"Study of the pion trajectory in the photoproduction of leading neutrons at HERA"

Chekanov, S.; Piotrzkowski, Krzysztof

Abstract

Energetic neutrons produced in $ep$ collisions at HERA have been studied with the ZEUS detector in the photoproduction regime at a mean photon-proton center-of-mass energy of 220 GeV. The neutrons carry a large fraction $0.64 < x_L < 0.925$ of the incoming proton energy, and the four-momentum-transfer squared at the proton-neutron vertex is small, $|t| < 0.425$ GeV$^2$. The $x_L$ distribution of the neutrons is measured in bins of $t$. The $(1-x_L)$ distributions in the $t$ bins studied satisfy a power law $dN/dx_L \propto (1-x_L)^{a(t)}$, with the powers $a(t)$ following a linear function of $t$: $a(t) = 0.88 \pm 0.09$ (stat.)$^{+0.34}_{-0.39}$ (syst.)$-(2.81 \pm 0.42$ (stat.)$^{+1.13}_{-0.62}$ (syst.) GeV$^{-2})t$. This result is consistent with the expectations of pion-exchange models, in which the incoming proton fluctuates to a neutron-pion state, and the electron interacts with the pion. Comment: 11 pages, 3 figures; revised analysis

Document type: Article de périodique (Journal article)

Référence bibliographique

DOI: 10.1016/j.physletb.2005.01.101
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ZEUS Collaboration
S. Chekanov, M. Derrick, D. Krakauer, J.H. Loizides, S. Magill, S. Miglioranzi, B. Musgrave, J. Repond, R. Yoshida

Argonne National Laboratory, Argonne, IL 60439-4815, USA

M.C.K. Mattingly

Andrews University, Berrien Springs, MI 49104-0380, USA

P. Antonioli, G. Bari, M. Basile, L. Bellagamba, D. Boschieri, A. Bruni, G. Bruni, G. Cara Romeo, L. Cifarelli, F. Cindolo, A. Contin, M. Corradi, S. De Pasquale, P. Giusti, G. Iacobucci, A. Margotti, A. Montanari, R. Nania, F. Palmonari, A. Pesci, G. Sartorelli, A. Zichichi

University and INFN Bologna, Bologna, Italy

G. Aghuzumtsyan, D. Bartsch, I. Brock, S. Goers, H. Hartmann, E. Hilger, P. Irrgang, H.-P. Jakob, O. Kind, U. Meyer, E. Paul, J. Rautenberg, R. Renner, A. Stifutkin, J. Tandler, K.C. Voss, M. Wang

Physikalisches Institut der Universität Bonn, Bonn, Germany

D.S. Bailey, N.H. Brook, J.E. Cole, G.P. Heath, T. Namsoo, S. Robins, M. Wing

H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom

M. Capua, A. Mastroberardino, M. Schioppa, G. Susinno

Calabria University, Physics Department and INFN, Cosenza, Italy
J.Y. Kim, I.T. Lim, K.J. Ma, M.Y. Pac

Chonnam National University, Kwangju, South Korea

A. Caldwell, M. Helbich, X. Liu, B. Mellado, Y. Ning, S. Paganis, Z. Ren, W.B. Schmidke, F. Sciulli

Nevis Laboratories, Columbia University, Irvington on Hudson, NY 10027, USA

J. Chwastowski, A. Eskreys, J. Figiel, A. Galas, K. Olkiewicz, P. Stopa, L. Zawiejski

Institute of Nuclear Physics, Cracow, Poland

L. Adamczyk, T. Bold, I. Grabowska-Bold, D. Kisielewska, A.M. Kowal, M. Kowal, J. Łukasik, M. Przybycień, L. Suszycki, D. Szuba, J. Szuba

Faculty of Physics and Nuclear Techniques, AGH-University of Science and Technology, Cracow, Poland

A. Kotański, W. Słomiński

Department of Physics, Jagellonian University, Cracow, Poland

V. Adler, U. Behrens, I. Bloch, K. Borras, V. Chiochia, D. Dannheim, G. Drews, J. Fourletova, U. Fricke, A. Geiser, P. Göttlicher, O. Gutsche, T. Haas, W. Hain, S. Hillert, C. Horn, B. Kahle, U. Kötz, H. Kowalski, G. Kramberger, H. Labes, D. Lelas, H. Lim, B. Löhr, R. Mankel, I.-A. Melzer-Pellmann, C.N. Nguyen, D. Notz, A.E. Nuncio-Quiroz, A. Polini, A. Raval, L. Rurua, U. Schneekloth, U. Stößlein, G. Wolf, C. Youngman, W. Zeuner

Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

S. Schlenstedt

DESY Zeuthen, Zeuthen, Germany

G. Barbagli, E. Gallo, C. Genta, P.G. Pelfer

University and INFN, Florence, Italy

A. Bamberger, A. Benen, F. Karstens, D. Dobur, N.N. Vlasov

Fakultät für Physik der Universität Freiburg i.Br., Freiburg i.Br., Germany
M. Bell, P.J. Bussey, A.T. Doyle, J. Ferrando, J. Hamilton, S. Hanlon, D.H. Saxon, I.O. Skillicorn

Department of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

I. Gialas

Department of Engineering in Management and Finance, University of Aegean, Greece

T. Carli, T. Gosau, U. Holm, N. Krumnack, E. Lohrmann, M. Milite, H. Salehi, P. Schleper, T. Schörner-Sadenius, S. Stonjek, K. Wichmann, K. Wick, A. Ziegler, Ar. Ziegler

Hamburg University, Institute of Experimental Physics, Hamburg, Germany

C. Collins-Tooth, C. Foudas, R. Gonçalo, K.R. Long, A.D. Tapper

Imperial College London, High Energy Nuclear Physics Group, London, United Kingdom

P. Cloth, D. Filges

Forschungszentrum Jülich, Institut für Kernphysik, Jülich, Germany

M. Kataoka, K. Nagano, K. Tokushuku, S. Yamada, Y. Yamazaki

Institute of Particle and Nuclear Studies, KEK, Tsukuba, Japan

A.N. Barakbaev, E.G. Boos, N.S. Pokrovskiy, B.O. Zhautykov

Institute of Physics and Technology of Ministry of Education and Science of Kazakhstan, Almaty, Kazakhstan

D. Son

Kyungpook National University, Center for High Energy Physics, Daegu, South Korea

K. Piotrzkowski

Institut de Physique Nucléaire, Université Catholique de Louvain, Louvain-la-Neuve, Belgium

F. Barreiro, C. Glasman, O. González, L. Labarga, J. del Peso, E. Tassi, J. Terrón, M. Zambrana

Departamento de Física Teórica, Universidad Autónoma de Madrid, Madrid, Spain

M. Barbi, F. Corriuveau, S. Gliga, J. Lainesse, S. Padhi, D.G. Stairs, R. Walsh

Department of Physics, McGill University, Montréal, PQ, H3A 2T8, Canada
T. Tsurugai

Meiji Gakuin University, Faculty of General Education, Yokohama, Japan

A. Antonov, P. Danilov, B.A. Dolgoshein, D. Gladkov, V. Sosnovtsev, S. Suchkov

Moscow Engineering Physics Institute, Moscow, Russia

R.K. Dementiev, P.F. Ermolov, I.I. Katkov, L.A. Khein, I.A. Korzhavina, V.A. Kuzmin, B.B. Levchenko, O.Yu. Lukina, A.S. Proskuryakov, L.M. Shcheglova, S.A. Zotkin

Moscow State University, Institute of Nuclear Physics, Moscow, Russia

N. Coppola, S. Grijpink, E. Koffeman, P. Kooijman, E. Maddox, A. Pellegrino, S. Schagen, H. Tiecke, M. Vázquez, L. Wiggers, E. de Wolf

NIKHEF and University of Amsterdam, Amsterdam, Netherlands

N. Brümmer, B. Bylsma, L.S. Durkin, T.Y. Ling

Physics Department, Ohio State University, Columbus, OH 43210, USA

A.M. Cooper-Sarkar, A. Cottrell, R.C.E. Devenish, B. Foster, G. Grzelak, C. Gwenlan, T. Kohno, S. Patel, P.B. Straub, R. Walczak

Department of Physics, University of Oxford, Oxford, United Kingdom

A. Bertolin, R. Brugnera, R. Carlin, F. Dal Corso, S. Dusini, A. Garfagnini, S. Limentani, A. Longhin, A. Parenti, M. Posocco, L. Stanco, M. Turcato

