LARGE - DISTANCE EFFECTS IN QCD AND SPIN ASYMMETRIES IN DIFFRACTIVE REACTIONS.

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Abstract

Large - distance effects in the hadron wave function for the hadron-Pomeron vertex in the QCD -model are discussed. It is shown that they lead to the spin-flip part of the Pomeron coupling which can reach $10 \div 20\%$ with respect to the non-flip part. The obtained structure of the Pomeron coupling modifies spin asymmetries in high-energy diffractive reactions where the Pomeron structure becomes determinative. We study spin asymmetries in exclusive reactions and in the diffractive $Q\bar{Q}$ and $J/\Psi$ production. We have found that spin effects in these diffractive processes are sensitive to the spin-flip part of the Pomeron coupling.

Key-words: Large - distance effects, polarization, diffractive reactions, Pomeron, spin asymmetries

Study of diffractive processes at HERA provides an excellent possibility of investigating the nature of the Pomeron. New results on the Pomeron intercept in diffractive events, information about the Pomeron partonic structure, have been obtained in H1 and ZEUS experiments [1]. Investigation of the diffractive vector meson and $Q\bar{Q}$ production should play a keystone role in future study of this object. Really, diffractive reactions give an important information on the Pomeron structure which has a nonperturbative character. At the same time, they can be used to study the gluon distribution in the nucleon at small $x$ [4].

The Pomeron is a color singlet exchange which describes high energy reactions at fixed momentum transfer. The two-particle amplitude determined by the Pomeron exchange can be written in the form

$$\hat{T}(s, t) = iI_{P}(s, t)V_{h_{1}h_{2}P}(p_{1}, t) \otimes V_{h_{2}P}(p_{2}, t).$$

Here $V_{h_{1}h_{2}P}^{P}$ are the Pomeron-hadron vertices of the particles with initial momenta equal to $p_{1}$ and $p_{2}$, and $I_{P}$ is a function caused by the Pomeron. The calculation of this amplitude in the nonperturbative two-gluon exchange model [3] and in the BFKL model [4] shows that the Pomeron couplings are simple in form (the standard coupling in what follows):

$$V_{h_{1}h_{2}P}^{P} = B_{h_{1}h_{2}P}(t) \gamma^{\mu}.$$  (2)

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

Since the Pomeron consists of a two-gluon [5], the Pomeron coupling should have two gluon indices. The Pomeron coupling with the proton can be written in the form

$$V_{p_{g}}^{\alpha\alpha'}(p, t, x_{P}) = 4p^{\alpha}p'^{\alpha'}A(t, x_{P}) + (\gamma^{\alpha}p^{\alpha'} + \gamma^{\alpha'}p^{\alpha})B(t, x_{P}).$$  (3)
where $r$ is the momentum transfer and $x_p$ is the fraction of the initial proton momentum carried by the gluon system.

Let us consider the single-flip amplitude of the elastic $pp$ scattering (11) with the vertex (3). In this case, we can fix the helicities of the one proton line at $+1/2$. The amplitude is then simplified to

$$T_{λ_4+;λ_2+} = F_{λ_4λ_2} = \bar{u}(p_4, λ_4)u(p_3, +)\bar{T}(s, t)u(p_2, λ_2)u(p_1, +).$$  \hspace{1cm} (4)

The leading term of the non-flip matrix element of the coupling (3) is found to be $\bar{u}(p_3, +)V_{pgg}^{α'α}(p_1)u(p_1, +) \propto p_1^αp_1^{α'}$. The $1/s$ term appears from the $δ$-function integration in the gluon loop. Finally, the $F_{λ_4λ_2}$ amplitude can be written as follows:

$$F_{λ_4λ_2} = \bar{u}(p_4, λ_4)[sA(t) + 4B(t)]u(p_2, λ_2)φ(t).$$ \hspace{1cm} (5)

Here $φ(t)$ represents an additional function of $t$ from the spin-independent Pomeron coupling and the Pomeron exchange.

The proton–proton helicity-non-flip and helicity-flip amplitudes are expressed in terms of the $A(t)$ and $B(t)$ functions

$$F_{++}(s, t) = is[B(t) + 2mA(t)]φ(t); \quad F_{+-}(s, t) = is\sqrt{|t|}A(t)φ(t),$$ \hspace{1cm} (6)

where $m$ is a proton mass.

