EPJ manuscript No.
(will be inserted by the editor)

Measurement of π^- and π^+ Photoproduction in Deuterium at Large Momentum Transfer for $\mathrm{E} = 1.7 - 5.6$ GeV

Hong Xiang [a]

MIT Laboratory for Nuclear Science, Cambridge, Massachusetts, 02139-4307, USA

For the Jefferson Lab Hall A and E94-104 Collaborations

Received: date / Revised version: date

Abstract. Single π^- and π^+ photoproduction from deuterium have been measured at energies of $\mathrm{E} = 1.7 - 5.6$ GeV and momentum transfers of $|\mathrm{t}| = 0.4 - 5.6$ $(\mathrm{GeV/c})^2$. The ratio of $\pi^-/\ \pi^+$ for data taken at $E = 3.4$ GeV are presented. Also the ratio of the π^+ from hydrogen to the π^+ from deuterium are extracted to examine the nucleon spectator assumption used in the cross section ratio analysis. Results are discussed in conjunction with the existing measurements with frameworks ranging from a hadronic description to parton constituent models which successfully characterize the scaling behaviors observed in the exclusive measurements.

PACS. 13.60.Le – 24.85.+p – 25.10.+s – 25.20.Lj

1 Introduction

High energy photo-reactions, especially when measured at high momentum transfer, have been used to probe the quark-gluon structure of the hadronic particles involved in the reactions. It is of primary interest to develop insight into the transition between the hadronic and quark-gluon descriptions of the fundamental photoproduction processes, particularly in the energy regions accessible with CEBAF at Jefferson Lab.

Current understanding presents two complementary scenarios of the photo-reaction process. In the low energy and low momentum transfer region, models built with nucleon-meson degrees of freedom through effective hadronic Lagrangian have proved to be valid in describing the existing data [1,2]. At high energy and large momentum transfer, constituent counting rules (CCR), a description based on the quark and gluon degrees of freedom within the domain of perturbative QCD, have been successful in characterizing the photoreaction cross section data [3,4]. Also, successful agreements between data and perturbative QCD calculations have been reported for high energy pion photoproduction at large transverse momentum for the inclusive process of $\gamma + N \to \pi^0 + X$ [5,6]. However, in the same momentum transfer region where the CCR are valid, another pQCD based prediction, hadronic helicity conservation (HHC), has not been successful in explaining the newly emerged polarization data from experiments at Jefferson Lab [7,8].

Among the proposed physics observables, the ratio of the differential cross section $\frac{d\sigma}{dt}(\gamma n \to \pi^- p)/\ \frac{d\sigma}{dt}(\gamma p \to \pi^+ n)$ is shown to be explicitly sensitive to the mechanisms of the scattering processes at high energy and high momentum transfer where pQCD based models presumably apply [9–15]. However, previous data on this observable have been available only in momentum transfer region of $|t|$ below 2.8 $(\mathrm{GeV/c})^2$[16–18] where they are compared to different hadronic model based calculations [1,2].

This paper reports a recent measurement of the charged pion cross section ratio from experiment E94-104 at Jefferson Lab [19] where single pions from the following processes are measured: $\gamma d \to \pi^- X$, $\gamma d \to \pi^+ X$ and $\gamma p \to \pi^+ X$. After a description of the measurement and data analysis, results of this experiment will be discussed in connection to the existing measurements and models based on both hadronic and quark-gluon degrees of freedom.

2 Experiment and Analysis

This experiment was performed in Hall A of the Continuous Electron Beam Accelerator Facility(CEBAF) at Jefferson Lab in the spring of 2001. The photon beam was generated via bremsstrahlung of the electron beam in a thin 6% Cu radiator located upstream of the target. The typical electron beam current was ~ 30 μA and data were taken at beam energies of $E = 1.723, 2.561, 3.400, 4.236$ and 5.614 GeV. The liquid hydrogen target was operated at a temperature of 19K and a pressure of ~ 0.17 MPa, giving a density of 0.072 g/cm^3. The liquid deuterium target was operated at a temperature of 22K and a pressure

[a] *Present address:* Schlumberger-Doll Research,Old Quarry Road, Ridgefield, Connecticut 06877-4108, USA.

of ~ 0.15 MPa, giving a density of 0.167 g/cm^3. The target cells for both the hydrogen and deuterium loops consisted of aluminum cylinders with their axes oriented along the beam direction. Special runs with radiator removed were taken for subtraction of the backgrounds from the electroproduction processes. In addition, dummy target cells were used to measure empty target backgrounds.

