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Jet Asymmetry and the Detection of Odderon Exchange in DIS *

C. Merino
Departamento de Física de Partículas
Universidade de Santiago de Compostela
Campus universitario s/n, 15706 Santiago de Compostela, Spain
and
Stanley J. Brodsky and J. Rathsman
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309,USA

Abstract

We show that the asymmetry in the fractional energy of charm versus anticharm jets produced in high energy diffractive photoproduction is sensitive to the interference of the Odderon ($C = -$) and Pomeron ($C = +$) exchange amplitudes in QCD. Measurements of this asymmetry at HERA could provide the first evidence for the presence of Odderon exchange in the high energy limit of strong interactions.

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1 Introduction

Recent results from the electron-proton collider experiments at HERA [1]—the rapidly-rising behavior of proton structure functions at small x, the rapidly-rising diffractive vector meson electroproduction rates, and the steep rise of the J/ψ photoproduction cross-section have brought renewed interest in the nature and behavior of the Pomeron in QCD (see for example [2, 3]). Also the existence of odd charge-conjugation, zero flavor-number exchange contributions to high energy hadron scattering amplitudes is a basic prediction of quantum chromodynamics, following simply from the existence of the color-singlet exchange of three reggeized gluons in the $t-$channel [4]. In Regge theory, the "Odderon" contribution is dual to a sum over $C = P = -1$ gluonium states in the t-channel [5]. In the case of reactions which involve high momentum transfer, the deviation of the Regge intercept of the Odderon trajectory from $\alpha_{\mathcal{O}}(t = 0) = 1$ can in principle be computed [6, 7, 8, 9] from perturbative QCD in analogy to the methods used to compute the properties of the hard BFKL Pomeron [10]. In [11] we have proposed an experimental test well suited to HERA kinematics which should be able to disentangle the contributions of both the Pomeron and the Odderon to diffractive production of charmed jets. By forming a charge asymmetry in the energy of the charmed jets, we can determine the relative importance of the Pomeron ($C = +$) and the Odderon ($C = -$) contributions, and their interference, thus providing a new experimental test of the separate existence of these two objects. Since the asymmetry measures the Odderon amplitude linearly, even a relatively weakly-coupled amplitude should be detectable.

2 Odderon-Pomeron interference

Consider the amplitude for diffractive photoproduction of a charm quark anti-quark pair. The leading diagram is given by single Pomeron exchange (two reggeized gluons), and the next term in the Born expansion is given by the exchange of one Odderon (three reggeized gluons). Both diffractive photoproduction and leptoproduction can be considered, although in the following we will specialize to the case of photoproduction for which the rate observed at HERA is much larger. Our results can easily be generalized to non-zero Q^2.

We use the conventional kinematical variables, and we denote by $z_{c(\bar{c})}$ the energy sharing of the $c\bar{c}$ pair ($z_c + z_{\bar{c}} = 1$ in Born approximation at the parton level), and we take into account that the finite charm quark mass restricts the range of z. Moreover, ξ is effectively the longitudinal momentum fraction of the proton carried by the Pomeron/Odderon, and the proton mass is neglected.

Regge theory, which is applicable in the kinematic region $s_{\gamma p} \gg M_X^2 \gg M_Y^2$, together with crossing symmetry, predicts the phases and analytic form of high energy amplitudes (see, for example, Refs. [12] and [13]). The amplitude for the diffractive process $\gamma p \to c\bar{c}p'$ with Pomeron (P) or Odderon ($\mathcal{O}$) exchange can be written as

