Cross-Section Measurement of Charged-Pion Photoproduction from Hydrogen and Deuterium

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We have measured the differential cross section for the $\gamma n \to \pi^- p$ and $\gamma p \to \pi^+ n$ reactions at $\theta_{\text{c.m.}} = 90°$ in the photon energy range from 1.1 to 5.5 GeV at Jefferson Lab (JLab). The data at $E_\gamma \gtrsim 3.3$ GeV exhibit a global scaling behavior for both π^- and π^+ photoproduction, consistent with the constituent counting rule and the existing π^+ photoproduction data. Possible oscillations around the scaling value are suggested by these new data. The data show enhancement in the scaled cross section at a center-of-mass energy near 2.2 GeV. The cross section ratio of exclusive π^- to π^+ photoproduction at high energy is consistent with the prediction based on one-hard-gluon-exchange diagrams.

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The study of the transition region from nucleon-meson degrees of freedom to quark-gluon degrees of freedom in quantum chromodynamics (QCD) is one of the most interesting subjects in nuclear physics. Scaling in the differential cross section $d\sigma/dt$ and hadron helicity conservation have been pursued experimentally as signatures of this transition for years. While global scaling behavior has been observed in many exclusive processes, no experimental evidence supports hadron helicity conservation. Furthermore, the exact nature governing the onset of the scaling behavior is not clear. The relatively large cross section of pion photoproduction allows the search for additional possible signatures: QCD oscillations and the charged pion cross section ratio. In this experiment, three signatures (scaling, QCD oscillations, charged pion ratio) for the transition are investigated.

For an exclusive two-body reaction $AB \to CD$ at high energy and large momentum transfer, the constituent counting rule predicts [1]

$$\frac{d\sigma}{dt}(AB \to CD) \sim s^{2-n} f(\theta_{\text{c.m.}}), \tag{1}$$

where s and t are the Mandelstam variables. The quantity n is the total number of interacting elementary fields in the reaction, and $f(\theta_{\text{c.m.}})$ is the angular dependence of the differential cross section. This rule was originally derived from dimensional analysis [1], and later confirmed within the framework of a perturbative QCD (pQCD) analysis up to a logarithmic factor of the strong coupling constant [2]. Many exclusive measurements at fixed center-of-mass angles agree remarkably with this rule [3–7].

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The applicability of pQCD to exclusive processes remains controversial in the few GeV region. Furthermore, the onset of scaling can be sometimes as low as 1 GeV [6,7], which is much lower than the scale where pQCD is expected to be valid. Moreover, hadron helicity conservation, another consequence of pQCD (this statement is currently under debate [8]), tends not to agree with polarization measurements at JLab for various exclusive processes [7,9–12].

In addition, two striking anomalies have been observed in pp elastic scattering. The ratio of $(d\sigma/dt)_{\uparrow\uparrow}/(d\sigma/dt)_{\uparrow\downarrow}$ with spin normal to the scattering plane can reach 4 at $\theta_{\text{c.m.}} = 90°$ [13]; the differential cross section $d\sigma/dt$ oscillates around the scaling value [14]. The interference between the short-distance and long-distance (Landshoff) subprocesses due to soft gluon radiation [15] can explain the above spin-spin correlation and oscillatory scaling behavior [16,17]. This interference is analogous to the QED effect of coulomb-nuclear interference observed in charged particle scattering at low energy. Alternatively, the above anomalies in pp scattering can be interpreted in terms of resonances associated with charm production threshold, interfering with a pQCD background [18].

It has been suggested that similar oscillations should occur in deuteron photodisintegration [19] and pion photoproduction at large center-of-mass angles [20]. The recent $d(\gamma, p)n$ data [6,7] showed that the oscillations if present are very weak, and the rapid decrease in the cross section with photon energy ($d\sigma/dt \propto s^{-11}$) makes it impractical to investigate such oscillatory behavior. Thus, it is essential to search for oscillations in pion photoproduction, which has a much larger cross section at high energy due to a slower decrease in the cross section with energy ($d\sigma/dt \propto s^{-7}$). In this Letter, we present cross section results for charged pion photoproduction from hydrogen and deuterium at $\theta_{\text{c.m.}} = 90°$.