Dipartimento di Fisica dell’Università and INFN, Padova, Italy

E.A. Heaphy, F. Metlica, B.Y. Oh, J.J. Whitmore

Department of Physics, Pennsylvania State University, University Park, PA 16802, USA

Y. Iga

Polytechnic University, Sagamihara, Japan

G. D’Agostini, G. Marini, A. Nigro

Dipartimento di Fisica, Università ‘La Sapienza’ and INFN, Rome, Italy

C. Cormack, J.C. Hart, N.A. McCubbin

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, United Kingdom
C. Heusch
University of California, Santa Cruz, CA 95064, USA

I.H. Park
Department of Physics, Ewha Womans University, Seoul, South Korea

N. Pavel
Fachbereich Physik der Universität-Gesamthochschule Siegen, Germany

H. Abramowicz, A. Gabareen, S. Kananov, A. Kreisel, A. Levy
Raymond and Beverly Sackler Faculty of Exact Sciences, School of Physics, Tel-Aviv University, Tel-Aviv, Israel

M. Kuze
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

T. Fusayasu, S. Kagawa, T. Tawara, T. Yamashita
Department of Physics, University of Tokyo, Tokyo, Japan

R. Hamatsu, T. Hirose, M. Inuzuka, H. Kaji, S. Kitamura, K. Matsuzawa
Department of Physics, Tokyo Metropolitan University, Tokyo, Japan

M. Costa, M.I. Ferrero, V. Monaco, R. Sacchi, A. Solano
Università di Torino and INFN, Torino, Italy

M. Arneodo, M. Ruspa
Università del Piemonte Orientale, Novara, and INFN, Torino, Italy

T. Koop, J.F. Martin, A. Mirea
Department of Physics, University of Toronto, Toronto, ON, M5S 1A7, Canada

J.M. Butterworth, R. Hall-Wilton, T.W. Jones, M.S. Lightwood, M.R. Sutton, C. Targett-Adams
Physics and Astronomy Department, University College London, London, United Kingdom
Abstract

Energetic neutrons produced in ep collisions at HERA have been studied with the ZEUS detector in the photoproduction regime at a mean photon–proton center-of-mass energy of 220 GeV. The neutrons carry a large fraction $0.64 < x_L < 0.925$ of the incoming proton energy, and the four-momentum transfer squared at the proton–neutron vertex is small, $|t| < 0.425$ GeV$^2$. The $x_L$ distribution of the neutrons is measured in bins of $t$. The $(1 - x_L)$ distributions in the $t$ bins studied satisfy a power law $dN/dx_L \propto (1 - x_L)^{a(t)}$, with the powers $a(t)$ following a linear function of $t$: $a(t) = 0.88 \pm 0.09$ (stat.) $^{+0.13}_{-0.62}$ (syst.) GeV$^{-2} t$. This result is consistent with the expectations of
pion-exchange models, in which the incoming proton fluctuates to a neutron–pion state, and the electron interacts with the pion.

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1. Introduction

Several studies of leading neutron production in $ep$ interactions at HERA have been reported previously [1–5]. Many features of the data are described by pion-exchange models, in which the incoming proton fluctuates into a neutron–pion state and the pion interacts with the incoming electron or positron. The kinematic variables $t$, the square of the four-momentum transfer at the proton–neutron vertex, and $x_L$, the energy fraction of the proton carried by the neutron, are convenient variables for studying energy-angle correlations. In this study of semi-inclusive photoproduction, $\gamma p \rightarrow nX$, where the photon is quasi-real, the energy distribution of leading neutrons is measured as

