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Search for odderon-induced contributions to exclusive π^0 photoproduction at HERA

H1 Collaboration

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Abstract

A search for contributions to the reaction $ep \to e\pi^0 N^*$ from photon–odderon fusion in the photoproduction regime at HERA is reported, at an average photon–proton centre-of-mass energy $\langle W \rangle = 215$ GeV. The measurement proceeds via detection of the π^0 decay photons, a leading neutron from the N^* decay, and the scattered electron. No π^0 signal is observed and an upper limit on the cross section for the photon–odderon fusion process of $\sigma(\gamma p \to \pi^0 N^*) < 49$ nb at the 95% confidence level is derived, integrated over the experimentally accessible range of the squared four-momentum transfer at the nucleon vertex $0.02 < |t| < 0.3$ GeV^2. This excludes a recent prediction from a calculation based on a non-perturbative QCD model of a photon–odderon fusion cross section above 200 nb.

1. Introduction

Despite the many successes of quantum-chromodynamics (QCD) in describing hard strong interactions, the bulk of hadronic cross sections remain relatively poorly understood. A conjecture by Pomeranchuk, known as the Pomeranchuk theorem [1], states that, for asymptotically large energies, the difference between hadron–hadron and hadron–antihadron total cross sections vanishes. This behaviour is explained by the dominant exchange of the Pomeranchuk trajectory, the "pomeron" $\mathbb{P}$, between the scattering particles. The pomeron trajectory carries the quantum numbers of the vacuum and is characterized by an intercept $\alpha_{\mathbb{P}}(0) \approx 1.08$ [2], leading to an approximate energy independence of the elastic and—via the optical theorem—the total cross sections ($\sigma_{tot} \sim s^{\alpha_{\mathbb{P}}(0)-1}$, s being the square of the centre of mass energy). It has been suggested, however, that a partner of the pomeron with odd parity P and charge conjugation parity C, the "odderon" $\mathbb{O}$ [3–5], exists. Such an additional $C = P = -1$ exchange contributes with opposite signs to the particle–particle and particle–antiparticle scattering amplitudes, creating a finite cross section difference at high energy if the corresponding odderon trajectory has an intercept $\alpha_{\mathbb{O}}(0)$ close to 1. However, in the explored energy range and within the accuracy of the present data [6], no difference remains at high energies between the measured total cross sections for proton–proton and proton–antiproton interactions. Hence, any difference between the cross sections must be small, necessitating a more sensitive search for the odderon. Within QCD, the pomeron is modelled, to lowest order, as a two gluon exchange in a net colour singlet state. Similarly a net colour singlet three gluon exchange, which is predicted by QCD, can be associated with the odderon. In perturbative QCD exact solutions for the odderon intercept have been found [7]. The search for the odderon has therefore become an additional part of the QCD tests to be performed at HERA, and expectations for its discovery are high.

Since hadron–hadron scattering at high energies is generally dominated by pomeron exchange, an odderon contribution is best searched for in final states with quantum numbers to which pomeron exchange cannot contribute. One possibility is the exclusive production of pseudoscalar mesons at HERA via photon–odderon fusion. The measurement presented here uses the H1 detector [8] to study exclusive π^0 photoproduction in the reaction (see Fig. 1)

$$ep \to e\pi^0 N^*, \tag{1}$$

where the photon virtuality is kept very small. The proton is excited to an ($I = 1/2$)-isobar with negative parity, which subsequently decays into a final state

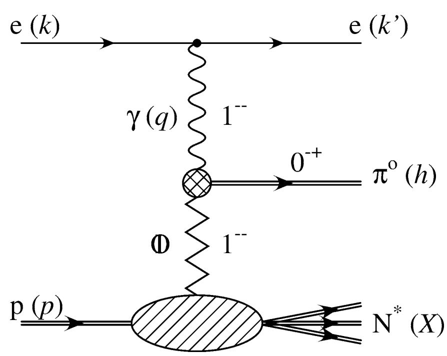

Fig. 1. Diagram for the process $ep \to e\pi^0 N^*$: the proton is excited into an ($I = 1/2$)-isobar while a high energy single π^0 is produced by photon–odderon fusion.

containing a highly energetic neutron. In this exclusive reaction the scattered electron, the two photons from the π^0 decay, and the leading neutron from the N^* decay are detected. The remaining decay products of the N^* go undetected.