Nonperturbative effects are expected to cancel out to first order in the differential cross section ratio $[\frac{d\sigma}{dt}(\gamma n \rightarrow \pi^- p)]/[\frac{d\sigma}{dt}(\gamma p \rightarrow \pi^+ n)]$. Therefore one may expect the $\frac{\pi^-}{\pi^+}$ ratio to give the first indication of a simple pQCD prediction since pions are simplest hadronic systems. In this Letter, we also provide data on the charged pion ratio up to a momentum transfer squared value of $5.0\ (\text{GeV}/c)^2$, the highest value ever achieved for this quantity.

Experiment E94-104 was carried out in Hall A [21] at the Thomas Jefferson National Accelerator Facility (JLab). The continuous electron beam, at currents around 30 μA and energies from 1.1 to 5.6 GeV, impinged on a 6% copper radiator generating an untagged bremsstrahlung photon beam. The production data were taken with the 15 cm cryogenic liquid hydrogen (LH2) target for single $p(\gamma, \pi^+)n$ measurements, or with the liquid deuterium (LD2) target for coincidence $d(\gamma, \pi^- p)p$ measurements. The two high resolution spectrometers (HRS), with a momentum resolution of better than 2×10^{-4} and a horizontal angular resolution of better than 2 mrad, were used to detect the outgoing pions and recoil protons. Based on two-body kinematics, the incident photon energy was reconstructed from final states, i.e., the momentum and angle of the π^+ in the singles measurement, momenta, and angles of the π^- and p in the coincidence measurement. Both spectrometers consisted of magnets to focus and bend the charged particles (45°), vertical drift chambers (VDCs) to record the tracks, and scintillator planes (S1/S2) to generate triggers. Two new aerogel Čerenkov detectors (A1/A2) in the left spectrometer provided particle identification for positive particles, mainly pions and protons. The CO_2 gas Čerenkov detector and preshower/shower detector in the right spectrometer provided particle identification for negative particles, mainly pions and electrons.

A 100 MeV bin of the reconstructed photon energy spectrum, centered 75 MeV below the beam energy, was chosen for the data analysis, where the multipion contribution is negligible. The data after background subtraction, with cuts on trigger-type, coincidence timing, PID (particle identification), acceptance, and photon energy, were compared to the Monte Carlo simulations to extract the raw cross section. The simulation was done with a modified JLab Hall A Monte Carlo program, MCEEP [22]. The bremsstrahlung photon flux was calculated with an estimated 3% uncertainty, by using the thick-radiator codes written by Meekins [23], based on the formulas of Matthews *et al.* [24]. The momentum distribution of the neutron inside the deuteron and the binding energy were considered in the simulation. Different neutron momentum distributions were used and little model dependence was found for the cross section ($< 1\%$). The angular distribution input for the cross sections was fitted from the π^+ photoproduction data at 4, 5, and 7.5 GeV [4], which has not been reproduced by the pQCD calculation [25]. It was used for all the kinematics including the π^- photoproduction since the extraction of cross section at $\theta_{\text{c.m.}} = 90°$ was insensitive to the angular distribution ($< 1\%$). The distributions of acceptance, reconstructed momentum, and photon energy from data were in good agreement with those from simulations.

Several correction factors were applied to deduce the final cross section, as shown in Table I. The largest correction, on the order of 20%, is the nuclear transparency in the deuteron due to final state interactions. The nuclear transparency was obtained for the $d(\gamma, \pi^- p)p$ process based on a Glauber calculation [26], which has been tested by the measured transparency from the quasielastic $d(e, e'p)$ process [27]. The correction due to material absorption was applied to compensate for the scattering losses in the target and in the spectrometers. The correction for a single pion or proton was approximately 6%, with major losses in the target, scintillators, and aerogel

TABLE I. The differential cross section $\frac{d\sigma}{dt}$ at $\theta_{\text{c.m.}} = 90°$ for $\gamma p \rightarrow \pi^+ n$ and $\gamma n \rightarrow \pi^- p$ reactions followed by the statistical and systematic errors.

