Odderon-Pomeron Interference

Stanley J. Brodsky and Johan Rathsman

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

Carlos Merino

Departamento de Física de Partículas
Universidade de Santiago de Compostela
15706 Santiago de Compostela, Spain

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. We predict the dynamical shape of the asymmetry in a simple model and estimate its magnitude to be of the order 15% using an Odderon coupling to the proton which saturates constraints from proton-proton vs. proton-antiproton elastic scattering. Measurements of this asymmetry at HERA could provide firm experimental evidence for the presence of Odderon exchange in the high energy limit of strong interactions.

Submitted to Physics Letters B.

*Research partially supported by the Department of Energy under contract DE–AC03–76SF00515, the Spanish CICYT under contract AEN96–1673, and the Swedish Natural Science Research Council, contract F–PD 11264–301.
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 $[1]$. In Regge theory, the “Odderon” contribution is dual to a sum over $C = P = -1$ gluonium states in the $t$-channel $[2]$. In the case of reactions which involve high momentum transfer, the deviation of the Regge intercept of the Odderon trajectory from $\alpha_O(t = 0) = 1$ can in principle be computed $[3–6]$ from perturbative QCD in analogy to the methods used to compute the properties of the hard BFKL Pomeron $[7]$. (For a more complete history of the Odderon we refer the reader to $[8]$ and $[9]$ and references therein.)

In the case of low momentum transfer reactions, the Odderon exchange amplitude should yield a roughly energy-independent contribution to the difference of proton-proton vs. proton-antiproton cross sections. It should also be seen in high energy diffractive pseudoscalar meson photoproduction, such as $\gamma p \rightarrow \pi^0 p$ $[10–12]$ and $\gamma\gamma \rightarrow \pi^0\pi^0$ $[13]$, since these amplitudes demand odd $C$ exchange. Despite these theoretical expectations, there is as yet no firm experimental evidence for any Odderon contribution in the high-energy limit $s \gg |t|$. A hint of the Odderon was seen in ISR results $[14] \left( \sqrt{s} = 52.8 \text{ GeV} \right)$ in the difference between the elastic $pp$ and $p\bar{p}$ differential cross-sections at the diffractive minimum, $t \sim -1.3 \text{ GeV}^2$. A realization of the Odderon in perturbation theory is represented by the Landshoff contribution to large angle $pp$ scattering $[15]$.

Recent results from the electron-proton collider experiments at HERA $[16]$—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 $J/\psi$ photoproduction cross section—have brought renewed interest in the nature and behavior of the Pomeron in QCD (see for example $[17,18]$). In this letter we propose 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.

Consider the diagrams in Fig. 1 describing 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). In the following we will focus on the situation when the diffractively scattered proton $p'$ stays intact; however, the formulae will be equally valid when the diffractively scattered proton is excited to a low mass system $Y$. We only require the invariant mass of the system $M_2^X$ to be small compared to the invariant mass of the $c\bar{c}$ pair $M_2^X$. In fact, as pointed out by Rueter et al. $[11]$, the cross-section for the diffractively excited protons can be significantly larger than the elastic cross-section in specific models such as diquark clustering in the proton. The virtuality of the incoming photon $Q^2$ can be zero or small since the invariant mass of the $c\bar{c}$ pair $M_2^X$ is large. Thus we are considering both diffractive photoproduction and leptoproduction, 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 $Q^2$. 
FIG. 1. The amplitude for the diffractive process $\gamma p \to c\bar{c}Y$ with Pomeron ($P$) or Odderon ($O$) exchange.

The total center of mass energy of the $\gamma p$ system will be denoted $s_{\gamma p}$ which should be distinguished from the total ep cms energy. Denoting the photon momentum by $q$, the proton momentum by $p$, and the momenta of the charm quark (antiquark) by $p_c$ ($p_{\bar{c}}$), the energy sharing of the $c\bar{c}$ pair is given by the variable

$$z_{c(\bar{c})} = \frac{p_{c(\bar{c})}}{q_p} = \frac{E_{c(\bar{c})}}{E_{\gamma^*}} \tag{1}$$

where the latter equality is true in the proton rest frame. It follows that $z_c + z_{\bar{c}} = 1$ in Born approximation at the parton level. The finite charm quark mass restricts the range of $z$ to

