |t| = 1\text{GeV}^2 \) for a standard quark-pomeron vertex (2) and a spin-dependent quark-pomeron vertex (3) are shown in Fig.1 for light-quark jets. It is easy to see that the shape of asymmetry is different for standard and spin-dependent pomeron vertices. In the first case it is approximately constant and in the second it depends on \( p^2_{\perp} \). The estimated errors for the integrated luminosity \( 240\text{ pb}^{-1} \) are shown in Fig.1 too. The structure of the quark-pomeron vertex can be studied from the \( p^2_{\perp} \) distribution of single-spin asymmetry (the region
with the errors smaller than 1% is \( 1 \text{GeV}^2 < p_\perp^2 < 10 \text{GeV}^2 \). So, from this asymmetry the structure of the quark-pomeron vertex can be determined.

The cross sections \( \sigma \) and \( \Delta \sigma \) integrated over \( p_\perp^2 \) of jet have been calculated too. The asymmetry obtained from these integrated cross sections does not practically depend on the quark-pomeron vertex structure. It can be written in both the cases in the form

\[
A_1 = \frac{\int dp_\perp^2 \Delta \sigma}{\int dp_\perp^2 \sigma} = 0.5 \ A^h_\perp
\]

(10)

Thus, the information on the transverse hadron asymmetry \( A^h_\perp \) at the pomeron-proton vertex can be obtained from the integrated asymmetry (10).

At the second phase of the HERA-N project, double–spin asymmetries can be studied. We shall discuss here the longitudinal double spin asymmetry determined by the relation

\[
A_{ll} = \frac{\Delta \sigma}{\sigma} = \frac{\sigma(\pm) - \sigma(-\pm)}{\sigma(\pm) + \sigma(-\pm)}.
\]

(11)

For the spin-average and longitudinal polarization of the proton beam the \( B \) term in (3) is predominant. As a result, the longitudinal double spin asymmetry does not depend on the pomeron-proton vertex structure.

The \( A_{ll} \) asymmetry of the \( Q\bar{Q} \) production in the \( pp \) diffractive reaction is proportional to the ratio

\[
C_g = \frac{\Delta g}{R}.
\]

(12)

Here \( \Delta g \) is the first moment of \( \Delta g(y) \)

\[
\Delta g = \int_0^1 dy \Delta g(y),
\]

(13)

which is unknown now, and \( R \) is determined in (9). To solve the proton spin crisis [22] a large magnitude of \( \Delta g \sim 3 \) is important. This leads to \( C_g \sim 1 \) which will be used in here. However, the magnitude \( \Delta g \sim 1 \) may be more preferable now [23]. Then, the resulting asymmetry will decrease by a factor of 3.

Our predictions for the \( A_{ll} \) asymmetry at \( \sqrt{s} = 40 \text{GeV} \) (HERA-N energy) for light and heavy (C) quark production can be found in [20].
magnitude of the obtained asymmetry strongly depends on the structure of the quark-pomeron vertex but the shapes of these curves are similar. For a spin-dependent quark-pomeron vertex the $A_{ll}$ asymmetry is smaller by a factor of 2 because $\sigma$ in (11) is larger in this case due to the contribution of other $u_i$ structures. Therefore, the knowledge of the proton spin-dependent structure function $\Delta g$ is necessary to study the pomeron spin structure from the $A_{ll}$ asymmetry in $pp$ polarized diffractive reactions.

The very important test of the pomeron coupling can be performed in polarized lepton–proton reactions. Really, in this case we know explicitly the lepton part of the interaction. As a result, the spin asymmetries in diffractive $Q\bar{Q}$ production will depend only on the structure of the pomeron couplings with the quark and proton. Here, we shall discuss the double–spin longitudinal asymmetry in the reaction $e + p \rightarrow e' + p' + Q\bar{Q}$ [24].

The asymmetry in the diffractive $Q\bar{Q}$ production is shown in Fig. 2. It is found that the asymmetry for the standard quark–pomeron vertex is very simple in form

$$A_{ll} = \frac{y x p (2 - y)}{2 - 2y + y^2}. \quad (14)$$

There is no any $k_\perp$ and $\beta$ dependence here. For the spin–dependent pomeron coupling the $A_{ll}$ asymmetry is smaller than for the standard pomeron vertex and depends on $k_\perp^2$. Thus, one can use the $A_{ll}$ asymmetry to test the quark-pomeron coupling structure. Note that $\Delta \sigma$ in (11) can be used to determined the diffractive contribution to the $g_1$ spin–dependent structure function can be determined [25]. The obtained low -$x$ behaviour of $g_1(x)$ has a singular form like $1/(x^{0.3} \ln^2(x))$ which is compatible with the SMC data for $g_1^p(x)$ [26].

### 3 Conclusion

In this report we have discussed the possibility to test the pomeron coupling structure in diffractive reactions. It is shown that the diffractive 2-jet production may be very suitable for this purpose. In all the cases the distribution of the asymmetries over the transverse jet momentum is very sensitive to the quark-pomeron vertex structure. For the standard pomeron vertex the asymmetry is practically independent of $k_\perp^2$ of jet. Otherwise, it should have a very definite $k_\perp^2$–dependence.
The information about the proton-pomeron coupling can be obtained from the single-spin transverse asymmetry integrated over the transverse momentum of jets. Moreover, one can understand if this diffractive pomeron coincides with the pomeron in elastic processes.

To study spin asymmetries with the transversely polarized protons, it is necessary to register the recoil hadron. Thus, it is important to have the RECOIL hadron detector. If this problem is solved at HERA-$\vec{N}$, the single and double transverse asymmetries ($A_L$ and $A_{LL}$) in the diffractive $Q\bar{Q}$ production reactions may be very useful to study the spin structure of the pomeron-proton coupling. Relevant asymmetries in the diffractive vector meson production can be used too. These reactions may be easy in detection of the final state but they have a smaller cross section. This should increase errors in asymmetries.

It is very important from the experimental point of view that the investigated here diffractive 2-jet production reactions have a large cross section. This permits one to study single and double spin asymmetries in lepton-proton and proton-proton reactions with the accuracy less than 1% at the integrated luminosity about 200 pb$^{-1}$. Thus, these reactions may be used to study the pomeron couplings in future polarized experiments at HERA and HERA-$\vec{N}$.

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Fig. 1 $p_{T}^{2}$–dependence of $A_{\perp}$ asymmetry and the estimated errors. Solid line - for standard; dot-dashed line - for spin-dependent quark-pomeron vertex.

Fig. 2 $k_{T}^{2}$– dependence of $A_{ll}$ asymmetry. Solid line - for the standard vertex; dot-dashed line - for the spin-dependent quark-pomeron vertex.