Odderon and Photon exchange in pseudoscalar meson production

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We consider exclusive $\pi^0$ production in ep-scattering. At high energies odderon and photon exchange contribute. The photon exchange contribution is evaluated exactly using data for the total virtual photon-proton absorption cross section. The odderon exchange contribution is calculated in nonperturbative QCD, using functional integral techniques and the model of the stochastic vacuum. For the proton we assume a quark-diquark structure as suggested by the small odderon amplitude in $pp$ and $p\bar{p}$ forward scattering. We show that odderon exchange leads to a much larger inelastic than elastic $\pi^0$ production cross section. Observing our process at HERA would establish the soft odderon.

1. Introduction

The soft (nonperturbative) odderon $O$ is introduced in elastic hadron-hadron scattering as the $C = P = -1$ partner of the pomeron $P$ [1]. In perturbation theory the existence of $C = P = -1$ contributions is clear (3-gluon exchange). It is even believed [2], that 3-gluon exchange dominates the $pp$-scattering amplitude $T_{pp}$ for momentum transfers $|t| \gtrsim 4 \text{ GeV}^2$. On the other hand, for $|t| \rightarrow 0$ it seems that odderon contributions play no role asymptotically or even are absent. An example is the measurement of $\rho_{pp} = \text{Re}(T_{pp})/\text{Im}(T_{pp})$ at $\sqrt{s} = 546 \text{ GeV}$ [3]. Together with $pp$ scattering data at smaller energies one deduces $|\rho_{pp} - \rho_{p\bar{p}}| \leq 0.05$. In other words the soft odderon couples very weakly to the nucleon.

Since soft elastic high energy scattering is totally dominated by the pomeron, it is useful to look at a reaction where pomeron exchange does not contribute. In the following we discuss some results of [4] considering exclusive $\pi^0$ production in high energy $ep$-scattering. The $\pi^0$ is produced (see Fig. 1) by $\gamma O$-fusion and by $\gamma \gamma$-fusion, but can not be produced by $\gamma P$-fusion since the $\pi^0$ has positive $C$-parity. In Fig. 1 X stands for a proton or resonances or a sum over resonances. Here we treat the very small $Q^2 := -q_2^2$ range. In the H1 experiment at HERA the kinematical cuts for this so called photoproduction region are

$$y_{\text{min}} \leq y \leq 0.7 = y_{\text{max}},$$
$$0 < Q^2 < 0.01 \text{ GeV}^2,$$

where, in the proton rest frame $y = (pq_1)/(pp_1)$ is the fractional energy loss of the incoming lepton. This allows us to use the equivalent photon approximation

$$\sigma_{ep} = \int_{y_{\text{min}}}^{y_{\text{max}}} \frac{dy}{y} n(y) \sigma_{\gamma p}(s_2),$$
$$s_2 = ys + (1 - y)m_p^2,$$

where $m_p$ is the nucleon mass, $\sigma_{\gamma p}$ is the total
photoproduction cross section for the reaction, and \( n(q) \) is the equivalent photon number.

2. Odderon exchange

We look at \( \gamma p \)-scattering in the c.m. system and choose \( \vec{q}_1 \) as 3-direction. Then the photon and the proton have very large momenta in \( \pm 3 \)-direction. In the following we discuss the cases, (i) that the proton, which is assumed to be a quark-diquark system with a scalar diquark stays intact or (ii) gets diffractively exited into the resonances \( N(1520) \) with \( J^P = \frac{3}{2}^- \) and \( N(1535) \) with \( J^P = \frac{1}{2}^- \), described as exited quark-diquark systems.

When considering unpolarised cross sections, summed over both resonances in case (ii), the quark spin degree of freedom becomes irrelevant and the calculation reduces to one where a spinless state stays intact or is exited to a 2P resonance. For (ii) the helicity amplitudes are

\[
T(s_2, t_2)_{\lambda, \lambda, \gamma} = -2i s_2 \int \frac{d^3 b}{4\pi} e^{i\vec{q}_2 \cdot \vec{r}_2} \hat{J}_{\lambda, \lambda, \gamma}(\vec{b}),
\]

\[
\hat{J}(\vec{b})_{\lambda, \lambda, \gamma} = \int \frac{d^2 r_1}{4\pi} dz \int \frac{d^2 r_2}{4\pi} \times \sum_{f_{h_1, h_2}} \Psi^*_{\lambda, f_{h_1, h_2}}(\vec{r}_1, z) \Psi_{\lambda, f_{h_1, h_2}}(\vec{r}_1, z) \times \Psi_{\lambda, 2P}(\vec{r}_2) \Psi_{p}(\vec{r}_2) \hat{J}(\vec{b}, \vec{r}_1, z, \vec{r}_2).
\]