Independent measurements of the oppositely charged pions were performed with both of the High Resolution Spectrometers (HRS) in Hall A. The beam-left HRS arm was used to measure positively charged particles and the beam-right arm to measure negatively charged particles. The position and angle of the emitted particles were tracked with two vertical drift chambers in each of the two HRS arms. Particle identification for positive tracks was obtained with a combination of scintillators and two aerogel Cerenkov counters. For negative tracks, particle separation was obtained by using a gas Cerenkov counter and two layers of lead glass shower counters in the right arm.

Charged pion cross section ratios are obtained from the analysis of bremsstrahlung yield curves. The incident photon energy is reconstructed on the basis of single-pion production kinematics under the assumption that the nucleon spectator model is valid. It is believed that the following is a good approximation

$$\frac{\pi^-}{\pi^+} \equiv \frac{d\sigma/dt(\gamma n \to \pi^- p)}{d\sigma/dt(\gamma p \to \pi^+ n)} \simeq \frac{d\sigma/dt(\gamma d \to \pi^- pp)}{d\sigma/dt(\gamma d \to \pi^+ nn)} \quad (1)$$

where the known effects that cause differences in cross sections between free nucleons in hydrogen and in deuterium partially cancelled out when the above ratio is formed [18], including (1) the Pauli exclusion principle, and (2) the Glauber corrections for interactions of the pion with the spectator nucleon and the final-state interactions of the two nucleons.

In extracting the π^-/π^+ ratios, it was required that the photon energy, calculated from the momentum and angle of the detected pion, fall within a range of $E - 125$ MeV $< E_\gamma < E - 25$ MeV for both π^+ and π^-. This procedure effectively eliminated multipion processes because of their higher threshold. By varying both the width and the location of this E_γ cut, the contribution of multipion processes to the π^-/π^+ ratio was examined and found to be less than $\sim$3%. Contaminations of electrons and protons to the measured π^- and π^+ yields are found to be at a level below $\sim$1%. Variations of both the acceptance cuts and the PID cuts reveal a maximum uncertainty in the π^-/π^+ ratio at a level below $\sim$3%. Other systematic errors should essentially cancel out when taking the ratio of π^- and π^+ yields.

3 Results and Discussion

3.1 Ratio of π^-/π^+ at $\mathrm{E} = 3.400$ GeV

The $|t|$ dependence of the π^-/π^+ ratio from deuterium for data taken at $\mathrm{E} = 3.400$ GeV is shown in Fig. 1, together with previous data obtained at the same beam energy from the Cambridge Electron Accelerator(CEA) [16] and DESY [17]. Using the same analysis approach as used in the previous measurements, results from this experiment suggest a very good agreement with the CEA results in their overlap region of momentum transfer. The π^-/π^+ ratio is close to unity in the forward direction, then falls sharply as |t| increases, reaching a $\sim 1/3$ minimum at $|t| \simeq 0.4$ (GeV/c)^2. Further, the π^-/π^+ ratio rises smoothly as |t| continue to increase between $|t| \simeq 0.4 - 2.8$ (GeV/c)^2.

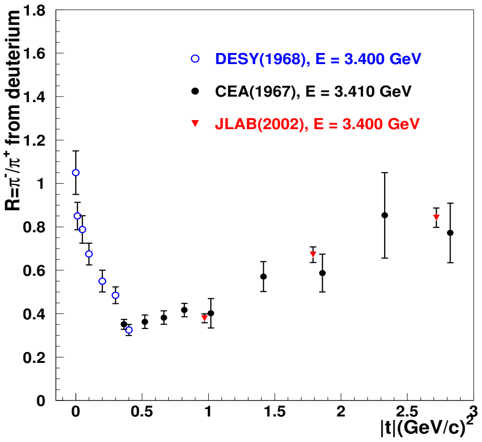

Fig. 1. $\frac{\pi^-}{\pi^+}$ ratio from deuterium measured at $E = 3.400$ GeV, comparing to the CEA and DESY data taken at same energy.