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1. E-mail address: rik.yoshida@desy.de (R. Yoshida).
2. 1 Also affiliated with University College London, London, UK.
3. 2 Retired.
4. 3 Self-employed.
5. 4 PPARC Advanced Fellow.
6. 5 Partly supported by Polish Ministry of Scientific Research and Information Technology, grant No. 2P03B 12225.
7. 6 Partly supported by Polish Ministry of Scientific Research and Information Technology, grant No. 2P03B 12625.
8. 7 Supported by the Polish State Committee for Scientific Research, grant No. 2P03B 09322.
9. 8 Supported by the Polish State Committee for Scientific Research, grant No. 2P03B 12225.
10. 9 Now at Columbia University, NY, USA.
11. 10 Now at DESY group FEB.
12. 11 Now at University of Oxford, Oxford, UK.
13. 12 Now at Royal Holloway University of London, London, UK.
14. 13 Also at Nara Women’s University, Nara, Japan.
15. 14 Also at University of Tokyo, Tokyo, Japan.
16. 15 Ramón y Cajal Fellow.
17. 16 PPARC Postdoctoral Research Fellow.
18. 17 On leave of absence at The National Science Foundation, Arlington, VA, USA.
19. 18 Present address: Tokyo Metropolitan University of Health Sciences, Tokyo 116-8551, Japan.
20. 19 Also at University of Hamburg, Alexander von Humboldt Fellow.
21. 20 Also at Łódź University, Poland.
22. 21 Supported by the Polish State Committee for Scientific Research, grant No. 2P03B 07222.
23. 22 Łódź University, Poland.
24. 23 Łódź University, Poland, supported by the KBN grant No. 2P03B 12925.
25. 24 Supported by the KBN grant No. 2P03B 12725.
26. 25 On leave from MSU, partly supported by the Weizmann Institute via the US–Israel BSF.
27. 26 Supported by the US National Science Foundation.
28. 27 Supported by the Polish State Committee for Scientific Research, grant No. 620/E-77/SPB/DESY/P-03/DZ 117/2003-2005.
29. 28 Supported by the Polish Ministry of Scientific Research and Information Technology, grant No. 112/E-356/SPUB/DESY/P-03/DZ 116/2003-2005.
30. 29 Supported by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and its grants for Scientific Research.
31. 30 Supported by the Spanish Ministry of Education and Science through funds provided by CICYT.
32. 31 Supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).
32. 32 Partially supported by the German Federal Ministry for Education and Research (BMBF).
33. 33 Supported by the US–Israeli Binational Science Foundation and the Benoziyo Center for High Energy Physics.
34. 34 Supported by the German Ministry of Education and Research (BMBF), under contract Nos. HZ1GUA 2, HZ1GUB 0, HZ1PDA 5, HZ1VEA 5.
35. 35 Supported by the Particle Physics and Astronomy Research Council, UK.
36. 36 Supported by the Korean Ministry of Education and Korea Science and Engineering Foundation.
a function of $t$, which is determined using a new position detector to measure the angle of the neutron. The $(1-x_L)$ distribution is presented as a function of $t$ for large $x_L$ ($0.64 < x_L < 0.925$) and small $|t|$ ($|t| < 0.425 \text{ GeV}^2$). The results are interpreted in the context of pion exchange, in order to provide a test of the consistency of this picture of leading neutron production.

2. Experimental set-up and kinematics

The data used for this measurement were collected in the year 2000 at the $ep$ collider HERA with the ZEUS detector, during a short run period in which a special trigger was implemented. The data set corresponds to an integrated luminosity of $9 \text{ pb}^{-1}$. During this period HERA collided 27.5 GeV positrons with 920 GeV protons at a center-of-mass energy of 318 GeV.

Charged particles are tracked in the central tracking detector [6], which operates in a magnetic field of 1.43 T provided by a thin superconducting solenoid and covers the polar-angle region $15^\circ < \theta < 164^\circ$. Outside the solenoid is a hermetic, high-resolution uranium-scintillator calorimeter (CAL) [7] used to measure the energies of the final-state particles.

Bremsstrahlung $ep \rightarrow e\gamma p$ and the photoproduction of hadrons $ep \rightarrow eX$ are tagged using the luminosity (LUMI) detectors [8]. The bremsstrahlung photons are measured with a lead-scintillator calorimeter located 107 m from the interaction point in the positron beam direction. A similar calorimeter at 35 m from the interaction point is used to measure positrons scattered at very small angles in an energy range 5–20 GeV, with an energy resolution of $0.19\sqrt{E}$ ($E$ in GeV).

ZEUS has two detectors for measuring forward particles, a leading proton spectrometer (LPS) [9], consisting of six stations of silicon strip detectors, and a forward neutron calorimeter (FNC) [10–12] downstream from the LPS, 105 m from the interaction point.

The FNC is a lead-scintillator sampling calorimeter, the front section of which is divided into 14 towers, as illustrated in Fig. 1. The hadronic energy resolution, as measured in a pion test beam at 120 GeV, is $0.65\sqrt{E}$ ($E$ in GeV). Three planes of veto counters, located 70, 78, and 199 cm in front of the calorimeter, are used to detect charged particles produced by neutrons interacting in inactive material in front of the FNC.

