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H. Kohri *et al.* (LEPS Collaboration)

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1 **Differential cross section and photon-beam asymmetry for the $\vec{\gamma}p$**
 2 **$\rightarrow \pi^+n$ reaction at forward π^+ angles for $E_\gamma=1.5-2.95$ GeV**

3 H. Kohri,^{1,2} S. Y. Wang,^{2,3} S. H. Shiu,^{2,4} W. C. Chang,² Y. Yanai,¹ D. S. Ahn,⁵
 4 J. K. Ahn,⁶ J. Y. Chen,⁷ S. Daté,⁸ H. Ejiri,¹ H. Fujimura,⁹ M. Fujiwara,^{1,10}
 5 S. Fukui,¹ W. Gohn,¹¹ K. Hicks,¹² A. Hosaka,¹ T. Hotta,¹ S. H. Hwang,¹³ K. Imai,¹⁴
 6 T. Ishikawa,¹⁵ K. Joo,¹¹ Y. Kato,¹⁶ S. H. Kim,^{17,1} Y. Kon,¹ H. S. Lee,¹⁸
 7 Y. Maeda,¹⁹ T. Mibe,²⁰ M. Miyabe,¹⁵ Y. Morino,²⁰ N. Muramatsu,¹⁵ T. Nakano,¹
 8 Y. Nakatsugawa,^{20,21} M. Niiyama,²² H. Noumi,¹ Y. Ohashi,⁸ T. Ohta,^{1,23} M. Oka,¹
 9 J. D. Parker,^{22,24} C. Rangacharyulu,²⁵ S. Y. Ryu,¹ T. Sawada,^{2,26} H. Shimizu,¹⁵
 10 Y. Sugaya,¹ M. Sumihama,²⁷ T. Tsunemi,²² M. Uchida,²⁸ M. Ungaro,¹¹ and M. Yosoi¹

11 (LEPS Collaboration)

12 ¹*Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*

13 ²*Institute of Physics, Academia Sinica, Taipei 11529, Taiwan*

14 ³*ChemMatCARS, The University of Chicago, Argonne, Illinois 60439, USA*

15 ⁴*Department of Physics, National Central University, Taoyuan City 32001, Taiwan*

16 ⁵*RIKEN, The Institute of Physical and Chemical Research, Wako, Saitama 351-0198, Japan*

17 ⁶*Department of Physics, Korea University, Seoul 02841, Republic of Korea*

18 ⁷*Light Source Division, National Synchrotron*

19 *Radiation Research Center, Hsinchu, 30076, Taiwan*

20 ⁸*Japan Synchrotron Radiation Research Institute, Sayo, Hyogo 679-5143, Japan*

21 ⁹*Wakayama Medical College, Wakayama, 641-8509, Japan*

22 ¹⁰*National Institutes for Quantum and Radiological*

23 *Science and Technology, Tokai, Ibaraki 319-1195, Japan*

24 ¹¹*Department of Physics, University of Connecticut, Storrs, CT 06269-3046, USA*

25 ¹²*Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA*

26 ¹³*Korea Research Institute of Standards and*

27 *Science (KRISS), Daejeon 34113, Republic of Korea*

28 ¹⁴*Advanced Science Research Center, Japan Atomic*

29 *Energy Agency, Tokai, Ibaraki 319-1195, Japan*

30 ¹⁵*Research Center for Electron Photon Science,*

1 *Tohoku University, Sendai, Miyagi 982-0826, Japan*

2 ¹⁶*Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Aichi 464-8602, Japan*

3 ¹⁷*Asia Pacific Center for Theoretical Physics, Pohang, Gyeongbuk, 37673, Republic of Korea*

4 ¹⁸*Department of Physics and Astronomy, Seoul*

5 *National University, Seoul 151-742, Republic of Korea*

6 ¹⁹*Proton Therapy Center, Fukui Prefectural Hospital, Fukui 910-8526, Japan*

7 ²⁰*High Energy Accelerator Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan*