$$\frac{1}{2} - \frac{1}{4} - \frac{m_c^2}{M_X^2} \leq z \leq \frac{1}{2} + \frac{1}{4} - \frac{m_c^2}{M_X^2} \tag{2}$$

where $M_X^2$ is the invariant mass of the $c\bar{c}$ pair which is related to the total $\gamma p$ cms energy $s_{\gamma p}$ by

$$M_X^2 = (\xi p + q)^2 \simeq 2\xi pq \simeq \xi s_{\gamma p} \tag{3}$$

where $\xi$ 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. [19] and [20]). The amplitude for the diffractive process $\gamma p \to c\bar{c}p'$ with Pomeron ($P$) or Odderon ($O$) exchange can be written as

$$M^{P/O}(t, s_{\gamma p}, M_X^2, z_c) \propto g^{P/O}_p(t) \left( \frac{s_{\gamma p}}{M_X^2} \right)^{\alpha_{P/O}(t)-1}$$

$$\times \left( 1 + S_{P/O} e^{-i\pi \alpha_{P/O}(t)} \right) \frac{g^{\gamma c\bar{c}}_{P/O}(t, M_X^2, z_c)}{\sin \pi \alpha_{P/O}(t)} \left( \frac{s_{\gamma p}}{M_X^2} \right)^{\alpha_{P/O}(t)-1} \tag{4}$$
where $S_{\mathcal{P}/\mathcal{O}}$ is the signature† which is $+(-)1$ for the Pomeron (Odderon). In the Regge approach the upper vertex $g_{\mathcal{P}/\mathcal{O}}(t, M^2, z_c)$ 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. For our purposes it will be convenient to rewrite the signature factor in the following way,

$$
\left(1 + S_{\mathcal{P}/\mathcal{O}} e^{-i\pi \alpha_{\mathcal{P}/\mathcal{O}}(t)}\right) \sin \pi \alpha_{\mathcal{P}/\mathcal{O}}(t) = \begin{cases} 
\frac{\cos \pi \alpha_{\mathcal{P}}(t) - i \sin \pi \alpha_{\mathcal{P}}(t)}{\sin \frac{\pi \alpha_{\mathcal{P}}(t)}{2}} & \text{for } S_{\mathcal{P}} = 1 \\
\frac{\sin \frac{\pi \alpha_{\mathcal{O}}(t)}{2} + i \cos \frac{\pi \alpha_{\mathcal{O}}(t)}{2}}{\cos \frac{\pi \alpha_{\mathcal{O}}(t)}{2}} & \text{for } S_{\mathcal{O}} = -1
\end{cases}.
$$

In the literature it has become customary to absorb the pole factors $1/\sin \frac{\pi \alpha_{\mathcal{P}}(t)}{2}$ and $1/\cos \frac{\pi \alpha_{\mathcal{O}}(t)}{2}$ into the couplings $\left(g_{pp'}^\mathcal{P}(t)\right)^2$, but we will keep them explicit since we want to treat the upper and lower vertex separately.

In general the Pomeron and Odderon exchange amplitudes will interfere, as illustrated in Fig. 2. 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.

![Figure 2](image_url)

**FIG. 2.** The interference between Pomeron ($\mathcal{P}$) or Odderon ($\mathcal{O}$) exchange in the diffractive process $\gamma p \rightarrow c\bar{c}p'$.

Given the amplitude (4), the contribution to the cross-section from the interference term depicted in Fig. 2 is proportional to

---

†Even (odd) signature corresponds to an exchange which is (anti)symmetric under the interchange $s \leftrightarrow u$. 

4
We note the different charge conjugation properties of the upper vertices:

\[
\frac{d\sigma^{\text{int}}}{dt dM_X^2 dz_c} \propto \mathcal{M}^P(t, s, M_X^2, z_c) \left\{ \mathcal{M}^O(t, s, M_X^2, z_c) \right\}^\dagger + h.c.
\]

\[
= g_{pp}^P(t)g_{pp}^O(t) \left( \frac{s}{M_X^2} \right)^{\alpha_P(t) + \alpha_O(t) - 2} \frac{2 \sin \left[ \frac{\pi}{2} (\alpha_O(t) - \alpha_P(t)) \right]}{\sin \frac{\pi \alpha_O(t)}{2} \cos \frac{\pi \alpha_O(t)}{2}}
\]

\[
\times g_P^{\gamma_{cc}}(t, M_X^2, z_c) g_O^{\gamma_{cc}}(t, M_X^2, z_c) .
\]