Magnet apertures limit the FNC geometric acceptance to neutrons inside the area outlined in Fig. 1. This limit corresponds to neutron production angles less than 0.8 mrad; i.e., to transverse momenta $p_T = E_n\theta_n \leq 0.74 x_L$ GeV. The neutron production angle, $\theta_n$, is measured with respect to the proton beam direction at the interaction point. The mean value of $p_T$ of the detected neutrons is 0.22 GeV. The overall acceptance of the FNC is about 25% for neutrons with energy $x_L > 0.6$ and $\theta_n < 0.8$ mrad.

The forward neutron tracker (FNT), designed to measure the position of neutron showers, was installed in the FNC in 1998. It consists of two hodoscope planes of 1.2 cm-wide scintillator strips, with 17 strips measuring the $X$ position and 15 strips measuring the $Y$ position. Fig. 1 shows the position of the FNT hodoscope in the FNC in the plane transverse to the beam as well as the zero-degree point, the projection of the
proton beam direction at the interaction point onto the FNT. The FNT is situated approximately one interaction length inside the FNC. This position is deep enough that a large fraction of the neutrons begin to shower in front of the FNT, but not so deep as to compromise the position resolution. The position resolution of neutron showers in the FNT was measured to be 0.23 cm by placing an adjustable collimator in front of the FNT during special test and calibration runs.

The kinematics of inclusive photoproduction $e\gamma p \rightarrow eX$ at HERA is specified by $W$, the photon–proton center-of-mass energy. This is related to the positron–proton center-of-mass energy, $\sqrt{s}$, by $W^2 = y s$. The inelasticity, $y$, of the scattered positron is defined by $y = (E - E')/E$, where $E$ ($E'$) is the energy of the incoming (scattered) positron.

To describe the neutron-tagged process $e\gamma p \rightarrow eX$, the variables $x_L$ and $p_T$ are also used. These are related to $t$ by

$$t \approx -\frac{p_T^2}{x_L} = \frac{1 - x_L}{x_L}(m_p^2 - x_Lm_n^2),$$

where $m_p$ is the mass of the proton and $m_n$ is the mass of the neutron.

3. Event selection

The data sample was collected using a trigger that required at least 5 GeV in the LUMI electron calorimeter in coincidence with at least 0.5 GeV in the rear part ($\theta > 127^\circ$) of the CAL. In addition, the trigger required an energy deposit in the FNC corresponding to $x_L > 0.2$. The trigger efficiency of the FNC was close to 100% for the $x_L$ range under consideration in this Letter ($x_L > 0.64$).

Photoproduction events were selected offline using cuts based on the reconstructed vertex position and calorimeter energy deposits. The events were required to have an energy in the LUMI electron calorimeter in the range $10 < E' < 18$ GeV and an energy in the LUMI photon calorimeter smaller than 1 GeV to eliminate bremsstrahlung overlap events. These cuts restricted the photon virtuality, $Q^2$, to values smaller than $\sim 0.02$ GeV$^2$, with a median value of $\approx 10^{-3}$ GeV$^2$, and resulted in a mean value for $W$ of 220 GeV.

Events with a leading neutron were selected offline by requiring $x_L > 0.64$ and by imposing the following cleaning cuts. Scattered protons, bent into the top towers 11 to 14 of the FNC (Fig. 1) by the HERA dipole magnets, were eliminated by requiring that the tower with the maximum energy deposit be in the range 6 to 9. Photons were removed by eliminating showers with a small energy-weighted vertical width.

Neutrons that started showering in front of the FNC were removed by requiring that the scintillator veto counter farthest from the FNC had an energy deposit below that of a minimum-ionizing particle. To minimize false vetoes due to calorimeter albedo, only the farthest counter was used.

Finally, only events with $x_L < 0.925$ were used in the analysis, since the effect of any error in the energy scale, and the influence of exchanges other than the pion, become significant at high $x_L$ (see Sections 5 and 6, respectively). After these selection cuts, the data sample consisted of 31 756 events.

Not all neutrons start to shower in front of the FNT. To select events with useful position information, it was required that the energy deposited in each plane of the FNT be well above pedestal and that the strips with the two largest energy deposits be adjacent. These cuts reduced the sample to 17 919 events.