8 ²¹*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*

9 ²²*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

10 ²³*Department of Radiology, The University of Tokyo Hospital, Tokyo 113-8655, Japan*

11 ²⁴*Neutron Science and Technology Center, Comprehensive Research*

12 *Organization for Science and Society (CROSS), Tokai, Ibaraki 319-1106, Japan*

13 ²⁵*Department of Physics and Engineering Physics, University*

14 *of Saskatchewan, Saskatoon, SK S7N 5E2, Canada*

15 ²⁶*Physics Department, University of Michigan, Michigan 48109-1040, USA*

16 ²⁷*Department of Education, Gifu University, Gifu 501-1193, Japan*

17 ²⁸*Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan*

18 (Dated: December 31, 2017)

19 **Abstract**

20 Differential cross sections and photon-beam asymmetries for the $\vec{\gamma}p \rightarrow \pi^+n$ reaction have been
21 measured for $0.6 < \cos\theta_\pi < 1$ and $E_\gamma=1.5-2.95$ GeV at SPring-8/LEPS. The cross sections mono-
22 tonically decrease as the photon beam energy increases for $0.6 < \cos\theta_\pi < 0.9$. However, the energy
23 dependence of the cross sections for $0.9 < \cos\theta_\pi < 1$ and $E_\gamma=1.5-2.2$ GeV ($W=1.9-2.2$ GeV) is
24 different, which may be due to a nucleon or Δ resonance. The present cross sections agree well
25 with the previous cross sections measured by other groups and show forward peaking, suggest-
26 ing significant t -channel contributions in this kinematical region. The asymmetries are found to
27 be positive, which can be explained by ρ -exchange in the t -channel. Large positive asymmetries
28 in the small $|t|$ region, where the ρ -exchange contribution becomes small, could be explained by
29 introducing π -exchange interference with the s -channel.

30 PACS numbers: 13.60.Le,14.20Gk,14.40Aq,14.70.Bh,25.20Lj

1 I. INTRODUCTION

2 Photoproduction of mesons is of special importance in the search of missing nucleon
3 resonances. In quark models, there exist more nucleon resonances than have been experi-
4 mentally observed so far [1]. Since the nucleon resonances have relatively wide widths and
5 are overlapping in mass, it is necessary to establish new resonances by performing partial
6 wave analyses based on rich physics observables over wide angular and energy regions. The
7 $\gamma p \rightarrow \pi^+ n$ reaction is one of the most basic photoproduction reactions. The $\gamma p \rightarrow \pi^+ n$ re-
8 action has relatively large cross sections of $\sim 10 \mu\text{b}$, which enables measurements of physics
9 observables to clarify the reaction dynamics. JLab/CLAS has measured differential cross
10 sections [2] in a wide angular region without forward and backward π^+ angles for $E_\gamma=0.725$ -
11 2.875 GeV. Existing data at forward π^+ angles taken for $E_\gamma=1.2$ - 3.0 GeV by DESY [3, 4] are
12 scarce and inadequate to search for missing resonances. The SPring-8/LEPS experiments,
13 with a spectrometer at forward angles, are complementary to CLAS experiments and can
14 provide valuable data for the missing resonance search.

15 We measured differential cross sections and photon-beam asymmetries for the $\pi^+ n$ reac-
16 tion. The photon beam asymmetries are sensitive to the existence of nucleon resonances.
17 Basically, the asymmetries are +1 for the ρ -exchange and are -1 for the π -exchange in the
18 t -channel [5]. Large positive asymmetries measured by CEA, DESY, and SLAC suggest that
19 ρ -exchange in the t -channel is the dominant reaction mechanism at $E_\gamma = 3.0$ GeV [6], 3.4
20 GeV [7], 12 GeV [8], and 16 GeV [9, 10]. However, some theoretical models predict asym-
21 metries with large positive values in the case of π -exchange in the t -channel [5, 11]. The
22 CLAS and GRAAL collaborations measured the asymmetries in a wide angular range with-
23 out forward and backward π^+ angles for $E_\gamma=1.102$ - 1.862 GeV [12] and $E_\gamma=0.8$ - 1.5 GeV [13],
24 respectively. Asymmetry data in the LEPS kinematical region are missing in the world data
25 set.