Thus, $(γ^αp^α + γ^α'p'^α)B(t)$ in (3) is a standard Pomeron coupling like (2) which determines the spin-non-flip amplitude. The term $p_αp_α'A(r)$ leads to the spin-flip in the Pomeron vertex which does not vanish in the $s → ∞$ limit. Note that in the model (3), the Pomeron effectively couples to the hadron like a $C = +1$ isoscalar photon. Then, the vertex (3) is equivalent to the isoscalar electromagnetic nucleon current with the Dirac and Pauli nucleon form factors (7). A similar form of the proton-Pomeron coupling has been used in (8). In the model (3) the form (3) was found to be valid for small momentum transfer $|t| < \text{few GeV}^2$ and the $A(t)$ amplitude was caused by the meson-cloud effects in the nucleon. In a QCD–based diquark model of the proton (10), the $pgg$ coupling in the form (3) has been found at moderate momentum transfer (10). There, the $A(t)$ contribution is determined by the effects of vector diquarks inside the proton, which are of the order of $α_s$. In all the cases the spin-flip $A(t)$ contribution is determined by the nonperturbative effects in the proton.

The absolute value of the ratio of $A$ to $B$ is proportional to the ratio of helicity-flip and non-flip amplitudes. This ratio is about $|A|/|B| \sim 0.1 − 0.2 \text{GeV}^{-1}$ (8, 11) and has a weak energy dependence. In the models (3, 11), the spin-flip amplitude is not in the phase with the non-flip amplitude. As a result, the single-spin asymmetry appears

$$A_N = -2\frac{\text{Im}[F_{++}F_{+-}^*]}{|F_{++}|^2 + 2|F_{+-}|^2}.\hspace{1cm} (7)$$

In the model (9), the amplitudes $A$ and $B$ have a phase shift caused by the soft Pomeron rescattering effect. The predicted asymmetry (12) is shown in Fig. 1. The diquark model (11) results in the helicity flips which are generated by vector diquarks. The $A$ amplitude is out of phase with the Pomeron contribution to the amplitude $B$ too. The model provides a single-spin asymmetry $A_N$ shown in Fig. 2 which is rather large for momentum transferred $|t| ≥ 3 \text{GeV}^2$.  

2
A convenient tool to study the spin-dependent Pomeron structure might be polarized diffractive leptoproduction reactions. We shall consider here the $A_h$ asymmetry of the $J/\Psi$ and $QQ$ production. The cross section of these reactions has the following important parts: leptonic and hadronic tensors and the amplitude of the $\gamma^* P \rightarrow J/\Psi (QQ)$ transition. The structure of leptonic tensor is quite simple. The hadronic tensor for the vertex (8) has the form

$$W^{\alpha\alpha';\beta\beta'}(s_p) = \sum_{\text{final spin}} \bar{u}(p')V_{p g g}^{\alpha\alpha'}(p, t, x_P)u(p)\bar{u}(p, s_p)u(p, s_p)\bar{u}(p, p')V_{p g g}^{*\beta\beta'}(p, t, x_P)u(p').$$  \hspace{1cm} (8)

Here $p$ and $p'$ are the initial and final proton momenta, and $s_p$ is a spin of the initial proton.

The spin-average and spin dependent cross sections with parallel and antiparallel longitudinal polarization of a lepton and a proton are determined by the relation

$$\sigma(\pm) = \frac{1}{2}\left(\sigma^{(+)\pm} + \sigma^{(+)\pm}\right).$$  \hspace{1cm} (9)

These cross sections can be expressed in terms of spin-average and spin dependent value of the lepton and hadron tensors. For the latter one can write

$$W^{\alpha\alpha';\beta\beta'}(\pm) = \frac{1}{2}\left(W^{\alpha\alpha';\beta\beta'}(\pm)\pm \frac{1}{2}\right)\pm W^{\alpha\alpha';\beta\beta'}(-\frac{1}{2}),$$  \hspace{1cm} (10)

where $W(\pm \frac{1}{2})$ are the hadron tensors with the helicity of the initial proton equal to $\pm 1/2$. The leading term of the spin average hadron tensor looks like

$$W^{\alpha\alpha';\beta\beta'}(+) = 16p^\alpha p'^\alpha p^\beta p'^\beta(|B(t) + 2mA(t)|^2 + |t||A(t)|^2).$$  \hspace{1cm} (11)

It is proportional to the proton-proton cross section up to a function of $t$.  

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Fig.1 Meson cloud model predictions for single-spin transverse asymmetry of the $pp$ scattering at RHIC energies [12]. Error bar indicates expected statistical errors for the PP2PP experiment at RHIC.