4. Neutron efficiencies and correction factors

The efficiencies and correction factors for the leading neutron were calculated with a single-particle Monte Carlo (MC) simulation. The MC program included the geometry of the proton beam-line magnets which define the geometric acceptance, the details of the absorbing material as obtained from survey measurements, the proton beam divergence, and the measured energy (FNC) and position (FNT) resolutions for hadronic showers. The MC program accounts for the different amount of absorbing material in front of the FNC for the two cases when the ZEUS LPS was, or was not, in the data-taking position. Events were generated using the observed $x_L$ spectrum and an exponential distribution in transverse momentum, $e^{-b(x_L)p_T^2}$. The slope $b(x_L)$ was iterated until the MC distributions matched the observed uncorrected distributions. The corrected data distributions were ob-
tained using bin-by-bin unfolding. The two samples of data, corresponding to the two cases when the LPS was, or was not, in the data-taking position, were corrected independently.

The simulation of the absorbing material was cross-checked by producing a material map from an analysis of low-energy ($x_L < 0.27$) neutron data, under the assumption that low $x_L$ neutrons are distributed uniformly over the geometric acceptance. This assumption is based on noting that both the maximum $p_T$ accepted by the FNC as well as the slope $b$ decrease with $x_L$ [3], and hence the geometric acceptance covers a small region of a slowly changing $p_T$ distribution. An analysis using this material map gives results consistent with those obtained using the material measurements from the survey.

The proton beam had a transverse momentum spread of approximately 0.04 GeV horizontally and 0.1 GeV vertically, as measured by the LPS. The variation of the proton beam orbit was considerably smaller than this spread. The spread broadens the observed position distribution of the neutrons in the FNC, but does not change the peak position.

5. Results

The events were binned in $x_L$ and $t$. The bins were chosen to be well within the acceptance in the $x_L$–$t$ plane and contained 12,523 events. The corrected $x_L$ distributions of leading neutrons as a function of $t$ are shown in Fig. 2. The distributions are consistent with a power-law dependence in $(1 - x_L)$ of the form $dN/dx_L \propto (1 - x_L)^a(t)$. For each $t$ bin the power $a(t)$ was obtained by a least-squares fit of this function to the observed distribution. Only statistical errors were used in the fits because the systematic uncertainties are highly correlated. The resulting fits are superposed on the measured data points.

There are two main sources of systematic uncertainty: an uncertainty of $\pm 2\%$ in the absolute energy scale of the FNC resulting from the calibration procedure [3,12,13], and an uncertainty of $\pm 0.2$ cm in each of the $X$ and $Y$ coordinates of the zero-degree point determined from the peak in the $X,Y$ distribution in the FNT [14]. The systematic uncertainties on $a(t)$ were obtained by varying the energy scale and beam-spot position within their uncertainties and then repeating the complete analysis. The dominant contribution comes from the energy-scale uncertainty.

Fig. 2. The $x_L$ distribution in bins of $t$. The curves show the results of fits to the data with $0.64 < x_L < 0.925$ to the form $(1 - x_L)^a(t)$. The inner error bars indicate the statistical uncertainties and the full bars indicate the quadratic sum of the statistical and systematic uncertainties.
The powers determined from the fits to the data in Fig. 2 are plotted as a function of $-t$ in Fig. 3. They are consistent with a linear function,

$$a(t) = 0.88 \pm 0.09 \text{(stat.)}^{+0.34}_{-0.39} \text{(syst.)} - (2.81 \pm 0.42 \text{(stat.)}^{+1.13}_{-0.62} \text{(syst.)} \text{ GeV}^{-2})t.$$ 

The correlation between the slope and the intercept is predominantly statistical; the coefficient of correlation is $-0.9$.

6. Discussion

Previous experiments ([3] and references therein) have shown that leading neutron production in lepton–hadron and hadron–hadron experiments can be described by pion-exchange models. The consistency of this description can be tested by assuming that pion exchange is the dominant mechanism and deriving the pion Regge trajectory from the measured values of $a(t)$.