3.2 Ratio of π^+ in hydrogen over π^+ in deuterium

As an examination of the validity of the assumption in Eq. 1, the ratio of the π^+ produced in hydrogen to the π^+ produced in deuterium was also extracted over the same momentum transfer region of $|t| = 0.4 - 2.8$ (GeV/c)^2,

$$\frac{\pi^+(H)}{\pi^+(D)} = \frac{d\sigma/dt(\gamma p \to \pi^+ n)}{d\sigma/dt(\gamma d \to \pi^+ nn)} \quad (2)$$

where the neutron in the deuterium target is viewed as a spectator when the π^+ is produced from the interaction between the photon and the struck proton. This ratio is plotted as a function of |t| in Fig. 2. Explicitly, the result reveals a prominent departure from unity as the measurement proceeded to increasingly higher momentum transfer. In the lower region of |t| below ~ 1.5 (GeV/c)^2, this ratio is found to be in the vicinity of unity which is in good agreement with the same check done in the CEA data [16]. Furthermore, in a window of $|t| = 1.5 - 2.0$ (GeV/c)^2, this ratio dropped abruptly from ~ 1 down to a value of $\sim 1/3$.

It is interesting to examine this apparent break-down of the simple nucleon spectator picture within the context of a series of exclusive cross section measurements, including the previous measurements at SLAC on the $\gamma p \to \pi^+ n$ process [18,20] and the latest measurements on both the $\gamma p \to \pi^+ n$ and $\gamma n \to \pi^- p$ processes from this experiment [21].

First, as shown in Fig. 2, both of the two data points down to the 1/3 ratio region are from measurements at center-of-mass energy $\sqrt{s}$ larger than 2.7 GeV, corresponding to a photon energy of 3.4 GeV, and at center-of-mass angle θ_{cm} larger than 70^o. It has been observed that for $\sqrt{s}$ larger than 2.7 GeV, the differential cross section for both $\gamma n \to \pi^- p$ and $\gamma p \to \pi^+ n$ at $\theta_{cm} = 90^o$ can be represented approximately by $d\sigma/dt \sim s^{-7} f(\theta_{cm})$ [18,20,21], which are in good agreement with the prediction of the parton constituent models [22–24].

Secondly, the break-down point in the vicinity of $|t| \sim$ 2.0 (GeV/c)^2 from Fig. 2 is coincident with the earlier observations made in the measurements at SLAC [20] where the cross section of $d\sigma/dt(\gamma p \to \pi^+ n)$ was measured as a function of momentum transfer |t| for E = 4.0 − 7.5 GeV. It revealed that after an exponential ($\sim e^{3|t|}$) falloff for |t| values up to about 2.0 (GeV/c)^2, the cross section $d\sigma/dt$ entered a central region of momentum transfer where $d\sigma/dt$ is independent of |t| and the cross section has a steep energy dependence of s^{-7}. In addition, by extracting the effective value of the Regge trajectory parameter $\alpha(|t|)$, as defined in $d\sigma/dt \sim s^{2[\alpha(|t|)-1]}$ [25,26], it was found that this parameter underwent a transition at $|t| \simeq 2.0$ (GeV/c)^2 from its nominal zero value at lower momentum transfer to a definitive departure from zero into the higher |t| region where the cross section scales with center-of-mass energy s^{2-n} with n $\simeq 7.3 \pm 0.4$.

With the convergent observations made in this measurement and other available data on the exclusive cross sections [20,21], it appears that in the region of energy and momentum transfer accessed by this experiment, *i.e.* E = 1.7 − 5.6 GeV and |t| = 0.4 − 2.8 (GeV/c)^2, an apparent transition might have happened where scaling in cross section is observed to set in as the process proceeds over a joint threshold in center-of-mass energy $\sqrt{s}$ at ~ 2.7 GeV and momentum transfer |t| at ~ 2.0 (GeV/c)^2. Nevertheless, the significance of other potential mechanisms such as multi-step pion production processes in driving the high-t behavior of the ratio in Eq. 2 remains to be investigated before a definitive conclusion may be drawn.