Fig.2 Model predictions for single-spin asymmetry for two fits of the $B$ amplitude (see [13] for details). Data from G. Fidecaro et al., Phys. Lett. B105, 309 (1981) (FNAL) and R.C. Fernow, A.D. Krisch, Ann. Rev. Nucl. 31, 107 (1981) (BNL).
The spin-dependent hadron tensor is quite complicated. It can be represented as a sum of structures which have different nature

\[ W^{\alpha\alpha';\beta\beta'}(-) = \Delta A_{full}^{\alpha\alpha';\beta\beta'} + \Delta A_1^{\alpha\alpha'} S_2^{\beta\beta'} - \Delta A_1^{\beta\beta'} S_2^{\alpha\alpha'}. \]  
(12)

The typical contribution to \( A_{full}^{\alpha\alpha';\beta\beta'} \) looks like as \( 2i|B(t)|^2 p^{\alpha'} p^{\beta'} \varepsilon^{\alpha\beta\gamma\delta}(p' - p)\gamma(s_p)\delta \). This term has indices of different Pomeron couplings in the \( \varepsilon \) function. This contribution is equivalent to the spin-dependent part which can be obtained from the coupling (2) and called by us a full block asymmetry. The other terms have a form of a product of the symmetric part of the other virtual photon is going to the \( q\bar{q} \) term has indices of different Pomeron couplings in the \( S \) momentum. The \( J/\Psi \) wave function has the form

\[ g(\vec{k} + m_c)\gamma_\mu \] where \( k \) is the momentum of \( c\bar{c} \)-quarks and \( m_c = m_J/2 \). The coupling constant \( g \) can be expressed through the \( e^+e^- \) decay width of the \( J/\Psi \) meson. The gluons from the Pomeron are coupled with the single and different quarks in the \( c\bar{c} \) loop. This ensure the gauge invariance of the final result.

The spin-dependent amplitude square looks like

\[ |T^\pm|^2 = N((2 - 2y + y^2)m_J^2 + 2(1 - y)Q^2)s^2||B + 2mA|^2 + |A|^2|t||I^2. \]  
(14)

For the spin-average amplitude square we find

\[ |T^+|^2 = N((2 - 2y + y^2)m_J^2 + 2(1 - y)Q^2)s^2||B + 2mA|^2 + |A|^2|t||I^2. \]  

Here \( N \) is a known normalization factor and \( I \) is the integral over transverse momentum of the gluon

\[ I = \frac{1}{(m_J^2 + Q^2 + |t|)} \int \frac{d^2l_\perp (l_\perp^2 + \vec{l}_\perp \vec{\Delta})}{(l_\perp^2 + \lambda^2)(l_\perp^2 + \vec{\Delta}^2 + \lambda^2)(l_\perp^2 + \vec{l}_\perp \vec{\Delta} + (m_J^2 + Q^2 + |t|)/4). \]  
(15)

The term proportional to \( (2 - 2y + y^2)m_J^2 \) in (14) represents the contribution of the virtual photon with transverse polarization. The \( 2(1 - y)Q^2 \) term describes the effect of longitudinal photons. It can be seen that for \( Q^2 \ll m_J^2 \) the contribution of the longitudinal photon might be omitted.

The spin-dependent amplitude square looks like

\[ |T^-|^2 = N(2 - y)s|t||B|^2 + m(A^*B + AB^*)|m_J^2I^2. \]  
(16)

As a result, we find the following form of asymmetry:

\[ A_{ll} \sim \frac{|t|}{s} \frac{||B(t)||^2 + m(A(t)^*B(t) + A(t)B(t)^*)}{(2 - 2y + y^2)||B(t)|^2 + 2mA(t)^2 + |t||A(t)||^2}. \]  
(17)

The important property of \( A_{ll} \) is that the asymmetry of vector meson production is equal to zero for the forward direction (\( t = 0 \)). The \( A_{ll} \) asymmetry might be connected
with the spin-dependent gluon distribution $\Delta G$ only for $|t| = 0$. Thus, $\Delta G$ cannot be extracted from $A_{UL}$ in agreement with the results of [14]. The rapid energy dependence of asymmetry is the another important property of (17). It has been shown in [15] that the $A_{UL}$ asymmetry in the diffractive processes is proportional to the fraction of the initial proton momentum $x_p$ carried off by the Pomeron. The mass of the produced hadron system is determined by $M_x^2 \sim syx_p$. For the diffractive $J/\Psi$ production $M_x$ coincides with the vector meson mass and we find that $x_p \sim (m_J^2 + Q^2 + |t|)/(sy)$. As a result, the relevant $A_{UL}$ asymmetry decreases with growing energy.