26 Data at higher energies in the small $|t|$ region ($|t| < 1 \text{ GeV}^2/c^2$) taken by SLAC were ex-
27 tensively studied by using Regge models [5, 14, 15]. The Regge models do not work correctly
28 near the threshold region where the s -channel is dominant. It is questionable whether the
29 Regge models work in the medium energy region. In the case of the $\gamma p \rightarrow K^+ \Lambda$ reaction,
30 Regge-Plus-Resonance model calculations successfully apply the Regge model at medium
31 energies [16, 17]. The present LEPS data, which were taken in the small $|t|$ region and

1 over a wide energy range, are suitable for studying the applicability of the Regge models.
2 The Mandelstam variable s dependence of the cross sections is expected to provide impor-
3 tant information on the Regge trajectories exchanged in the t -channel, as demonstrated by
4 Refs. [18–20]. Testing the consistency between the results from the photon-beam asymme-
5 tries and the cross sections helps us understand the π^+ photoproduction reaction.

6 Since the LEPS spectrometer [21] was designed to efficiently detect a ϕ meson decaying to
7 K^+ and K^- in the forward angles, there were huge backgrounds of positrons and electrons.
8 Using an Aerogel cherenkov counter was necessary to obtain clean ϕ -meson production [22–
9 26] and hyperon production [27–33] data although high-momentum charged pion data were
10 rejected by the online trigger. When the wavelength of the laser was changed from the UV
11 to the deep-UV region, the photon beam intensity and trigger rate decreased. We took
12 charged pion data for the first time in 2007. In this article, new LEPS data on differential
13 cross sections and photon-beam asymmetries for the $\vec{\gamma}p \rightarrow \pi^+n$ reaction are presented.

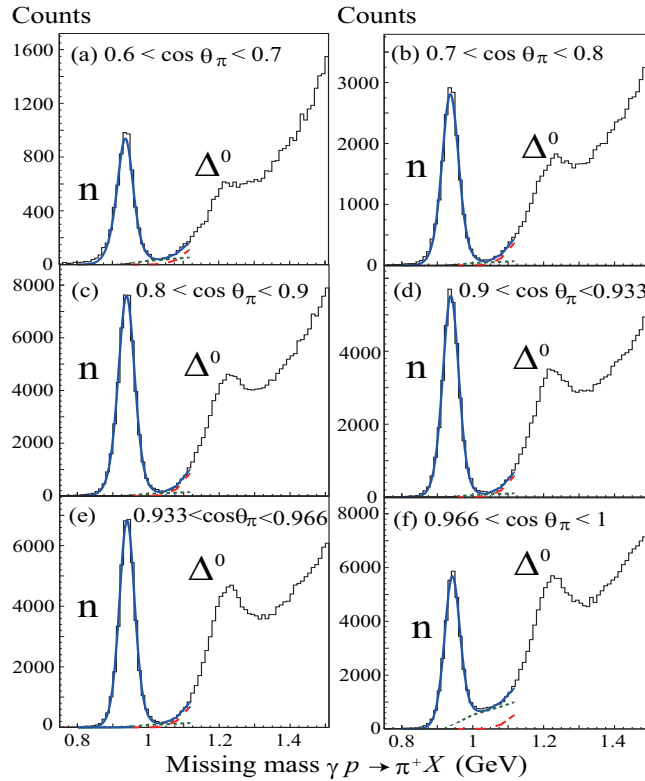
14 II. EXPERIMENT AND DATA ANALYSIS

15 The experiment was carried out by using the LEPS beam line [21] at the SPring-8 facility.
16 The photon beam was produced by the laser backscattering technique using a deep-UV laser
17 with a wavelength of 257 nm [34]. The energy range of the tagged photon beam was from
18 1.5 to 2.96 GeV. The laser light was linearly polarized with a typical polarization degree of
19 98%. The polarization of the tagged photon beams was 88% at 2.96 GeV and was 28% at
20 1.5 GeV. The photon beam was incident on a liquid hydrogen target (LH₂) with a length of
21 16 cm.