E_γ (GeV)	$\frac{d\sigma}{dt}(\gamma p \rightarrow \pi^+ n)$ (nb/GeV^2)	$\frac{d\sigma}{dt}(\gamma n \rightarrow \pi^- p)$ (nb/GeV^2)
1.106	$(1.16 \pm 0.01 \pm 0.09) \times 10^4$	$(5.72 \pm 0.03 \pm 0.46) \times 10^3$
1.659	$(1.36 \pm 0.01 \pm 0.11) \times 10^3$	$(2.39 \pm 0.01 \pm 0.19) \times 10^3$
1.815	$(1.06 \pm 0.01 \pm 0.08) \times 10^3$	$(1.58 \pm 0.01 \pm 0.13) \times 10^3$
2.481	$(1.87 \pm 0.02 \pm 0.15) \times 10^2$	$(2.43 \pm 0.03 \pm 0.19) \times 10^2$
3.321	$8.07 \pm 0.09 \pm 0.65$	$(1.16 \pm 0.01 \pm 0.09) \times 10^1$
4.158	$2.34 \pm 0.04 \pm 0.19$	$4.05 \pm 0.08 \pm 0.32$
5.536	$0.33 \pm 0.02 \pm 0.03$	$0.56 \pm 0.01 \pm 0.04$

detectors. The pion decay losses were calculated from the flight distance. As some muons from pion decay may still fall into the acceptance and be misidentified as pions, an additional correction has to be applied, which was ~4%–7% based on Monte Carlo simulations [28]. The computer dead time correction was considered run-by-run and was mostly a few percent. The detector efficiencies also led to some corrections, mostly less than 1%.

The total errors were dominated by systematic uncertainties, which were estimated to be 8% in cross section. The point-to-point systematic uncertainty for the three kinematics at 3.3, 4.2, and 5.5 GeV is 4%. The statistical errors were approximately 2%. The major systematic uncertainties arose from the calculation of the bremsstrahlung photon yield, the simulation of the acceptance, and the estimation of the nuclear transparency, material absorption, and pion decay factor, approximately 3% for each item. Also, there were 2% uncertainties from PID and the energy loss calculations. Other systematic uncertainties were less than 1%.

The upper plot in Fig. 1 shows the results of the scaled differential cross section ($s^7 \frac{d\sigma}{dt}$) for the $\gamma p \rightarrow \pi^+ n$ process at $\theta_{\text{c.m.}} = 90°$. The new results with fitted value $n = 9.0 \pm 0.2$ [see Eq. (1)] agree with those of Anderson *et al.* [4] and exhibit the scaling behavior predicted by the constituent counting rule with nine elementary fields. The lowest energy datum in the inset box of Fig. 1 corresponds to a center-of-mass energy of approximately 2.7 GeV and photon energy of 3.3 GeV. The corresponding transverse momentum is approximately 1.2 GeV/c.

The lower plot in Fig. 1 shows the results of the scaled differential cross section ($s^7 \frac{d\sigma}{dt}$) for the $\gamma n \rightarrow \pi^- p$ process at $\theta_{\text{c.m.}} = 90°$. The new results greatly extend the existing measurements and exhibit, for the first time, a global scaling behavior at high energy for this reaction with fitted value $n = 8.6 \pm 0.2$. The scaling behavior in π^- production is similar to that in π^+ production. Furthermore, data in these two channels show possible oscillations around the scaling behavior in similar ways as suggested by the insets of Fig. 1. Note that this possible oscillatory behavior occurs above the known baryon resonance region. Measurements with much finer binning,