$$\mathcal{M}^{\mathcal{P}/\mathcal{O}}(t, s_{\gamma p}, M_X^2, z_c) \propto \\ g_{pp'}^{\mathcal{P}/\mathcal{O}}(t) \left(\frac{s_{\gamma p}}{M_X^2}\right)^{\alpha_{\mathcal{P}/\mathcal{O}}(t)-1} \frac{\left(1 + S_{\mathcal{P}/\mathcal{O}} e^{-i\pi\alpha_{\mathcal{P}/\mathcal{O}}(t)}\right)}{\sin \pi \alpha_{\mathcal{P}/\mathcal{O}}(t)} g_{\mathcal{P}/\mathcal{O}}^{\gamma c\bar{c}}(t, M_X^2, z_c) \qquad (1)$$

where $S_{\mathcal{P}/\mathcal{O}}$ is the signature (even (odd) signature corresponds to an exchange which is (anti)symmetric under the interchange $s \leftrightarrow u$), which is $+(-)1$ for the Pomeron (Odderon). In the Regge approach the upper vertex $g_{\mathcal{P}/\mathcal{O}}^{\gamma c\bar{c}}(t, M_X^2, z_c)$ can be treated as a local real coupling such that the phase is contained in the signature factor. In the same way the factor $g_{pp'}^{\mathcal{P}/\mathcal{O}}(t)$ represents the lower vertex.

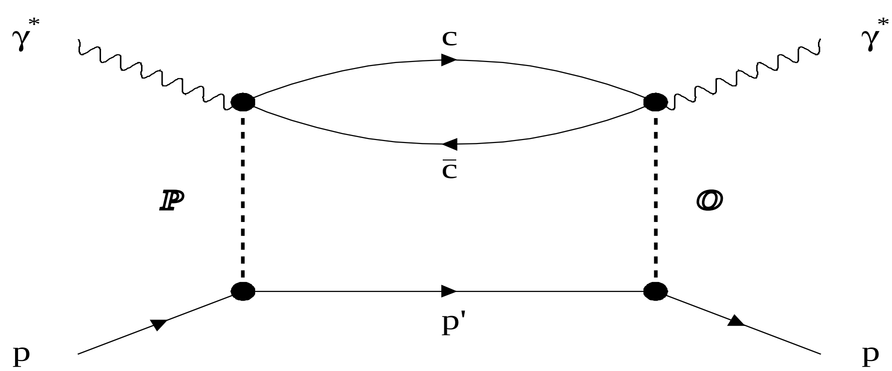

Figure 1: The interference between Pomeron (P) or Odderon ($\mathcal{O}$) exchange in the diffractive process $\gamma p \to c\bar{c}p'$.

In general the Pomeron and Odderon exchange amplitudes will interfere, as illustrated in Fig. 1. The contribution of the interference term to the total cross-section is zero, but it does contribute to charge-asymmetric rates. Thus we propose to study photoproduction of c-$\bar{c}$ pairs and measure the asymmetry in the energy fractions z_c and $z_{\bar{c}}$. More generally, one can use other charge-asymmetric kinematic configurations, as well as bottom or strange quarks.

Given the amplitude (1), the contribution to the cross-section from the interference term depicted in Fig. 1 is proportional to

$$\begin{aligned}\frac{d\sigma^{int}}{dtdM_X^2dz_c} &\propto \mathcal{M}^{\mathcal{P}}(t, s_{\gamma p}, M_X^2, z_c)\left\{\mathcal{M}^{\mathcal{O}}(t, s_{\gamma p}, M_X^2, z_c)\right\}^{\dagger} + h.c. \\ &= g_{pp'}^{\mathcal{P}}(t)g_{pp'}^{\mathcal{O}}(t)\left(\frac{s_{\gamma p}}{M_X^2}\right)^{\alpha_{\mathcal{P}}(t)+\alpha_{\mathcal{O}}(t)-2}\frac{2\sin\left[\frac{\pi}{2}\left(\alpha_{\mathcal{O}}(t)-\alpha_{\mathcal{P}}(t)\right)\right]}{\sin\frac{\pi\alpha_{\mathcal{P}}(t)}{2}\cos\frac{\pi\alpha_{\mathcal{O}}(t)}{2}} \\ &\quad\times g_{\mathcal{P}}^{\gamma c\bar{c}}(t, M_X^2, z_c)g_{\mathcal{O}}^{\gamma c\bar{c}}(t, M_X^2, z_c)\ . \end{aligned} \tag{2}$$