A calculation by Berger et al. [9] predicts a sizeable cross section for the photoproduction process $\gamma p \to \pi^0 N^*$. For this prediction a model in the framework of non-perturbative QCD, the Stochastic Vacuum Model (SVM) [10], was extended and applied to high energy scattering by functional methods [11]. The proton is treated as a quark–diquark system in transverse space. A large variety of high energy reactions has been described successfully with this model, including data from HERA [12]. For $\gamma p \to \pi^0 N^*$, a cross section of about 300 nb is predicted [9] at a photon–proton centre of mass energy of $W = 20$ GeV, with an uncertainty of about a factor of 2 [9,13]. The energy dependence of the process is not predicted by the model. However, assuming that odderon exchange leads to a cross section that is flat or rises with energy, the cross section at HERA is expected to be at least 300 nb. For an energy dependence $\propto (W^2)^{0.15}$ [9] the cross section at HERA would be a factor of approximately two larger than that at $W = 20$ GeV.

2. Detector description

The analysis presented here is based on data taken with the H1 detector [8] at HERA in 1999 and 2000 where electrons (or positrons) with an energy of 27.5 GeV collided with protons of 920 GeV energy. The data used for this analysis correspond to an integrated luminosity of 30.6 pb^{-1}. In the following a short overview is given of the essential detector components of H1 used in this analysis.

Electrons are identified at $z = -33.4$ m in the electron tagger [19] which is a crystal Cherenkov calorimeter with 49 channels, a total transverse size of $15.4 \times 15.4\ \text{cm}^2$ and a depth of 22 radiation lengths.

[19] The proton beam points to the "forward" ($+z$) direction, where $z = 0$ corresponds to the nominal interaction point. Polar angles θ are measured with respect to this direction.

The study presented here is the first published analysis based on the Very Low Q^2 calorimeter ("VLQ") [14]. Originally constructed for the detection of scattered electrons in the transition region between the deep inelastic scattering (DIS) and photoproduction regimes, the VLQ is sensitive in the range $0.02 < Q^2 < 1\ \text{GeV}^2$. Here Q^2 is the modulus of the squared four-momentum transfer between the incoming and scattered electrons. The VLQ is used here as a photon detector. It is situated at $z = -3.02$ m and covers the polar angular range $177.3^\circ < \theta < 179.4^\circ$. The VLQ is a tungsten-scintillator strip sandwich calorimeter with a "projective readout" [14]. Its total thickness amounts to 16.7 radiation lengths, and its Molière radius is 1.25 cm. It consists of two identical modules which are located above and below the beam pipe. Each module is read out at either end by photodiodes. The energy and position resolution for electromagnetic showers are $\sigma_E/E = 0.19/\sqrt{E/\text{GeV}} \oplus 0.064 \oplus 0.23/(E/\text{GeV})$ and $\sigma_x = \sigma_y = (2.1\ \text{mm})/\sqrt{E/\text{GeV}}$, respectively. The double photon resolution is 1.5 cm, which is sufficient to separate the photons from the decay of a 50 GeV π^0. This distance is much smaller than the minimal separation in the VLQ of 4 cm for the two photons from decays of π^0 mesons with an actual maximum energy of 20 GeV. From an investigation of samples of QED Compton events ($ep \to ep\gamma$) the absolute positions of the VLQ modules are known to better than 1 mm and the energy scale is determined with an uncertainty of $\pm 4\%$ [15].

The SpaCal ("Spaghetti Calorimeter") [16] is a lead-scintillating fibre calorimeter which is positioned at $z \approx -1.55$ m and covers the polar angular range $153^\circ < \theta < 178^\circ$ with an energy resolution of $\sigma_E/E = 0.075/\sqrt{E/\text{GeV}} \oplus 0.010$, a polar angular resolution better than 2.5 mrad for energies above 1 GeV and an energy scale uncertainty of $\pm 4\%$.

The Forward Neutron Calorimeter (FNC) [17], located at $z = +107$ m in the HERA tunnel, detects high-energy neutrons. The acceptance, determined using inclusive events with a leading neutron [17], is $\approx 90\%$ for scattering angles of $\theta \lesssim 0.1$ mrad and vanishes above 0.6 mrad.

The tracking system consists of 2 m long coaxial cylindrical central drift chambers ($25^\circ < \theta < 155^\circ$), a forward tracking detector ($7^\circ < \theta < 25^\circ$) and a backward drift chamber in front of the SpaCal. The

Liquid Argon (LAr) calorimeter ($4^\circ < \theta < 154^\circ$) surrounds the central and the forward trackers.