22 Charged particles produced at the target were detected at forward angles using the LEPS
23 spectrometer. Since the main purpose of the present experiment was to detect K^{*0} decaying
24 to K^+ and π^- with high momenta [35, 36], the Aerogel cherenkov counter was not used.
25 Electrons and positrons were effectively vetoed by installing a plastic scintillation counter
26 at the downstream position of the three drift chambers. The size of the scintillation counter
27 was 40 mm in height, 185 mm in width, and 20 mm in thickness. The scintillation counter
28 had a small hole 20 mm in height and 50 mm in width that allowed the incident γ -ray
29 beam to pass through. The details concerning the detector configuration and the quality of
30 particle identification are given in Refs. [21, 28, 36].

1 The π^+ meson events were identified from its measured mass within 3σ where σ is the
 2 momentum dependent mass resolution. The events of π^+ -mesons generated in the LH₂
 3 target were selected by the z-vertex distribution, and the contamination events from the
 4 start counter placed downstream from the target are 0.3% at most.

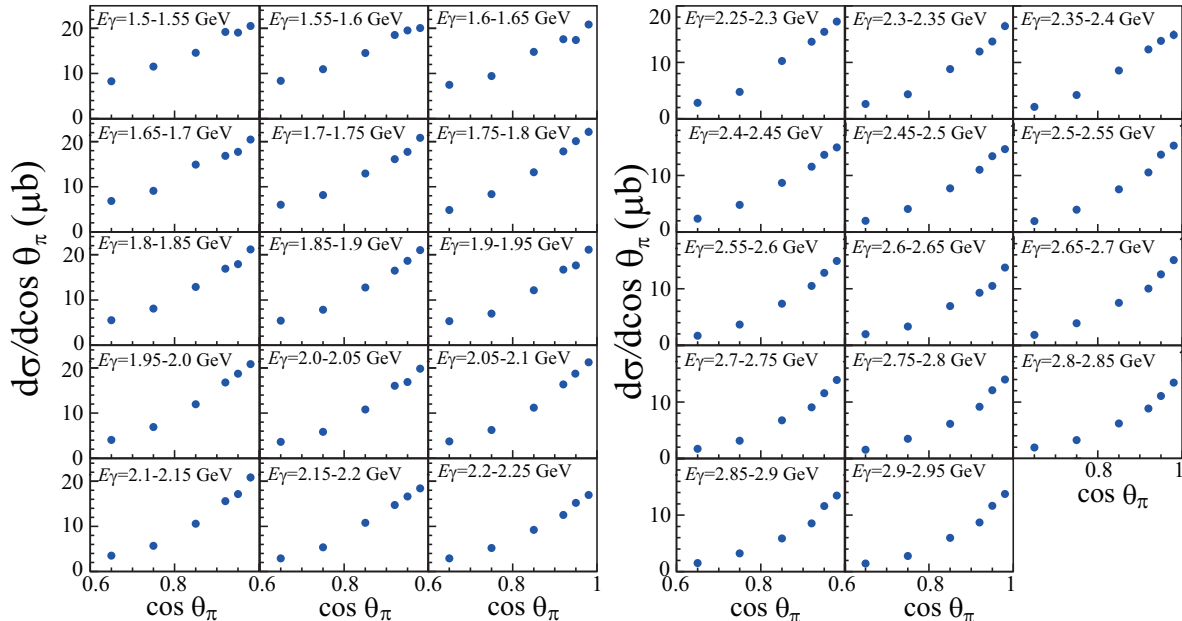
5 Figure 1 shows the missing mass spectra for the $\gamma p \rightarrow \pi^+ X$ reaction. Neutron peaks
 6 are clearly observed at 0.94 GeV/ c^2 and bumps due to $\Delta^0(1232)$ are also observed. The
 7 results for the $\pi^+ \Delta^0(1232)$ production are reported elsewhere [37, 38], although they are
 8 still preliminary. The number of $\pi^+ n$ events is about 171 k in total. The $\gamma p \rightarrow \pi^+ n$ reaction
 9 events are selected by fitting the missing mass spectra with a Gaussian function for the
 10 neutron peak, a positron background curve, and a $\pi\pi$ production curve. The acceptance of
 11 the LEPS spectrometer for π^+ -mesons is obtained by GEANT simulations.