Inserting Eqs. (6), (7) and (8) into Eq. (9) then gives the predicted asymmetry.

\[
\frac{d\sigma^{P/O}}{dt dM_X^2 dz_c} \propto \begin{cases} 
\left[ g_{pp}^P(t) \left( \frac{s}{M_X^2} \right)^{\alpha_P(t) - 1} g_P^{\gamma_{cc}}(t, M_X^2, z_c) / \sin \frac{\pi \alpha_P(t)}{2} \right]^2 & \text{for } S_P = 1 \\
\left[ g_{pp}^O(t) \left( \frac{s}{M_X^2} \right)^{\alpha_O(t) - 1} g_O^{\gamma_{cc}}(t, M_X^2, z_c) / \cos \frac{\pi \alpha_O(t)}{2} \right]^2 & \text{for } S_O = -1 
\end{cases}
\]

We note the different charge conjugation properties of the upper vertices:

\[
g_P^{\gamma_{cc}}(t, M_X^2, z_c) = -g_P^{\gamma_{cc}}(t, M_X^2, z_c)
\]

\[
g_O^{\gamma_{cc}}(t, M_X^2, z_c) = g_O^{\gamma_{cc}}(t, M_X^2, z_c) .
\]

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

\[
\mathcal{A}(t, M_X^2, z_c) = \frac{\frac{d\sigma}{dt dM_X^2 dz_c} - \frac{d\sigma}{dt dM_X^2 dz_c}}{\frac{d\sigma}{dt dM_X^2 dz_c} + \frac{d\sigma}{dt dM_X^2 dz_c}} .
\]

Inserting Eqs. (6), (7) and (8) into Eq. (9) then gives the predicted asymmetry.

\[
\mathcal{A}(t, M_X^2, z_c) = \frac{g_{pp}^P g_{pp}^O \left( \frac{s}{M_X^2} \right)^{\alpha_P + \alpha_O} \frac{2 \sin \left[ \frac{\pi}{2} (\alpha_O - \alpha_P) \right]}{\sin \frac{\pi \alpha_O}{2} \cos \frac{\pi \alpha_O}{2}} g_P^{\gamma_{cc}} g_O^{\gamma_{cc}}}{\left[ g_{pp}^P \left( \frac{s}{M_X^2} \right)^{\alpha_P} g_P^{\gamma_{cc}} / \sin \frac{\pi \alpha_P}{2} \right]^2 + \left[ g_{pp}^O \left( \frac{s}{M_X^2} \right)^{\alpha_O} g_O^{\gamma_{cc}} / \cos \frac{\pi \alpha_O}{2} \right]^2} .
\]

where the arguments have been dropped for clarity. This is 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 [23].

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, \((s_{\gamma p}/M_X^2)^{\alpha_O(t)-\alpha_P(t)}\), and it will thus provide direct information about the difference between \(\alpha_O\) and \(\alpha_P\). Another interesting question which can be addressed from observations of the asymmetry is the difference in the \(t\)-dependence of \(g_{pp'}^O\) and \(g_{pp'}^P\).

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 \(\sin\left[\frac{\pi}{2} (\alpha_O(t) - \alpha_P(t))\right] = 0\). 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, \(\gamma Z \rightarrow \ell^+\ell^- Z\), where the interference of the one- and two-photon exchange amplitudes can explain \([22]\) the observed lepton asymmetries, energy dependence, and nuclear target dependence of the experimental data \([23]\) for large angles. The asymmetry is in the QED case proportional to the opening angle such that it vanishes in the limit \(s \gg |t|\).

- In general, photon exchange will also contribute to the asymmetry since the photon and the Odderon have the same quantum numbers. The size of the photon exchange amplitude is \(\frac{2}{3}e^2F_p(t)\) where \(F_p\) is the proton form-factor and \(2/3\) is the charm quark electric charge. The relative size of the photon and Odderon contributions will be discussed below when we give numerical estimates.