In the same way we can obtain the contributions to the cross-section from the non-interfering terms for Pomeron and Odderon exchange. We note the different charge conjugation properties of the upper vertices:

$$\begin{aligned} g_{\mathcal{P}}^{\gamma c\bar{c}}(t, M_X^2, z_c) &= -g_{\mathcal{P}}^{\gamma c\bar{c}}(t, M_X^2, z_{\bar{c}}) \\ g_{\mathcal{O}}^{\gamma c\bar{c}}(t, M_X^2, z_c) &= g_{\mathcal{O}}^{\gamma c\bar{c}}(t, M_X^2, z_{\bar{c}})\ . \end{aligned} \tag{3}$$

The interference term can then be isolated by forming the charge asymmetry,

$$\mathcal{A}(t, M_X^2, z_c) = \frac{\dfrac{d\sigma}{dtdM_X^2dz_c} - \dfrac{d\sigma}{dtdM_X^2dz_{\bar{c}}}}{\dfrac{d\sigma}{dtdM_X^2dz_c} + \dfrac{d\sigma}{dtdM_X^2dz_{\bar{c}}}}\ . \tag{4}$$

giving the general form of the Pomeron-Odderon interference contribution in Regge theory. In the following we will give numerical estimates for the different components and also calculate the asymmetry using the Donnachie-Landshoff model for the Pomeron[14].

The functional dependence of the asymmetry on the kinematical variables can be obtained by varying the kinematic variables one at a time. In this way it will be possible to obtain new information about Odderon exchange in relation to Pomeron exchange. Furthermore, we expect the main dependence in the different kinematic variables to come from different factors in the asymmetry. For instance, the invariant mass M_X dependence is mainly given by the power behavior, $(s_{\gamma p}/M_X^2)^{\alpha_{\mathcal{O}}(t)-\alpha_{\mathcal{P}}(t)}$, and it will thus provide direct information about the difference between $\alpha_{\mathcal{O}}$ and

$\alpha_{\mathcal{P}}$. Another interesting question which can be addressed from observations of the asymmetry is the difference in the t-dependence of $g^{\mathcal{O}}_{pp'}$ and $g^{\mathcal{P}}_{pp'}$.

We also make the following general observations about the predicted asymmetry:

- As a consequence of the differing signatures for the Pomeron and Odderon, there is no interference between the two exchanges if they have the same power $\alpha(t)$ since then $\sin\left[\frac{\pi}{2}\left(\alpha_{\mathcal{O}}(t)-\alpha_{\mathcal{P}}(t)\right)\right]=0$. In fact, in a perturbative calculation at tree-level the interference would be zero in the high-energy limit $s \gg |t|$ since the two- and three-gluon exchanges are purely imaginary and real respectively. This should be compared with the analogous QED process, $\gamma Z \to \ell^+\ell^- Z$, where the interference of the one- and two-photon exchange amplitudes can explain [15] the observed lepton asymmetries, energy dependence, and nuclear target dependence of the experimental data [16] for large angles. The asymmetry is in the QED case proportional to the opening angle such that it vanishes in the limit $s \gg |t|$.

- The overall sign of the asymmetry is not predicted by Regge theory. (The sign of the Odderon amplitude is unknown.) However, the pole at $\alpha_{\mathcal{O}} = 1$ leads to the asymmetry having different sign for $\alpha_{\mathcal{O}}(t) < 1$ and $\alpha_{\mathcal{O}}(t) > 1$ respectively. Thus, if the Odderon intercept is larger than one, which however is not supported by recent theoretical developments [7, 8, 9], then the asymmetry will change sign for some larger t where $\alpha_{\mathcal{O}}(t)$ goes through 1.