12
 13 FIG. 1. Missing mass spectra for the $\gamma p \rightarrow \pi^+ X$ reaction for (a) $0.6 < \cos \theta_\pi < 0.7$, (b) $0.7 < \cos \theta_\pi$
 14 < 0.8 , (c) $0.8 < \cos \theta_\pi < 0.9$, (d) $0.9 < \cos \theta_\pi < 0.933$, (e) $0.933 < \cos \theta_\pi < 0.966$, and (f) $0.966 < \cos \theta_\pi$
 15 < 1 with $E_\gamma = 1.5\text{--}2.95$ GeV. The thick solid curves are the results of the fits, and the dotted and
 16 dashed curves are the contributions from the positron background and the $\pi\pi$ production events,
 17 respectively.

1 III. RESULTS

2 A. Differential cross sections $d\sigma/d\cos\theta_\pi$



3 FIG. 2. Differential cross sections $d\sigma/d\cos\theta$ for the $\gamma p \rightarrow \pi^+ n$ reaction as a function of $\cos\theta_\pi$.

4 Figure 2 shows the differential cross sections for the $\gamma p \rightarrow \pi^+ n$ reaction as a function of
5 $\cos\theta_\pi$ in the center-of-mass frame. Systematic uncertainties of target thickness and photon
6 flux are 1% and 3%, respectively. The cross sections increase rapidly as $\cos\theta_\pi$ approaches
7 1 in most of the energy regions. The angular dependence is relatively small at around
8 $E_\gamma=1.5$ GeV. Forward peaking of the cross sections is observed, which suggests that there are
9 significant t -channel contributions in the reaction mechanisms for this kinematical region. In
10 the present work, we could not confirm the sharp rising of the cross sections at very forward
11 π^+ angles observed in the SLAC data [18].

12 Differential cross sections as a function of E_γ are shown in Fig. 3. The cross sections
13 monotonically decrease with increasing photon beam energy for $0.6 < \cos\theta_\pi < 0.9$. For $0.9 <$
14 $\cos\theta_\pi < 1$, the cross sections are almost constant for $E_\gamma=1.5-2.2$ GeV ($W=1.9-2.2$ GeV) and
15 decrease above $E_\gamma=2.2$ GeV. The constant cross sections are considered to be due to a
16 nucleon or Δ resonance at forward π angles as reported by DESY [3, 4].