3. Event selection

The relevant Lorentz-invariant kinematical variables for process (1) are Q^2, the inelasticity y and the squared four-momentum transfer t at the nucleon vertex. The quantity y denotes the fractional energy transfer from the electron to the proton in the rest frame of the proton and is calculated as $y = (q \cdot p)/(k \cdot p) \approx 1 - E'/E$ where q, p and k are the four-momenta of the quasi-real photon, the target proton and the incident lepton and E (E') is the energy of the incoming (scattered) electron. The variable $t = (p - X)^2$, where X is the four-momentum of the outgoing N^*, can be reconstructed from the squared transverse momentum of the π^0 candidate as $t \simeq -h_\perp^2$ (see Fig. 1).

Candidate events for the reaction (1) are selected through the detection of an electron scattered through a very small angle, of two photons with combined invariant mass consistent with a π^0, and of a high energy neutron in the forward direction. Scattered electrons with energies between 8.25 GeV and 19.25 GeV, corresponding to $0.3 < y < 0.7$ and $Q^2 < 0.01\ \mathrm{GeV}^2$, were selected with the electron tagger. Odderon-induced π^0 production is expected very close to the beam pipe in the backward direction due to the small values of t and the large photon energy. Two electromagnetic calorimeters covering different regions in polar angle in the backward region are therefore used to detect photons from the π^0 decay, reconstructed as two separate clusters. Photons in the SpaCal or the VLQ are selected by requiring a narrow cluster with an energy well above the noise levels, i.e., larger than 90 MeV or 2 GeV, respectively. For trigger reasons at least one of the photons must be reconstructed in the VLQ, with a total energy of at least 6 GeV in one VLQ module. The intermediate excited nucleonic state N^* is selected by demanding a neutron in the FNC with an energy above 200 GeV.

No activity is allowed in the central detectors of H1, i.e., the tracking chambers and the Liquid Argon calorimeter, and no additional energy deposition apart from the two photon candidates is allowed in the VLQ or SpaCal calorimeters. Events with charged particles measured in the central tracking detectors in the range $20^\circ < \theta < 160^\circ$ are rejected. Due to the absence of charged particles in the selected exclusive π^0 candidate events, the interaction vertex cannot be reconstructed, and the event kinematics are calculated using the mean interaction vertex as the origin.

If no particles escape undetected, the variable $\sum_i (E - P_z)_i$, where i runs over all final state particles detected in the backward direction, namely the scattered electron and the two photons from the π^0 decay, assumes a value equal to twice the electron beam energy within detector resolution effects. A cut of $49\ \mathrm{GeV} < \sum_{i=e',\gamma,\gamma} (E - P_z)_i < 60\ \mathrm{GeV}$ serves to reject events with additional particles emitted unobserved in the backward direction, including photons from QED radiation. For a more detailed description of the event selection see [18].

4. Monte Carlo models

The process (1) and its expected backgrounds are simulated using the OPIUM [19] and PYTHIA [20] event generators. The OPIUM generator is derived from DIFFVM [21], which was originally designed to simulate exclusive vector mesons produced by pomeron exchange. This generator has been extended to OPIUM to include odderon exchange with an exclusive π^0 in the final state according to the prescription in [9]. The t dependence of the cross section is as given in [9] and is approximately proportional to e^{bt} with a slope of $b = 5.44\ \mathrm{GeV}^{-2}$.

PYTHIA [20] is used to simulate the background from inclusive γp interactions which mainly consists of low multiplicity events with a neutral pion in the final state together with further unobserved particles, for example events from exclusive ω or ρ^0 photoproduction where the vector meson decays into $\pi^0\gamma$. Contributions to elastic single π^0 production from reggeon exchange (ω-trajectory[20]) or $\gamma\gamma$ fusion ("Primakoff effect") [9] are negligible.

Since the hadronisation model applied in PYTHIA gives rise to a few processes which do not conserve isospin, a modified version of the program, referred to as "PYTHIA-mod", is also used for the background

[20] Measurements [23] at low energies ($W \approx 3$ GeV) were extrapolated to HERA energies.

description. Here, all processes violating isospin conservation are excluded. It is expected that the background is bounded by the predictions of these two versions of the model [22]. All Monte Carlo samples went through the same reconstruction procedure as the data.

5. Results

In order to demonstrate the capability to reconstruct π^0's in the backward calorimeters using the nominal interaction vertex only, Fig. 2 shows the two-photon invariant mass distribution for all events with two photons reconstructed in the VLQ, or one photon in the VLQ and one in the SpaCal, as well as a scattered electron in the electron tagger and a neutron in the FNC. The additional veto cuts on the activity in the central detectors of H1 and the variable $\sum_i (E - P_z)_i$ were not applied for this sample. A clear π^0 signal is observed. On the basis of this sample, two-photon candidates with combined invariant mass in the range $M_{\gamma\gamma} < 335$ MeV are accepted as neutral pion candidates.