4 Summary

Data of single π^- and π^+ have been taken for the beam energies of E = 1.7 − 5.6 GeV and momentum transfer of |t| = 0.4 − 5.6 (GeV/c)^2. Ratio of π^-/π^+ from deuterium for data taken at E = 3.400 GeV are in good agreement with the CEA data taken over a region of overlapped kinematics. In addition, the ratio of the π^+ from hydrogen to the π^+ from deuterium is extracted with an intention to examine the validity of the nucleon spectator model. A prominent break-down from the naive expectation is observed at $|t| \simeq 2.0$ (GeV/c)^2. This finding, though revealed with a different observable, is concurrent to the observations made by earlier measurements from SLAC on the exclusive cross sections. Due to this apparent breakdown, π^-/π^+ ratios at higher momentum transfer are to be investigated with additional input from the exclusive measurements.

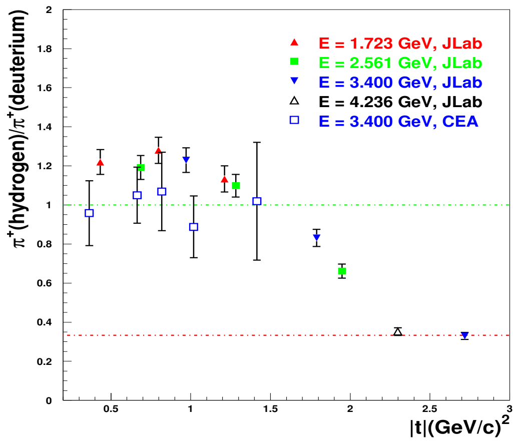

Fig. 2. Ratio of π^+ from hydrogen target over the π^+ from deuterium target. Earlier result from CEA[16] is also shown as open squares.

5 Acknowledgements

We acknowledge the support of JLab Hall A technical staff and the Accelerator Division during this experiment. This work is supported in part by US Dept. of Energy under the contract of DE-AC05-84ER40150, DE-FC02-94ER40818 and the National Science Foundation. The Southeastern Universities Research Association operates the Thomas Jefferson National Accelerator Facility under Department of Energy contract DE-AC05-84ER40150.

References

1. M. Guidal, *et al.*, Phys. Lett. **B 400** (1997) 6.
2. M. Rahnama, J. K. Storrow, J. Phys. G, **17** (1991) 243.
3. E. C. Schulte, *et al.*, Phys. Rev. Lett., **87** (2001) 102302.
4. C. Bochna, *et al.*, Phys. Rev. Lett., **81** (1998) 4576.
5. E. Auge, *et al.*, Phys. Lett., **B 168** (1986) 163.
6. P. Aurenche, *et al.*, Phys. Lett., **B 135** (1984) 164.
7. K. Wijesooriya, *et al.*, Phys. Rev. Lett., **14** (2001) 2975.
8. K. Wijesooriya, *et al.*, Phys. Rev. Lett., **66** (2002) 034614.
9. S. J. Brodsky, *et al.*, Phys. Lett., **B 449** (1997) 306.
10. X. Ji, Physical Review, **D 55** (1997) 7114.
11. X. Ji and J. Osborne, Phys. Rev., **D 58** (1998) 094018.
12. A. V. Radyushkin, Physical Review, **D 56** (1997) 5524.
13. J. C. Collins, *et al.*, Phys. Rev., **D 56** (1997) 2982.
14. C. E. Carlson, A. B. Wakely, Phys. Rev., **D 48** (1993) 2000.
15. A. Afanasev, C. E. Carlson and C. Wahlquist, Phys. Rev., **D 58** (1998) 054007.
16. Z. Bar-Yam, *et al.*, Phys. Rev. Lett., **19** (1967) 40.
17. P. Heide, *et al.*, Phys. Rev. Lett., **21** (1968) 248.
18. A. M. Boyarski, *et al.*, Phys. Rev. Lett., **21** (1968) 1767.
19. H. Gao and R. Holt, *et al.*, JLab Experiment E94-104.
20. R. L. Anderson, *et al.*, Phys. Rev., **D 14** (1976) 679.
21. L. Y. Zhu, *et al.*, to be submitted to Phys. Rev. Lett.
22. S. J. Brodsky and G. R. Farrar, PRL, **31** (1973) 1153.
23. S. J. Brodsky, G. R. Farrar, Phys. Rev. **D 11** (1975) 1309.
24. V. A. Matveev, *et al.*, Lett. Nuovo Cimento **7** (1973) 719.
25. G. Zweig, Nuovo Cimento, **32**, (1964) 689.
26. P. Stichel, Z. Physik, **178**, (1964) 519.