The ratio of the Odderon and Pomeron couplings to the proton, $g^{\mathcal{O}}_{pp'}/g^{\mathcal{P}}_{pp'}$, is limited by data on the difference of the elastic proton-proton and proton-antiproton cross-sections at large energy s. Following [17] we use the estimated limit on the difference between the ratios of the real and imaginary part of the proton-proton and proton-antiproton forward amplitudes,

$$|\Delta\rho(s)| = \left|\frac{\Re\{\mathcal{M}^{pp}(s,t=0)\}}{\Im\{\mathcal{M}^{pp}(s,t=0)\}} - \frac{\Re\{\mathcal{M}^{p\bar{p}}(s,t=0)\}}{\Im\{\mathcal{M}^{p\bar{p}}(s,t=0)\}}\right| \leq 0.05 \qquad (5)$$

for $s \sim 10^4$ GeV^2 to get a limit on the ratio of the Odderon and Pomeron couplings to the proton. Using the amplitude corresponding to Eq. (1) for proton-proton and proton-antiproton scattering we get for $t = 0$,

$$\Delta\rho(s) = 2\frac{\Re\{\mathcal{M}^{\mathcal{O}}(s)\}}{\Im\{\mathcal{M}^{\mathcal{P}}(s)\} + \Im\{\mathcal{M}^{\mathcal{O}}(s)\}} \simeq -2\left(\frac{g^{\mathcal{O}}_{pp'}}{g^{\mathcal{P}}_{pp'}}\right)^2 \left(\frac{s}{s_0}\right)^{\alpha_{\mathcal{O}}-\alpha_{\mathcal{P}}} \tan\frac{\pi\alpha_{\mathcal{O}}}{2}, \qquad (6)$$

where s_0 is a typical hadronic scale ~ 1 GeV^2 which replaces M_X^2 in Eq. (1). In the last step we also make the simplifying assumption that the contribution to the denominator from the Odderon is numerically much smaller than from the Pomeron and therefore can be neglected. The maximally allowed Odderon coupling at t=0 is then given by

$$\left|g_{pp'}^{\mathcal{O}}\right|_{\max} = \left|g_{pp'}^{\mathcal{P}}\right| \sqrt{\frac{\Delta\rho_{\max}(s)}{2} \cot\frac{\pi\alpha_{\mathcal{O}}}{2} \left(\frac{s}{s_0}\right)^{\alpha_{\mathcal{P}}-\alpha_{\mathcal{O}}}}. \tag{7}$$

Strictly speaking this limit applies for the soft Odderon and Pomeron and are therefore not directly applicable to charm photoproduction which is a harder process, *i.e.* with larger energy dependence. According to recent data from HERA [18] the energy dependence, parameterised as $s_{\gamma p}^{\delta}$, for photoproduction of J/ψ mesons is $\delta = 0.39 \pm 0.09$ for exclusive production and $\delta = 0.45 \pm 0.13$ for inclusive production corresponding to a Pomeron intercept of $\alpha_{\mathcal{P}}(0) \simeq 1.2$. Even so we will use this limit to get an estimate of the maximal Odderon coupling to the proton.

The amplitudes for the asymmetry can be calculated using the Donnachie-Landshoff [14] model for the Pomeron and a similar ansatz for the Odderon [17]. The coupling of the Pomeron/Odderon to a quark is then given by $\kappa_{\mathcal{P}/\mathcal{O}}^{\gamma c\bar{c}}\gamma^{\rho}$, *i.e.* assuming a helicity preserving local interaction. In the same way the Pomeron/Odderon couples to the proton with $3\kappa_{pp'}^{\mathcal{P}/\mathcal{O}} F_1(t)\gamma^{\sigma}$ if we only include the Dirac form-factor $F_1(t)$. The amplitudes for the asymmetry can then be obtained by replacing $g_{pp'}^{\mathcal{P}/\mathcal{O}}(t) g_{\mathcal{P}/\mathcal{O}}^{\gamma c\bar{c}}(t, M_X^2, z_c)$ in Eq. (1) by