- The overall sign of the asymmetry is not predicted by Regge theory. (The sign of the Odderon amplitude is unknown.) However, the pole at \(\alpha_O = 1\) leads to the asymmetry having different sign for \(\alpha_O(t) < 1\) and \(\alpha_O(t) > 1\) respectively. Thus, if the Odderon intercept is larger than one, which however is not supported by recent theoretical developments \([4–6]\), then the asymmetry will change sign for some larger \(t\) where \(\alpha_O(t)\) goes through 1.

The ratio of the Odderon and Pomeron couplings to the proton, \(g_{pp'}^O/g_{pp'}^P\), is limited by data on the difference of the elastic proton-proton and proton-antiproton cross-sections at large energy \(s\). Following \([12]\) 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,

\[
|\Delta \rho(s)| = \left| \frac{\Re\{\mathcal{M}_{pp}(s, t = 0)\}}{\Im\{\mathcal{M}_{pp}(s, t = 0)\}} - \frac{\Re\{\mathcal{M}_{p\bar{p}}(s, t = 0)\}}{\Im\{\mathcal{M}_{p\bar{p}}(s, t = 0)\}} \right| \leq 0.05 \tag{11}
\]

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. \([11]\) for proton-proton and proton-antiproton scattering we get for \(t = 0\),

\[
\Delta \rho(s) = 2\frac{\Re\{\mathcal{M}_O(s)\}}{\Im\{\mathcal{M}_P(s)\} + \Im\{\mathcal{M}_O(s)\}} \approx -2\left(\frac{g_{pp'}^O}{g_{pp'}^P}\right)^2 \left(\frac{s}{s_0}\right)^{\alpha_O-\alpha_P} \tan\frac{\pi \alpha_O}{2}, \tag{12}
\]
where \( s_0 \) is a typical hadronic scale \( \sim 1 \text{ GeV}^2 \) which replaces \( M_X^2 \) in Eq. (4). 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,

\[
|g_{pp'}^{O}|_{\text{max}} = |g_{pp'}^{P}| \sqrt{\frac{\Delta \rho_{\text{max}}(s)}{2} \cot \frac{\pi \alpha_O}{2} \left( \frac{s}{s_0} \right)^{\alpha_P - \alpha_O}}.
\]  

(13)

Strictly speaking this limit applies for the soft Odderon and Pomeron and is therefore not directly applicable to charm photoproduction which is a harder process, \( i.e. \) with larger energy dependence. According to recent data from HERA [24] the energy dependence, parameterized as \( s^\delta \gamma_p \), for photoproduction of \( J/\psi \) 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 \( \alpha_P(0) \approx 1.2 \). Even so we will use this limit to get an estimate of the maximal Odderon coupling to the proton.

![FIG. 3. The amplitudes for the asymmetry using the Donnachie-Landshoff [21] model for the Pomeron/Odderon coupling to the quark and the proton.](image)

The amplitudes can be calculated using the Donnachie-Landshoff [21] model for the Pomeron and a similar ansatz for the Odderon [12]. The coupling of the Pomeron/Odderon to a quark is then given by \( \kappa_{\gamma c}^{P/O} \gamma^\rho \), \( i.e. \) assuming a helicity preserving local interaction. In the same way the Pomeron/Odderon couples to the proton with \( 3\kappa_{pp'}^{P/O} F_1(t) \gamma^\rho \) if we only include the Dirac form-factor \( F_1(t) \). The amplitudes shown in Fig. 3 can then be obtained by replacing \( g_{pp'}^{P/O}(t)g_{\gamma c/O}(t, M_X^2, z_c) \) in Eq. (4) by,

\[
g_{pp'}^{P/O}(t)g_{\gamma c/O}(t, M_X^2, z_c) = 3\kappa_{pp'}^{P/O} F_1(t) \bar{u}(p - \ell) \gamma^\rho u(p) \left( g^{\rho\sigma} - \frac{\ell^\rho q^\sigma + \ell^\sigma q^\rho}{\ell q} \right) \kappa_{\gamma c/O}^{P/O} \epsilon^\mu(q) \times \bar{u}(p_c) \left\{ \gamma^\mu \ell - \frac{\ell^\rho \gamma^\rho}{\ell q} + \frac{\ell^\mu q^\rho + \ell^\rho q^\rho}{\ell q} \right\} v(p_c)
\]