Here \( \lambda, (\lambda) \) is the helicity of the photon (2P state) and \( z \) is the momentum fraction of the photon, carried by the quark. The physical picture arising from (3) is the following (Fig. 2). The photon fluctuates into a \( q \bar{q} \) pair, described by \( \Psi^* \). By soft colour interaction (odderon exchange), calculated from the functional integral of two lightlike Wegner-Wilson loops (\( \hat{J} \)) the \( q \bar{q} \) pair turns into a \( \pi^0 \) and the proton either stays intact or is exited (described by \( \Psi_{2P} \)).

Now, when the proton stays intact there occurs in (3) the quark-diquark density \( \Psi_{\lambda, 2P} \rightarrow \Psi_{p} \). But, since this density is symmetric under a parity transformation whereas the odderon coupling changes sign, there is a cancellation when we integrate over all angles. On the other hand when the proton gets exited to a negative parity state like the resonances \( N(1520) \) and \( N(1535) \) there is no cancellation (the overlap is odd under parity) and the odderon couples to the nucleon without any restriction [4,5]. Thus in our model the odderon couples only if breakup of the proton occurs.

2.1. Results

In Fig. 3 we show our result for the differential cross section in \( \gamma p \)-scattering, \( d\sigma / dt \). The slope of \( d\sigma / dt \) at \( t = 0 \) is around \( 5/\text{GeV}^2 \). The integrated cross section is [4]:

\[
\sigma_{\gamma p}(\gamma p \rightarrow \pi^0\{2P\}) = 294 \text{ nb.}
\]

As this photoproduction cross section is constant, i.e. independent of \( s_2 \), the EPA conversion to
electroproduction can be achieved by simply multiplying it with a constant $c_{\text{EPA}} = 0.0136$ corresponding to the $y$ integration in (2). This gives

$$\sigma^O(ep \to e\pi^0\{2P\}) = 4010 \text{ pb}.$$  \hspace{1cm} (5)

In the following we consider only $ep$-scattering. An experimentally preferred observable is the $k_T$ spectrum, the transverse momentum distribution of the $\pi^0$ with respect to the beam direction. At HERA $k_T$ distributions can be measured for values of $k_T$ greater than $O(0.1 \text{ GeV})$. The photo-production cuts of (1) restrict the transverse momentum of the incident photon to be smaller than $O(0.1 \text{ GeV})$, so in our case there is practically no distinction between the beam axis and the photon axis. The $k_T$ spectrum is displayed in Fig. 4.

![Figure 4. The $k_T$ distribution in pion production from the 2P resonance channels for odderon exchange (solid line) compared to the complete electromagnetic result (dashed line). Interference contributions are not taken into account.](image)

3. Photon exchange

In this section we consider PS production mediated by photon rather than odderon exchange (Fig. 1). Again the proton, now hit by the photon, is allowed to go into some hadron final state $X$. The process has been calculated in [6] for $X$ being a proton. In [4] we have calculated the cross section, when $X$ is a hadron final state in the invariant mass ($M_X$) range $1.11 \leq M_X \leq 1.99 \text{ GeV}$. In Fig. 4 we show the distribution of the pion’s $k_T$ summed over the elastic and all inelastic channels for the electromagnetic exchange. As we can see there the photon exchange is larger than the odderon exchange only for very small $k_T$. For $k_T \gtrsim 0.1 \text{ GeV}$ the Odderon exchange dominates by orders of magnitude. The integrated cross section is [4]:

$$\sigma^\gamma(ep \to e\pi^0\{p+X\}) = 80.1 \text{ pb}.$$  \hspace{1cm} (6)

which has to be compared with the odderon cross section (4).

In addition we have estimated in [4] contributions from reggeon ($\omega$) exchange and from a possible background process, namely an additional final state photon emitted from the $\pi^0$ vertex (Fig. 1), where we have used realistic cuts. Both contributions are of the same order of magnitude as the photon exchange contribution.

The conclusion is: With the large odderon cross section as given in our model the process should be observable at HERA. This would establish the soft odderon as an exchange-object in high energy scattering on an equal footing with the soft pomeron.

REFERENCES