17 The LEPS cross sections for the $\pi^+ n$ reaction are in good agreement with the CLAS [2]

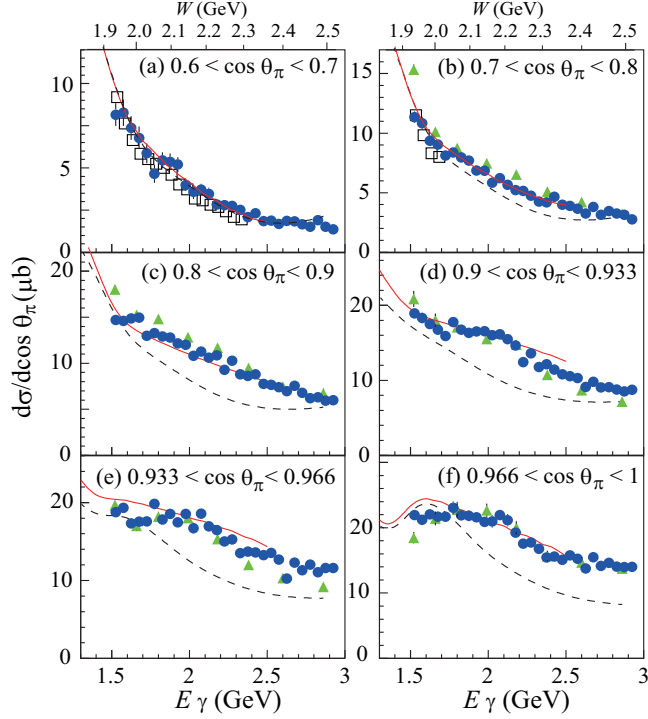


FIG. 3. Differential cross sections for the $\gamma p \rightarrow \pi^+ n$ reaction for (a) $0.6 < \cos \theta_\pi < 0.7$, (b) $0.7 < \cos \theta_\pi < 0.8$, (c) $0.8 < \cos \theta_\pi < 0.9$, (d) $0.9 < \cos \theta_\pi < 0.933$, (e) $0.933 < \cos \theta_\pi < 0.966$, and (f) $0.966 < \cos \theta_\pi < 1$ with $E_\gamma = 1.5 - 2.95$ GeV. The closed circles are the present LEPS data. The open squares and the closed triangles are the CLAS [2] and DESY data [3, 4], respectively. The solid curves are the results of the SAID analysis by the George Washington University group [11]. The dashed curves are the results of partial wave analysis by the Bonn-Gatchina group [39].

1 and DESY [3, 4] cross sections. The SAID analysis [11] reproduced the present data very
 2 well for $E_\gamma < 2.5$ GeV. The Bonn-Gatchina partial wave analysis calculations [39] reproduce
 3 the present data well for $0.6 < \cos \theta_\pi < 0.8$, but the calculations underestimate the data at
 4 small angles. The Bonn-Gatchina calculations were not fit to the DESY data, and the curves
 5 for $\cos \theta_\pi > 0.7$ are pure predictions.

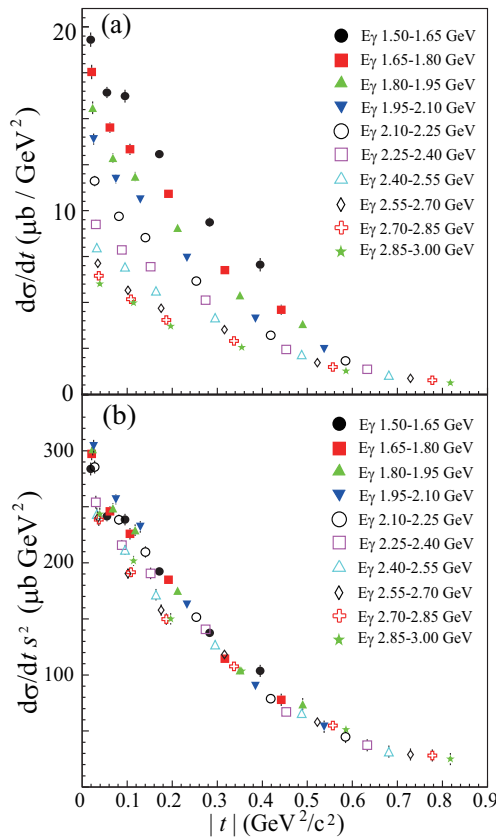
6 B. Differential cross sections $d\sigma/dt$

7 Figure 4(a) shows differential cross sections $d\sigma/dt$ for the $\gamma p \rightarrow \pi^+ n$ reaction as a function
 8 of $|t|$. With increasing photon energy, the cross sections decrease. Based on the Regge theory