The pion “flux”, the splitting function of a proton to a neutron and pion ($p \rightarrow n\pi^+$), can be written [15] as

$$f_{\pi/p}(x_L, t) = \frac{1}{4\pi} \frac{g_{\pi\pi}^2}{4\pi} \frac{-t}{(m_\pi^2 - t)^2} \times (1 - x_L)^{1 - 2\alpha_\pi(t)}(F(x_L, t))^2,$$

(1)

where $g_{\pi\pi}$ is the coupling at the $\pi\pi p$ vertex, $m_\pi$ is the mass of the pion, and $\alpha_\pi(t) = \alpha_\pi'(t - m_\pi^2)$ is the Regge trajectory of the pion [16]. The function $F(x_L, t)$ is a form-factor which accounts for the effect of hadronic structure on the $p \rightarrow \pi n$ amplitude and for final-state rescattering of the neutron. As discussed elsewhere [2], this prescription for the flux with $F(x_L, t)$ set to 1 describes most of the $pn \rightarrow Xp$ data and also gives a good description of the ZEUS $x_L$ spectrum for photoproduced neutrons [2,3]. In this analysis it is assumed that $F(x_L, t)$ is a function of $t$ only.

The flux is thus of the form $f_{\pi/p} = A(t)(1 - x_L)^{1 - 2\alpha_\pi(t)}$. The cross section for neutron production is given by the product of the flux and the total $\gamma\pi$ cross section $\sigma_{\gamma\pi}(s) = \sigma_{\gamma\pi}((1 - x_L)W^2)$ as

$$\frac{d^2\sigma}{dx_L \, dt} = A(t)(1 - x_L)^{1 - 2\alpha_\pi(t)} \sigma_{\gamma\pi}(1 - x_L)W^2,$$
where $s' = (1 - x_L)W^2$ is the square of the $\gamma \pi$ center-of-mass energy. The total $\gamma \pi$ cross section is assumed to have a power law dependence on $s'$, for large $s'$, of the Donnachie–Landshoff form [17]

$$\sigma_{\gamma\pi}(s') = \mathcal{A}(s')^\epsilon + \mathcal{B}(s')^{-\eta},$$

where $\epsilon \approx 0.1$ and $\eta \approx 0.5$. The two terms correspond to the exchange of the pomeron ($\mathcal{P}$) and the reggeon ($\mathcal{R}$), respectively. For large $s'$ the pomeron contribution dominates that of the reggeon. In this case the $(1 - x_L)$ distribution is proportional to $(1 - x_L)a(t)$, where

$$a(t) = 1 + \epsilon - 2\alpha' t.$$

Here $m_\pi^2$ has been ignored, since its effect on the result is much smaller than the systematic error. Therefore, the measured linear function $a(t)$ discussed in Section 5 has an intercept of $\alpha_P(0) = (1 + \epsilon)$, the value of the pomeron trajectory at $t = 0$, and a slope of $2\alpha'_t$, twice the slope of the pion trajectory.

It is assumed that the $\mathcal{P}$ term dominates in the $x_L$ region of this measurement. The fit [17] to the total $\gamma p$ cross section suggests that the highest contribution of the $\mathcal{R}$ term is about 12% at $x_L = 0.925$. As $x_L$ decreases ($s'$ increases), the reggeon contribution falls rapidly. No correction for the reggeon contribution is applied in this analysis.

Previous measurements of the effective Regge trajectory in the $p \rightarrow n$ transition in hadronic interactions [16,18,19] found it to be dominated by the pion, with the intercept in the range $0.1$ to $0.3$ and the slope in the range $1.1$ to $1.3$ GeV$^{-2}$.

The values extracted from the experimental results,

$$1 + \epsilon = \alpha_P(0) = 0.88 \pm 0.09 \text{(stat.)}^{+0.34}_{-0.39} \text{(syst.)},$$

and

$$\alpha'_t = 1.40 \pm 0.21 \text{(stat.)}^{+0.56}_{-0.31} \text{(syst.) \text{ GeV}^{-2}},$$

are consistent with the expectation that $\alpha_P(0)$ is about 1.1 and $\alpha'_t$ is about 1 GeV$^{-2}$ in the range of $0.08 < -t < 0.425$ GeV$^2$, and so support the hypothesis that pion exchange is the dominant process in this reaction. Note that the data rule out a significant role for $\rho$ exchange. If the $\rho$ trajectory, $\alpha_\rho = 0.5 + t$ [20], is substituted for the pion trajectory in Eq. (1), the value for $1 + \epsilon$ extracted from the data is 1.88 rather than 0.88, which is an inconsistent result for $\alpha_P(0)$.