Fig. 3 shows the $|t|$ distribution for exclusive π^0 candidate events with $M_{\gamma\gamma} < 335$ MeV after the full event selection. Mainly due to the limited angular coverage of the VLQ, the acceptance in $|t|$ vanishes at very small $|t|$, reaches a maximum at $|t| \approx 0.05$ GeV^2 and drops again at larger $|t|$ values.

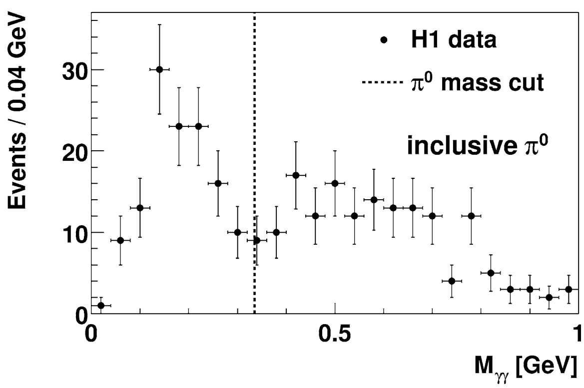

Fig. 2. Invariant mass distribution of two-photon candidates for all events with both photons in the VLQ, or one photon in the VLQ and one photon in the SpaCal. No restrictions are made on additional particles produced in the phase space region not covered by the VLQ and SpaCal (for full selection criteria, see text). The dashed line indicates the cut on $M_{\gamma\gamma}$ applied in the exclusive analysis.

A cut of $0.02 < |t| < 0.3$ GeV^2 is used to define the accessible $|t|$ range and changes the predicted cross section [9] $\sigma(\gamma p \to \pi^0 N^*)$ via $\gamma\mathbb{O}$ fusion by a factor of approximately 2/3, such that the measurable cross section is expected to remain above 200 nb.

Fig. 4 shows the distribution of the two-photon invariant mass $M_{\gamma\gamma}$ after the complete event selection, including the $|t|$ cut. A total of 10 events containing two-photon candidates with invariant mass $M_{\gamma\gamma} <$

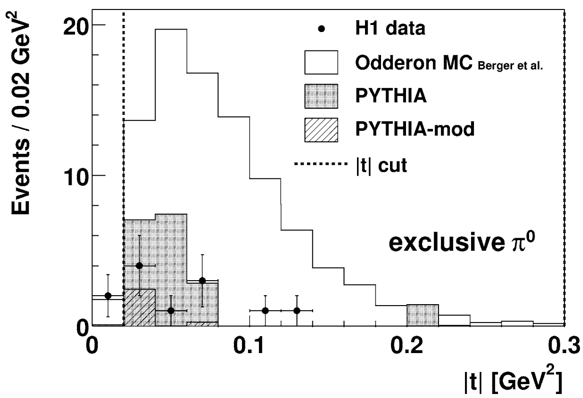

Fig. 3. Measured t distribution for odderon candidate events with $M_{\gamma\gamma} < 335$ MeV. The background expectation from PYTHIA and PYTHIA-mod are also shown together with the predicted number of odderon-induced events [9]. In the final selection the two events in the first bin are rejected due to the acceptance cut $|t| > 0.02$ GeV^2.

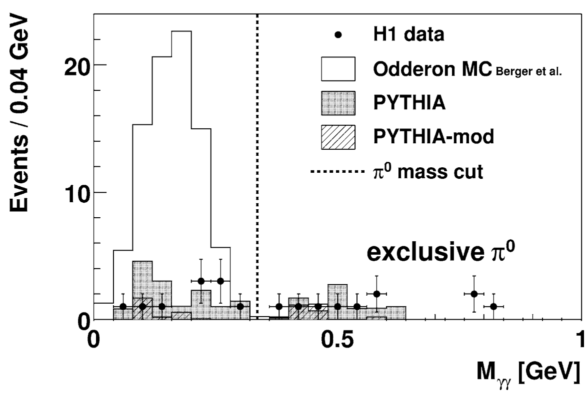

Fig. 4. Invariant mass distribution of two-photon candidates for exclusive events with both photons in the VLQ, or one photon in the VLQ and one photon in the SpaCal (for selection criteria see text). The backgrounds computed from the PYTHIA and PYTHIA-mod models are also shown together with the distribution for odderon exchange predicted from [9] where the experimentally observed width of the π^0 signal is taken from the inclusive π^0 sample (see Fig. 2).