1 assuming a single trajectory, the s dependence of the cross sections is written as

$$2 \quad \frac{d\sigma}{dt} = C(t) \left(\frac{s}{s_0} \right)^{2\alpha(t)-2}, \quad (1)$$

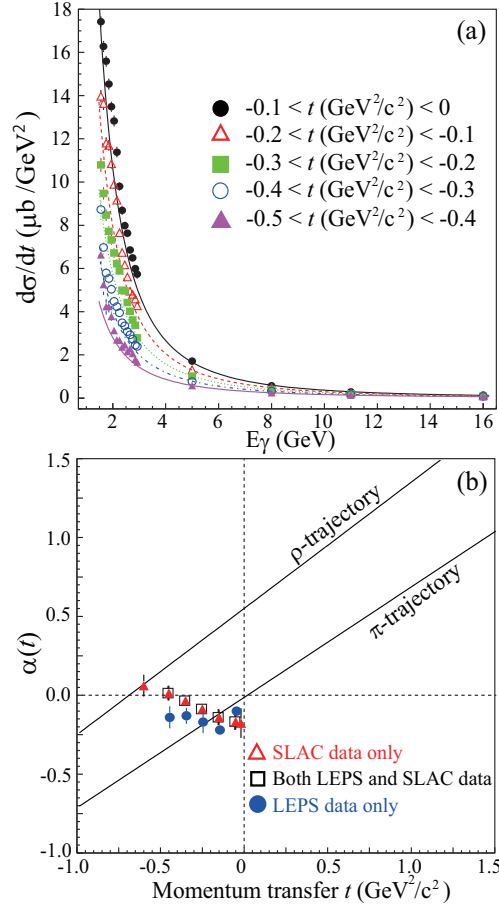
3 where $C(t)$ and $\alpha(t)$ are functions of t only, s_0 is a baryonic scale factor taken to be 1 GeV^2
 4 and s is calculated as $s = M_p^2 + 2M_p E_\gamma$ with M_p as the proton mass. The scaling of $d\sigma/dt$
 5 with s^2 almost removes the energy dependence as shown in Fig. 4(b). This result suggests
 6 $\alpha(t) \approx 0$. A similar result was obtained by CLAS collaboration for the $\gamma p \rightarrow K^+ \Lambda$ reaction
 7 for $E_\gamma=0.91\text{-}2.95 \text{ GeV}$ [40].



8
 9 FIG. 4. (a) Differential cross sections $d\sigma/dt$ for the $\gamma p \rightarrow \pi^+ n$ reaction as a function of $|t|$. (b)
 10 Differential cross sections scaled with s^2 as a function of $|t|$.

11 A small energy dependence still remains in the small $|t|$ region for $E_\gamma > 2.4 \text{ GeV}$ in
 12 Fig. 4(b). The assumption of $\alpha(t) \approx 0$ does not work well. Further studies are necessary
 13 to obtain effective $\alpha(t)$ values which give information on what trajectory is effective in the
 14 $\gamma p \rightarrow \pi^+ n$ reaction. Figure 5(a) shows the differential cross sections $d\sigma/dt$ for the $\gamma p \rightarrow$
 15 $\pi^+ n$ reaction measured by LEPS and SLAC. The cross sections were fit with the function

1 $C(t)s^{2\alpha(t)-2}$, where $C(t)$ and $\alpha(t)$ are free parameters for each t . Each curve is a result
 2 of fitting exclusively to the SLAC data, which were measured at high energies and are
 3 considered to be dominated by t -channel contributions. The curves slightly underestimate
 4 the LEPS data.