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 \(g^{\mu\nu} = \frac{\epsilon^{\mu\nu\rho\sigma}p^{\rho}p^{\sigma}}{p^2} \) (for a thorough analysis of the gauge-dependence of the Pomeron model see [25]). 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,

\[
\begin{align*}
\left(\frac{g_{pp}^O g_{\gamma\gamma}^{P}}{\kappa_{pp}^{O} \kappa_{\gamma\gamma}^{P}}\right)^2 & \propto \frac{z_c^2 + z_e^2(1 - \xi)}{\zeta z_c z_e} \\
\left(\frac{g_{pp}^O g_{\gamma\gamma}^{P}}{\kappa_{pp}^{O} \kappa_{\gamma\gamma}^{P}}\right)^2 & \propto \frac{z_e^2}{\zeta z_c z_e} \\
g_{pp} g_{pp} g_{\gamma\gamma}^{P} g_{\gamma\gamma}^{O} & \propto \frac{z_c - z_e(1 - \xi)}{\zeta z_c z_e} ,
\end{align*}
\]

(14)

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,

\[
\frac{g_{pp}^O g_{\gamma\gamma}^{P}}{g_{pp} g_{\gamma\gamma}^{P}} = \frac{\kappa_{pp}^{O} \kappa_{\gamma\gamma}^{P} z_c - z_e}{\kappa_{pp}^{P} \kappa_{\gamma\gamma}^{P} z_c^2 + z_e^2} = \frac{\kappa_{pp}^{O} \kappa_{\gamma\gamma}^{P} 2 z_c - 1}{\kappa_{pp}^{P} \kappa_{\gamma\gamma}^{P} z_c^2 + (1 - z_c)^2}
\]

(15)

Inserting this into the asymmetry given by Eq. (10) and making the simplifying assumption that the Odderon contribution can be dropped in the denominator gives

\[
A(t, M_X^2, z_c) \simeq 2 \frac{\kappa_{pp}^{O} \kappa_{\gamma\gamma}^{P}}{\kappa_{pp}^{P} \kappa_{\gamma\gamma}^{P}} \sin \left[ \frac{\pi (\alpha_O - \alpha_P)}{2} \right] \left( \frac{s_{pp}}{M_X^2} \right)^{\alpha_O - \alpha_P} \frac{\sin \frac{\pi \alpha_O}{2}}{\cos \frac{\pi \alpha_P}{2}} \frac{2 z_c - 1}{z_c^2 + (1 - z_c)^2} .
\]

(16)

To obtain a numerical estimate of the asymmetry, we shall assume that \(t \simeq 0\) and use \(\alpha_P^{hard} = 1.2\) and \(\alpha_O = 0.95\) [3] for the Pomeron and Odderon intercepts respectively. In addition we will also assume \(\kappa_{\gamma\gamma}^{P} / \kappa_{\gamma\gamma}^{O} \sim \sqrt{C_F \alpha_s(m_c^2)} \approx 0.6\), in analogy to the couplings which occur in the higher order corrections to Bethe-Heitler pair production [26], and use the maximal Odderon-proton coupling, \(\kappa_{pp}^{O} / \kappa_{pp}^{P} = g_{pp}^{O} / g_{pp}^{P} \approx 0.1\), which follows from Eq. (13) for \(\alpha_P^{soft} = 1.08, \ s = 10^4 \text{ GeV}^2, \ s_0 = 1 \text{ GeV}^2\) and \(\Delta p_{max}(s) = 0.05\). Inserting the numerical values discussed above then gives

\[
A(t \simeq 0, M_X^2, z_c) \simeq 0.45 \left( \frac{s_{pp}}{M_X^2} \right)^{-0.25} \frac{2 z_c - 1}{z_c^2 + (1 - z_c)^2} ,
\]

(17)

which for a typical value of \(\frac{s_{pp}}{M_X^2} = 100\) becomes a \(\sim 15\%\) asymmetry for large \(z_c\) as illustrated in Fig. [4]. We also note that the asymmetry can be integrated over \(z_c\) giving

\[
A(t \simeq 0, M_X^2) = \int_{0.5}^{1} A(t \simeq 0, M_X^2, z_c) - \int_{0}^{0.5} A(t \simeq 0, M_X^2, z_c) \approx 0.3 \left( \frac{s_{pp}}{M_X^2} \right)^{-0.25} .
\]

(18)

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
FIG. 4. The asymmetry in fractional energy $z_c$ of charm versus anticharm jets predicted by our model using the Donnachie-Landshoff Pomeron for $\alpha_P = 1.2$, $\alpha_O = 0.95$ and $s_{\gamma p}/M_X^2 = 100$.