$$\begin{aligned} g_{pp'}^{\mathcal{P}/\mathcal{O}}(t) g_{\mathcal{P}/\mathcal{O}}^{\gamma c\bar{c}}(t, M_X^2, z_c) \;=\; & 3\kappa_{pp'}^{\mathcal{P}/\mathcal{O}} F_1(t) \bar{u}(p-\ell)\gamma^{\sigma} u(p) \\ & \times \left(g^{\rho\sigma} - \frac{\ell^{\rho} q^{\sigma} + \ell^{\sigma} q^{\rho}}{\ell q}\right) \kappa_{\mathcal{P}/\mathcal{O}}^{\gamma c\bar{c}} \epsilon^{\mu}(q) \\ & \times \bar{u}(p_c) \left\{ \gamma^{\mu} \frac{\not{\ell} - \not{p}_{\bar{c}} + m_c}{(1-z)M_X^2} \gamma^{\rho} - S_{\mathcal{P}/\mathcal{O}} \gamma^{\rho} \frac{\not{p}_c - \not{\ell} + m_c}{z M_X^2} \gamma^{\mu} \right\} \\ & \times v(p_{\bar{c}}) \end{aligned}$$

where $\ell = \xi p$ is the Pomeron/Odderon momentum and $g^{\rho\sigma} - \frac{\ell^{\rho} q^{\sigma} + \ell^{\sigma} q^{\rho}}{\ell q}$ stems from the Pomeron/Odderon "propagator". Note the signature which is inserted for the crossed diagram to model the charge conjugation property of the Pomeron. The Pomeron amplitude written this way is not gauge invariant and therefore we use radiation gauge also for the photon, *i.e.* the polarization sum is obtained using $g^{\mu\nu} - \frac{q^{\mu} p^{\nu} + q^{\nu} p^{\mu}}{pq}$.

The leading terms in a t/M_X^2 expansion of the squared amplitudes for the Pomeron and Odderon exchange as well as the interference are then given by

$$\begin{aligned}
\left(\frac{g_{pp'}^{\mathcal{P}} g_{\mathcal{P}}^{\gamma c\bar{c}}}{\kappa_{pp'}^{\mathcal{P}} \kappa_{\mathcal{P}}^{\gamma c\bar{c}}}\right)^2 &\propto \frac{z_c^2 + z_{\bar{c}}^2}{z_c z_{\bar{c}}} \frac{(1-\xi)}{\xi^2} \\
\left(\frac{g_{pp'}^{\mathcal{O}} g_{\mathcal{O}}^{\gamma c\bar{c}}}{\kappa_{pp'}^{\mathcal{O}} \kappa_{\mathcal{O}}^{\gamma c\bar{c}}}\right)^2 &\propto \frac{z_c^2 + z_{\bar{c}}^2}{z_c z_{\bar{c}}} \frac{(1-\xi)}{\xi^2} \\
\frac{g_{pp'}^{\mathcal{P}} g_{pp'}^{\mathcal{O}} g_{\mathcal{P}}^{\gamma c\bar{c}} g_{\mathcal{O}}^{\gamma c\bar{c}}}{\kappa_{pp'}^{\mathcal{P}} \kappa_{pp'}^{\mathcal{O}} \kappa_{\mathcal{P}}^{\gamma c\bar{c}} \kappa_{\mathcal{O}}^{\gamma c\bar{c}}} &\propto \frac{z_c - z_{\bar{c}}}{z_c z_{\bar{c}}} \frac{(1-\xi)}{\xi^2},
\end{aligned} \tag{8}$$

with corrections that are of order t/M_X^2 and therefore can be safely neglected. The ratio between the interference term and the Pomeron exchange is thus given by,