7. Summary

The dependence of the energy distribution of photon-produced leading neutrons on the momentum transfer at the proton–neutron vertex has been studied at an average photon–proton center-of-mass energy of 220 GeV. The $(1 - x_L)$ distributions in bins of $t$ are described by a power law, $dN/dx_L \propto (1 - x_L)^{a(t)}$, with the powers $a(t)$ following a linear function of $t$: $a(t) = 0.88 \pm 0.09 \text{(stat.)}^{+0.34}_{-0.39} \text{(syst.)} - (2.81 \pm 0.42 \text{(stat.)}^{+1.13}_{-0.62} \text{(syst.) \text{ GeV}^{-2}}) t$.

The linear function can be interpreted in the framework of Regge theory. The measured values of the intercept and slope are in agreement with the expectations from pion exchange: i.e., the intercept is the value of the pomeron trajectory at $t = 0$, and the slope is twice the slope of the pion trajectory. The data thus confirm that the production of leading neutrons in photon–proton collisions is well described by the pion-exchange model.

Acknowledgements

We thank the DESY Directorate for their strong support and encouragement, and the HERA machine group for their diligent efforts. We are grateful for the support of the DESY computing and network services. The design, construction and installation of the ZEUS detector have been made possible owing to the ingenuity and effort of many people who are not listed as authors. This study was only made possible by the physics insight and work of G. Levman, to whom we are greatly indebted.

References

[1] ZEUS Collaboration, M. Derrick, et al., Phys. Lett. B 384 (1995) 388.
[2] ZEUS Collaboration, J. Breitweg, et al., Nucl. Phys. B 596 (2001) 3.
[3] ZEUS Collaboration, S. Chekanov, et al., Nucl. Phys. B 637 (2002) 3.
[4] ZEUS Collaboration, S. Chekanov, et al., Phys. Lett. B 590 (2004) 143.
[5] H1 Collaboration, C. Adloff, et al., Eur. Phys. J. C 6 (1999) 587.
[6] N. Harnew, et al., Nucl. Instrum. Methods A 279 (1989) 290; B. Foster, et al., Nucl. Phys. B (Proc. Suppl.) 32 (1993) 181;
B. Foster, et al., Nucl. Instrum. Methods A 338 (1994) 254.

[7] M. Derrick, et al., Nucl. Instrum. Methods A 309 (1991) 77;
A. Andersen, et al., Nucl. Instrum. Methods A 309 (1991) 101;
A. Caldwell, et al., Nucl. Instrum. Methods A 321 (1992) 356;
A. Bernstein, et al., Nucl. Instrum. Methods A 336 (1993) 23.

[8] J. Andrzejkow, et al., Preprint DESY-92-066, DESY, 1992;
ZEUS Collaboration, M. Derrick, et al., Z. Phys. C 63 (1994) 391;
J. Andrzejkow, et al., Acta Phys. Pol. B 32 (2001) 2025.

[9] ZEUS Collaboration, M. Derrick, et al., Z. Phys. C 73 (1997) 253.

[10] S. Bhadra, et al., Nucl. Instrum. Methods A 354 (1995) 479.

[11] S. Bhadra, et al., Nucl. Instrum. Methods A 394 (1997) 121.

[12] S. Bhadra, et al., in: E. Cheu, et al. (Eds.), Proceedings of the
Seventh International Conference on Calorimetry in High Energy Physics, Tuscon, AZ, November 1997, World Scientific, Singapore, 1998, p. 295.

[13] C.-P. Fagerstroom, PhD thesis, University of Toronto, 1999, unpublished.

[14] T. Koop, PhD thesis, University of Toronto, 2004, unpublished.

[15] M. Bishara, Phys. Lett. B 38 (1972) 510.

[16] H. Abramowicz, et al., Nucl. Phys. B 166 (1980) 62.

[17] A. Donnachie, P.V. Landshoff, Phys. Lett. B 296 (1992) 227.

[18] J. Hanlon, et al., Phys. Rev. D 20 (1979) 2135.

[19] W. Flauger, F. Monnig, Nucl. Phys. B 109 (1976) 347.

[20] R.J. Eden, Rep. Prog. Phys. 34 (1971) 995.