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. [27]) and this could also be true for the hard Odderon.

There is also a small irreducible asymmetry from photon-Pomeron interference. Adding the photon exchange amplitude to the Odderon amplitude modifies the asymmetry as follows (again only taking into account the Dirac form-factor),

$$A(t \simeq 0, M_X^2, z_c) = 2 \frac{\sin \frac{\pi \alpha_P}{2}}{\kappa_{pp'}^P \kappa_{p'}^{CC}} \left( \frac{s_{\gamma p}}{M_X^2} \right)^{1-\alpha_P} \frac{2z_c - 1}{z_c^2 + (1 - z_c)^2} \left\{ -\kappa_{pp'}^O \kappa_{g}^{CC} \left( \frac{s_{\gamma p}}{M_X^2} \right)^{\alpha_O-1} \frac{2 \sin \left[ \pi \left( \alpha_O - \alpha_P \right) \right]}{\pi (\Delta_O + \alpha'_O t)} + \frac{12 e^2}{3} \frac{\cos \pi \alpha_P}{t} \right\}.$$

where $\alpha_O = 1 + \Delta_O + \alpha'_O t$ has been used to expand the pole-factor for the Odderon, $\cos \frac{\pi \alpha_O}{2} \simeq -\frac{\pi}{2} (\Delta_O + \alpha'_O t)$, for small $t$. Note that if $\Delta_O = 0$ then the Odderon amplitude appears to have a $1/t$ pole just as photon exchange. However this pole must be screened by an effective mass for the corresponding 3-gluon state. The extra factor $1/3$ for photon exchange reflects the relative factor of 3 for the Pomeron/Odderon couplings to the proton [28]. Using the soft
Pomeron-proton coupling \[21\] to estimate \(\kappa_{pp}^{P}, \kappa_{P}^{cc}/\sin \frac{\pi \alpha_{P}}{2} \simeq 3.4 \text{ GeV}^{-2}\) gives the minimal asymmetry from photon-Pomeron interference (neglecting the Odderon contribution),

\[
A_{\gamma P}(t \simeq 0, z_{c}) \simeq -\frac{0.002}{t} \frac{2z_{c} - 1}{z_{c}^{2} + (1 - z_{c})^{2}} \text{GeV}^{2},
\]

where we again have used \(\frac{s_{\gamma p}}{M_{X}^{2}} = 100\) and \(\alpha_{P} = 1.2\). Thus for very small \(t\) the photon-Pomeron interference can be sizeable, but for larger \(t\) it is presumably negligible compared to Odderon-Pomeron interference.

In specific models, such as diquark clustering in the proton \[11\], the Odderon coupling to the proton in diffractive dissociation is expected to be larger. In such a scenario the asymmetry from Odderon-Pomeron interference will be correspondingly larger for proton dissociation.

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 and possibly COMPASS 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.

**ACKNOWLEDGMENTS**

C. M. thanks the Theory Group at SLAC for their kind hospitality and Prof. C. Pajares of the University of Santiago de Compostela, the Director of the research project which partially financed this work. We would also like to thank Markus Diehl for conversations.
REFERENCES

[1] J. Kwiecinski and M. Praszalowicz, Phys. Lett. 94B (1980) 413; J. Bartels, Nucl. Phys. B 175 (1980) 365.
[2] L. Lukaszuk and B. Nicolescu, Nuovo Cimento Letters 8 (1973) 405.
[3] P. Gauron, L.N. Lipatov, and B. Nicolescu, Z. Phys. C63 (1994) 253.
[4] N. Armesto and M.A. Braun, Z. Phys. C75 (1997) 709.
[5] R.A. Janik and J. Wosiek, Phys. Rev. Lett. 82 (1999) 1092.
[6] M.A. Braun, P. Gauron, and B. Nicolescu, [hep-ph/9809567].
[7] E.A. Kuraev, L.N. Lipatov, and V.S. Fadin, Sov. Phys. JETP 44 (1976) 443; Sov. Phys. JETP 45 (1977) 199.