$$\frac{g_{pp'}^{\mathcal{O}} g_{\mathcal{O}}^{\gamma c\bar{c}}}{g_{pp'}^{\mathcal{P}} g_{\mathcal{P}}^{\gamma c\bar{c}}} = \frac{\kappa_{pp'}^{\mathcal{O}} \kappa_{\mathcal{O}}^{\gamma c\bar{c}}}{\kappa_{pp'}^{\mathcal{P}} \kappa_{\mathcal{P}}^{\gamma c\bar{c}}} \frac{z_c - z_{\bar{c}}}{z_c^2 + z_{\bar{c}}^2} = \frac{\kappa_{pp'}^{\mathcal{O}} \kappa_{\mathcal{O}}^{\gamma c\bar{c}}}{\kappa_{pp'}^{\mathcal{P}} \kappa_{\mathcal{P}}^{\gamma c\bar{c}}} \frac{2z_c - 1}{z_c^2 + (1-z_c)^2} \tag{9}$$

Inserting this into the expression of the asymmetry and making the simplifying assumption that the Odderon contribution can be dropped in the denominator gives

$$\begin{aligned}
\mathcal{A}(t, M_X^2, z_c) &\simeq 2\frac{\kappa_{pp'}^{\mathcal{O}} \kappa_{\mathcal{O}}^{\gamma c\bar{c}}}{\kappa_{pp'}^{\mathcal{P}} \kappa_{\mathcal{P}}^{\gamma c\bar{c}}} \sin\left[\frac{\pi\left(\alpha_{\mathcal{O}} - \alpha_{\mathcal{P}}\right)}{2}\right] \left(\frac{s_{\gamma p}}{M_X^2}\right)^{\alpha_{\mathcal{O}} - \alpha_{\mathcal{P}}} \\
&\quad \times \frac{\sin\frac{\pi\alpha_{\mathcal{P}}}{2}}{\cos\frac{\pi\alpha_{\mathcal{O}}}{2}} \frac{2z_c - 1}{z_c^2 + (1-z_c)^2} .
\end{aligned} \tag{10}$$

To obtain a numerical estimate of the asymmetry, we shall assume that $t \simeq 0$ and use $\alpha_{\mathcal{P}}^{hard} = 1.2$ and $\alpha_{\mathcal{O}} = 0.95$ [8] for the Pomeron and Odderon intercepts respectively. In addition we will also assume $\kappa_{\mathcal{O}}^{\gamma c\bar{c}}/\kappa_{\mathcal{P}}^{\gamma c\bar{c}} \sim \sqrt{C_F \alpha_s(m_c^2)} \simeq 0.6$, motivated by the Davies, Bethe, and Maximon calculation [19], and use the maximal Odderon-proton coupling, $\kappa_{pp'}^{\mathcal{O}}/\kappa_{pp'}^{\mathcal{P}} = g_{pp'}^{\mathcal{O}}/g_{pp'}^{\mathcal{P}} = 0.1$, which follows from Eq. (7) for $\alpha_{\mathcal{P}}^{soft} = 1.08$, $s = 10^4$ GeV^2, $s_0 = 1$ GeV^2 and $\Delta\rho_{\max}(s) = 0.05$. Inserting the numerical values discussed above then gives

$$\mathcal{A}(t \simeq 0, M_X^2, z_c) \simeq 0.45 \left(\frac{s_{\gamma p}}{M_X^2}\right)^{-0.25} \frac{2z_c - 1}{z_c^2 + (1-z_c)^2} , \tag{11}$$

which for a typical value of $\frac{s_{\gamma p}}{M_X^2} = 100$ becomes a ~ 15 % asymmetry for large z_c as illustrated in Fig. 2. We also note that the asymmetry can be integrated over z_c

giving

$$\begin{aligned}\mathcal{A}(t \simeq 0, M_X^2) &= \int_{0.5}^{1} \mathcal{A}(t \simeq 0, M_X^2, z_c) - \int_{0}^{0.5} \mathcal{A}(t \simeq 0, M_X^2, z_c) \\ &\simeq 0.3 \left(\frac{s_{\gamma p}}{M_X^2}\right)^{-0.25} . \end{aligned} \tag{12}$$