335 MeV remains, and no π^0 peak is observed. The background estimates from PYTHIA and PYTHIA-mod are 12 and 3 events, respectively. The measured data are found to be consistent with the simulated background from PYTHIA or PYTHIA-mod, both in magnitude and shape. By varying the normalization of the PYTHIA-mod simulation by $\pm 100\%$ and by estimating the background from the PYTHIA-mod prediction or the data for $M_{\gamma\gamma} > 335$ MeV, the background is estimated to be below 12 events. From the photon–odderon fusion model [9] described above, assuming the cross section has no dependence on W, 90 events are expected.

In order to reduce the model dependence in limit calculations, the PYTHIA predictions are disregarded and a background of zero events is assumed. Within this most conservative scenario an upper limit for the cross section of reaction (1) is determined, using the statistical method described in [24,25]. In addition to the statistical uncertainties in the data a systematic uncertainty of 25% is taken into account. The latter arises mainly from the acceptances of the forward neutron calorimeter (20%), the electron tagger (5%) and the VLQ (4%). To calculate the limit for negative parity N^* production the four dominant states are considered: $N(1535)$ and $N(1650)$ (pion and neutron in relative S-wave), and $N(1520)$ and $N(1700)$ (pion and neutron in D-wave), as also used in the theoretical estimate [9]. Higher mass negative-parity states and nucleon resonances with positive parity might also contribute to the final event sample. Since these contributions are not subtracted, the limit derived from the sample is a conservative upper bound to be compared to the theoretical prediction. Table 1 summarizes the branching ratios, acceptances and efficiencies used to determine the limit on the γp cross section, which is extracted [26,27] by calculating a limit for the ep cross section and dividing by a photon flux factor integrated over the kinematic region $Q^2 < 0.01$ GeV^2 and $0.3 < y < 0.7$. Assuming a slope of $b = 5.44$ GeV^{-2} for the differential cross section $d\sigma/dt$ as given in [9], the limit for the photoproduction cross section integrated over the accessible $|t|$ range $0.02 < |t| < 0.3$ GeV^2 is

$$\sigma_{\gamma p \to \pi^0 N^*}(\gamma \mathbb{O} \text{ fusion}) < 49 \text{ nb} \quad (95\% \text{ CL}) \tag{2}$$

at an average γp centre-of-mass energy $\langle W \rangle = 215$ GeV. The limit changes by $+29\%$ (-17%) for a slope b of 3 GeV^{-2} (8 GeV^{-2}) instead of 5.44 GeV^{-2}.

The derived limit is clearly incompatible with the predicted value [9] of at least 200 nb for this kinematical range at HERA energies.

Table 1
Summary of branching ratios, acceptances and efficiencies with the respective errors necessary for the determination of the limit on the cross section (2)

$\mathrm{BR}(N^* \to n + X)$	$(42 \pm 3)\%$
$\mathrm{BR}(\pi^0 \to \gamma\gamma)$	$(98.80 \pm 0.03)\%$
Neutron acceptance	$(11 \pm 2)\%$
π^0 acceptance	$(6.0 \pm 0.3)\%$
Electron acceptance	$(40 \pm 3)\%$
FNC trigger efficiency	$(98 \pm 1)\%$
VLQ trigger efficiency	$(95 \pm 2)\%$
Photon flux factor	0.0136

6. Conclusion and outlook

A first search for events produced through odderon exchange in the process $ep \to e\pi^0 N^*$ is reported in the kinematical range $174 < W < 266$ GeV, $Q^2 < 0.01$ GeV^2 and $0.02 < |t| < 0.3$ GeV^2. No π^0 signal is observed and the number of reconstructed events containing two photons with invariant mass in the π^0 region is found to be compatible with background estimates. An upper limit for the photoproduction cross section of $\sigma_{\gamma p \to \pi^0 N^*}(\gamma \mathbb{O}$ fusion$) < 49$ nb is derived, which depends only weakly on the details of the production mechanism.

An odderon-induced process for exclusive π^0 production of the magnitude predicted by Berger et al. [9] is not compatible with the data. There are two possible interpretations of this result within the assumptions of [9]. The first is that the odderon intercept $\alpha_{\mathbb{O}}(0)$, which characterizes the energy dependence of the cross section, is considerably smaller than that of the pomeron. A value of $\alpha_{\mathbb{O}}(0) < 0.7$ would be compatible with the measurement and with alternative predictions [28]. The second interpretation is that the process is of diffractive nature but that the coupling at the $\gamma\mathbb{O}\pi$-vertex is smaller than anticipated in [9]. Further insight might come from a search for the production of heavier tensor mesons [13] or from charge asymmetry measurements in exclusive $\pi^+\pi^-$ production [29] or charm production [30].

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