The form of the $A_{UL}$ asymmetry depends on the ratio of the spin-flip to the non-flip parts of the Pomeron coupling $\alpha_{\text{flip}}^2 / A(t) / B(t)$ which have been found in [9, 11] to be about 0.1. The predicted asymmetry at HERMES energies is shown in Fig. 3. At HERA energy, the asymmetry will be negligible. Note that our results show the essential role of the ”full block asymmetry” from (12) in the $A_{UL}$ asymmetry of the $J/\Psi$ production.

\[
\Delta \sigma(t) = \frac{d^5 \sigma(\to \leftarrow)}{dx_2 dy_2 dx_3 d^2 k_\perp} - \frac{d^5 \sigma(\to \Rightarrow)}{dx_2 dy_2 dx_3 d^2 k_\perp} = \frac{3(2 - y)\beta_0^4 F(t)^2 [9 \sum e_i^2] \alpha^2}{128 x_p^{2\alpha(t)-1} Q^2 \pi^3} \frac{A(\beta, k_2^\perp, x_p, t)}{\sqrt{1 - 4k_2^\perp \beta / Q^2 (k_2^\perp + M_Q^2)^2}}. \tag{18}
\]

Here $\beta_0$ is the quark–Pomeron coupling, $F(t)$ is the Pomeron-proton form factor and $e_i$ are the quark charges. The function $A$ is determined by the trace over the quark loop. The contribution of the standard Pomeron vertex to $A$ looks like

\[
A(\beta, k_2^\perp, t) = 16(2(1 - \beta)k_2^2 - |t|\beta - 2M_Q^2(1 + \beta)|t|). \tag{19}
\]

Similar forms can be written for spin-average cross sections. The strong dependence of the cross sections on $\beta \simeq Q^2/(Q^2 + M_x^2)$ and on the mass of the produced quarks has been found. Really, because of the negative sign in the mass term in (19) we predict positive asymmetry for light and negative asymmetry for heavy quark production.

In the case of $Q\bar{Q}$ diffractive leptoproduction, the produced hadron mass is not fixed and $x_p$ is arbitrary, typically, of about $0.5 - 1$. The $A_{UL}$ asymmetry in this case is proportional to $x_p$ as previously and it should have a weak energy dependence. The predicted asymmetry for open charm production is about $1 - 2$. Some results for the spin-dependent vertex and forms of the cross sections can be found in [15].

To summarize, we have presented here the study of spin effects in diffractive processes. The discussed spin-dependent form of the Pomeron coupling modifies spin-average and
spin-dependent cross sections. The predicted single spin asymmetry in the elastic $pp$ scattering is about 10-20%. A not small value of the $A_\parallel$ asymmetry in the diffractive $Q\bar{Q}$ and $J/\Psi$ production has been found. The spin-dependent form of the coupling (3) is connected with the large–distance effects in QCD. Note that the interaction of the gluons with the proton can be expressed in terms of the gluon distribution inside the proton for zero momentum transfer [4]. For nonzero momentum transfer, on the other hand, the gluon-proton vertex should be related to the nonforward gluon distributions. If so, the function $B$ might be connected with the spin-independent gluon distribution $G(r, x_P)$ and $A$ with the spin-dependent distribution $\Delta G(r, x_P)$. As a result, the study of asymmetry in diffractive processes might be a convenient test of the Pomeron coupling structure and of nonforward spin-dependent gluon distributions.

The complicated form of the Pomeron vertices is determined by the large–distance nonperturbative effects in QCD. Thus, the important information on the spin structure of QCD at large distances can be carried out by studying diffractive reactions in future polarized experiments.

References

[1] ZEUS Collaboration, M.Derrick et al., Z.Phys. C68, 569 (1995); H1 Collaboration, T.Ahmed et al., Phys.Lett. B348, 681 (1995).
[2] M.G.Ryskin, Z.Phys C57, 89 (1993); S.J.Brodsky at al., Phys.Rev., D50, 3134 (1994).
[3] P.V.Landshoff, O.Nachtman, Z.Phys. C35, 405 (1987).
[4] E.A.Kuraev, L.N.Lipatov, V.S.Fadin, Sov.Phys. JETP 44, 443 (1976);
[5] F.E. Low, Phys. Rev. D12, 163 (1975); S. Nussinov, Phys. Rev. Lett. 34, 1286 (1975).
[6] A. Donnachie, P.V. Landshoff, Nucl. Phys. B244, 322 (1984).
[7] T. Arens, M. Diehl, O. Nachtmann, P. V. Landshoff, Z.Phys. C74, 651 (1997).
[8] J.Klenner, A.Schäfer, W.Greiner, Z.Phys. A352, 203 (1995).
[9] S.V.Goloskokov, S.P.Kuleshov, O.V.Selyugin, Z.Phys. C50, 455 (1991).
[10] M. Anselmino, P. Kroll, B. Pire, Z.Phys. C36, 36 (1987).
[11] S.V. Goloskokov, P. Kroll, e-print: hep-ph/9807529.
[12] N. Akchurin, S. V. Goloskokov, O. V. Selyugin, hep-ph/9703307
[13] M. Diehl, Eur.Phys.J. C4 497 (1998).
[14] M. Vänttinen. L. Mankiewicz, hep-ph/9805338.
[15] S.V. Goloskokov, Mod. Phys. Lett. 12, 173 (1997); hep-ph 9506347; 9509238.