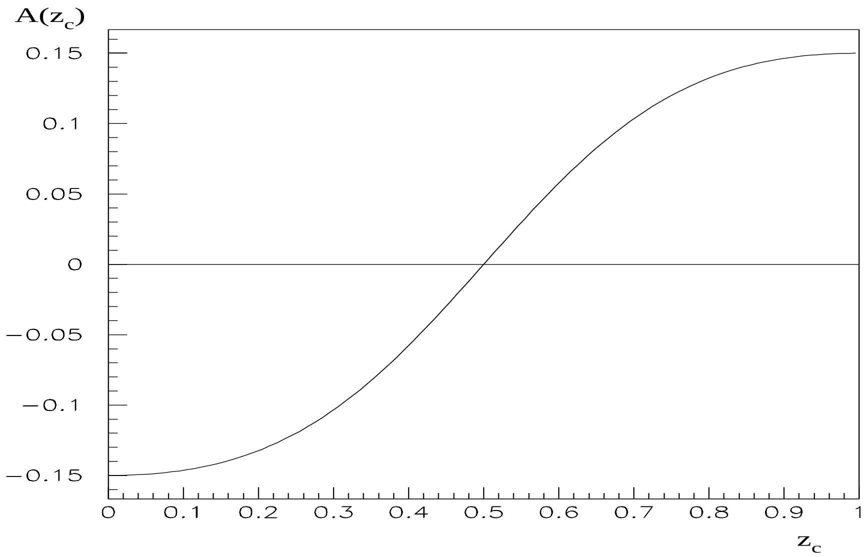

Figure 2: The asymmetry in fractional energy z_c of charm versus anticharm jets predicted by our model using the Donnachie-Landshoff Pomeron for $\alpha_{\mathcal{P}} = 1.2$, $\alpha_{\mathcal{O}} = 0.95$ and $s_{\gamma p}/M_X^2 = 100$.

It should be emphasized that the magnitude of this estimate is quite uncertain. The Odderon coupling to the proton which we are using is a maximal coupling for the soft Odderon in relation to the soft Pomeron. So on the one hand the ratio may be smaller than this, and on the other hand the ratio may be larger if the hard Odderon and Pomeron have a different ratio for the coupling to the proton. For the hard Pomeron the coupling is in general different at the two vertices (see e.g. [20]) and this could also be true for the hard Odderon.

3 Conclusions

In summary we have presented a sensitive test for detecting the separate existence of the Pomeron and the Odderon exchange contributions in the high-energy limit $s \gg |t|$

as predicted by QCD. By observing the charge asymmetry of the quark/antiquark energy fraction (z_c) in diffractive $c\bar{c}$ pair photoproduction, the interference between the Pomeron and the Odderon exchanges can be isolated and the ratio to the sum of the Pomeron and the Odderon exchanges can be measured. Using a model with helicity conserving coupling for the Pomeron/Odderon to quarks, the asymmetry is predicted to be proportional to $(2z_c - 1)/(z_c^2 + (1 - z_c)^2)$. The magnitude of the asymmetry is estimated to be of order 15%. However this estimate includes several unknowns and is thus quite uncertain. Such a test could be performed by current experiments at HERA measuring the diffractive production of open charm in photoproduction or electroproduction. Such measurements could provide the first experimental evidence for the existence of the Odderon, as well as the relative strength of the Odderon and Pomeron couplings. Most important, the energy dependence of the asymmetry can be used to determine whether the Odderon intercept is in fact greater or less than that of the Pomeron.

4 Acnowlwdgements

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