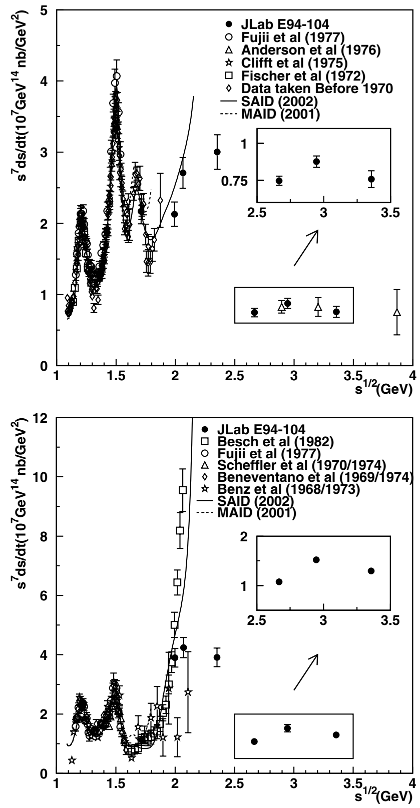

FIG. 1. The scaled differential cross section $s^7 \frac{d\sigma}{dt}$ versus center-of-mass energy for the $\gamma p \rightarrow \pi^+ n$ (upper plot) and $\gamma n \rightarrow \pi^- p$ (lower plot) at $\theta_{\text{c.m.}} = 90°$. The data from JLab E94-104 are shown as solid circles. The error bars for the new data and Anderson *et al.* data [4] include statistical and systematic uncertainties, except that those in the insets include only point-to-point uncertainties to highlight the possible oscillatory scaling behavior. Other data sets [29,30] are shown with only statistical errors. The open squares in the lower plot were averaged from data at $\theta_{\text{c.m.}} = 85°$ and $95°$ [31]. The solid line was obtained from the recent partial-wave analysis of single-pion photoproduction data [32] up to $E_\gamma = 2$ GeV, while the dashed line from the MAID analysis [33] up to $E_\gamma = 1.25$ GeV.

planned at JLab [34], are essential for the confirmation of such oscillatory scaling behavior.

Another interesting feature of the data is an apparent enhancement in the scaled differential cross section below the scaling region, at a center-of-mass energy ranging approximately from 1.8 to 2.5 GeV, in both channels of the charged pion photoproduction, as shown in Fig. 1. This effect was also observed in neutral pion photoproduction [29,30]. Without any conclusive statements for the present, some speculations can be made. The observed enhancement around 2.2 GeV might relate to some unknown baryon resonances, as some of the well-known baryon resonances (Δ, $N^\star$s around 1.5 and 1.7 GeV) are clearly seen in the scaled cross section below 2.2 GeV. Several baryon resonances are predicted to be in this energy region by the constituent quark model [35], but have not been seen experimentally, i.e., the so-called

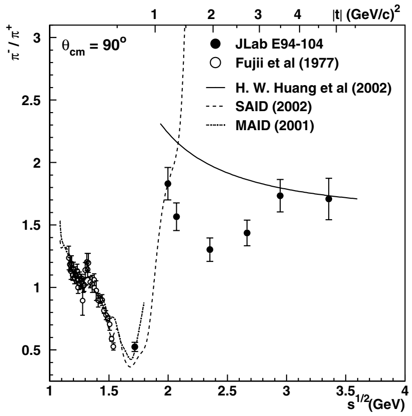

FIG. 2. The cross section ratio of π^- to π^+ photoproduction versus $\sqrt{s}$ and $|t|$.

"missing resonances." The observed enhancement might be associated with the strangeness production threshold.

The cross section ratio of π^- to π^+ photoproduction can be calculated [36] based on one-hard-gluon-exchange diagrams as

$$\frac{d\sigma(\gamma n \rightarrow \pi^- p)}{d\sigma(\gamma p \rightarrow \pi^+ n)} \simeq \left(\frac{ue_d + se_u}{ue_u + se_d}\right)^2, \qquad (2)$$

where u and s are the Mandelstam variables, and e_q denotes the charge of the quark q. The nonperturbative components are represented by the form factors which divide out when the ratio is taken. The calculation is expected to be valid only at high energy. As shown in Fig. 2, the calculation agrees with the two data points at the highest energies.

In summary, we have measured the differential cross section $d\sigma/dt$ for the photoproduction processes of $\gamma n \rightarrow \pi^- p$ and $\gamma p \rightarrow \pi^+ n$ at $\theta_{\text{c.m.}} = 90°$ with photon energies from 1.1 to 5.5 GeV. The data with $E_\gamma \gtrsim 3.3$ GeV exhibit a global scaling behavior in both processes, consistent with the constituent counting rule. The data with $E_\gamma \gtrsim 3.3$ GeV also suggest a possible oscillatory scaling behavior, the confirmation of which awaits future measurement with finer binning in energy. Furthermore, the scaled cross section data show an enhancement at a center-of-mass energy near 2.2 GeV and the exact nature of such a structure requires further investigation. The data also provide π^- to π^+ cross section ratios, consistent with the one-hard-gluon-exchange prediction at high energies.

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