Y.Y. Balitski and L.N. Lipatov, Sov. J. Nucl. Phys. 28 (1978) 822.
[8] P.V. Landshoff and O. Nachtmann, [hep-ph/9808233].
[9] B. Nicolescu, [hep-ph/9810465].
[10] A. Schäfer, L. Mankiewicz and O. Nachtmann, in proceedings ‘Physics at HERA’, Eds. W. Buchmüller, G. Ingelman, DESY Hamburg 1992, vol. 1, p. 243-251; J. Czyzewski, J. Kwiecinski, L. Motyka and M. Sadzikowski, Phys. Lett. B398 (1997) 400; Erratum-ibid. B411 (1997) 402; R. Engel, D.Y. Ivanov, R. Kirschner and L. Szymanowski, Eur. Phys. J. C4 (1998) 93; E.R. Berger et al., [hep-ph/9901376].
[11] M. Rueter, H.G. Dosch and O. Nachtmann, Phys. Rev. D59 (1999) 014018.
[12] W. Kilian and O. Nachtmann, Eur. Phys. J. C5 (1998) 317.
[13] I.F. Ginzburg, D.Y. Ivanov and V.G. Serbo, Phys. Atom. Nucl. 56 (1993) 1474.
[14] A. Breakstone et al., Phys. Rev. Lett. 54 (1985) 2180.
[15] P.V. Landshoff, Phys. Rev. D10 (1974) 1024.
[16] H1 Collaboration, T. Ahmed et al., Nucl. Phys. B429, 477 (1994); Phys. Lett. B348 (1995) 681; C. Adloff et al., Z. Phys. C74 (1997) 221. ZEUS Collaboration, M. Derrick et al., Phys. Lett. B315 (1993) 481; J. Breitweg et al., Z. Phys. C75 (1997) 421; Eur. Phys. J. C2 (1998) 237.
[17] S.J. Brodsky, L. Frankfurt, J.F. Gunion, A.H. Mueller, and M. Strikman, Phys. Rev. D50 (1994) 3134.
[18] A. Capella, A.B. Kaidalov, C. Merino, and J. Tran Thanh Van, Phys. Lett. B337 (1994) 358; A. Capella, A.B. Kaidalov, C. Merino, D. Petermann, and J. Tran Thanh Van, Phys. Rev. D53 (1996) 2309.
[19] P.D.B. Collins, An introduction to Regge theory and high energy physics, Cambridge University Press (1977).
[20] A.B. Kaidalov, Phys. Rep. 50 (1979) 157.
[21] A. Donnachie and P.V. Landshoff, Nucl. Phys. B 244 (1984) 322; ibid. B 267 (1986) 690; Phys. Lett. B185 (1987) 403.
[22] S.J. Brodsky and J. Gillespie, Phys. Rev. 173 (1968) 1011.
[23] C.C.C. Ting, Proceedings of the International School of Physics Ettore Majorana, Erice (Trapani), Sicily, July 1967.

J.G. Ashbury et al., Phys. Lett. B25 (1967) 565.
[24] H1 Collaboration, C. Adloff et al., [hep-ex/9903008]; A. Aid et al., Nucl. Phys. B472
(1996) 3.
ZEUS Collaboration, J. Breitweg et al., Z. Phys. C75 (1997) 215; ibid. C76 (1997) 599.
See also H1 Collaboration, “Energy Dependence of the Cross Section for the Exclusive Photoproduction of J/Psi Mesons at HERA”, Conf. Paper 572.2, 29th Intern. Conf. on High-Energy Physics, Vancouver, Canada (1998), and ZEUS Collaboration, “Study of Vector Meson production at Large |t| at HERA and Determination of the Pomeron Trajectory”, Conf. Paper 788, 29th Intern. Conf. on High-Energy Physics, Vancouver, Canada (1998).

[25] M. Diehl, Eur. Phys. J. C6 (1999) 503, hep-ph/9803290.
[26] H.A. Bethe, and L.C. Maximon, Phys. Rev. 93 (1954) 768; H. Davies, H.A. Bethe, and L.C. Maximon, Phys. Rev. 93 (1954) 788.
[27] S.J. Brodsky, F. Hautmann and D.E. Soper, Phys. Rev. D56 (1997) 6957.
[28] P.V. Landshoff and J.C. Polkinghorne, Nucl. Phys. B 32 (1971) 541; G.A. Jaroszkiewicz and P.V. Landshoff, Phys. Rev. D10 (1974) 170.