5

6 FIG. 5. (a) Differential cross sections $d\sigma/dt$ for the $\gamma p \rightarrow \pi^+ n$ reaction as a function of E_γ . The
 7 data $E_\gamma < 3.0$ GeV were measured by LEPS and the data $E_\gamma \geq 5$ GeV were measured by SLAC.
 8 The curves are the results of exclusive fits to the SLAC data. (b) The $\alpha(t)$ values for the γp
 9 $\rightarrow \pi^+ n$ reaction are the results from the SLAC(triangle), the LEPS and SLAC(squares), and the
 10 LEPS(circles). The π and ρ trajectories are represented using the functions of $\alpha_\pi(t)=0.7(t - m_\pi^2)$
 11 and $\alpha_\rho(t)=0.55+0.8t$, respectively [5].

12 The effective $\alpha(t)$ values are shown in Fig. 5(b). The $\alpha(t)$ values obtained from the
 13 SLAC data, the LEPS and SLAC data, and the LEPS data are close to each other. The
 14 present cross sections measured for $E_\gamma=1.5-2.95$ GeV are found to have almost the same s
 15 dependence as the SLAC data. The $\alpha(t)$ values obtained from the LEPS data are slightly

1 smaller than those from the SLAC data for $t < -0.1 \text{ GeV}^2/c^2$. The differences of the $\alpha(t)$
 2 values are considered to come from the differences of reaction mechanisms between the
 3 LEPS data and the SLAC data. Differences between the LEPS data and the curves in
 4 Fig. 5(a) are about 10-20% on average and estimated to be due to resonance contributions
 5 in the s -channel. The resonance contributions are small and the t -channel contributions are
 6 dominant in the LEPS kinematical region. The application of the Regge theory to the LEPS
 7 kinematical region seems to be acceptable. The $\alpha(t)$ values range between -0.22 and 0.06.
 8 The s dependence of the cross sections at t close to $0 \text{ GeV}^2/c^2$ favors the single π trajectory,
 9 while the dependence at t close to $-0.5 \text{ GeV}^2/c^2$ cannot be simply explained by the single
 10 π -trajectory.

11 C. Photon-beam asymmetry

12 We have measured the $\vec{\gamma}p \rightarrow \pi^+n$ data using vertically and horizontally polarized photon
 13 beams. The photon-beam asymmetry Σ is given as

$$14 \quad P_\gamma \Sigma \cos 2\phi_\pi = \frac{N_V - N_H}{N_V + N_H}, \quad (2)$$

15 where N_V and N_H are the π^+ yields with vertically and horizontally polarized photon beams,
 16 respectively, after correcting the difference of photon counts in both polarizations. P_γ is the
 17 polarization of the photon beams and ϕ_π is the π^+ azimuthal angle. Figure 6 shows the
 18 ratio $(N_V - N_H)/(N_V + N_H)$ for the $\vec{\gamma}p \rightarrow \pi^+n$ reaction events for $E_\gamma=1.5\text{-}2.9 \text{ GeV}$.

19 Since the LEPS spectrometer has a wide acceptance for the horizontal direction and a
 20 narrow acceptance for the vertical direction, the number of events is small at $\phi_\pi=\pm 90^\circ$ for
 21 $0.6 < \cos \theta_\pi < 0.9$. On the other hand, the number of events is small at $\phi_\pi=\pm 0^\circ$ and $\pm 180^\circ$
 22 for $0.966 < \cos \theta_\pi < 1$ because the veto counter for removing e^+e^- was installed. The ratio
 23 $(N_V - N_H)/(N_V + N_H)$ is large at 0° and $\pm 180^\circ$ and small at $\pm 90^\circ$, so π^+ -mesons prefer to
 24 scatter at ϕ_π angles perpendicular to the polarization plane. The photon-beam asymmetries
 25 are found to be positive. The amplitude of the ratio increases as the polar angle (θ_π) of the
 26 π^+ -mesons becomes smaller.

27 Figure 7 shows the photon-beam asymmetries for the $\vec{\gamma}p \rightarrow \pi^+n$ reaction. The systematic
 28 uncertainty of the measurement of the laser polarization is $\delta\Sigma=0.02$. The effects of the
 29 positron contamination in the π^+ sample and the start counter contamination in the LH₂

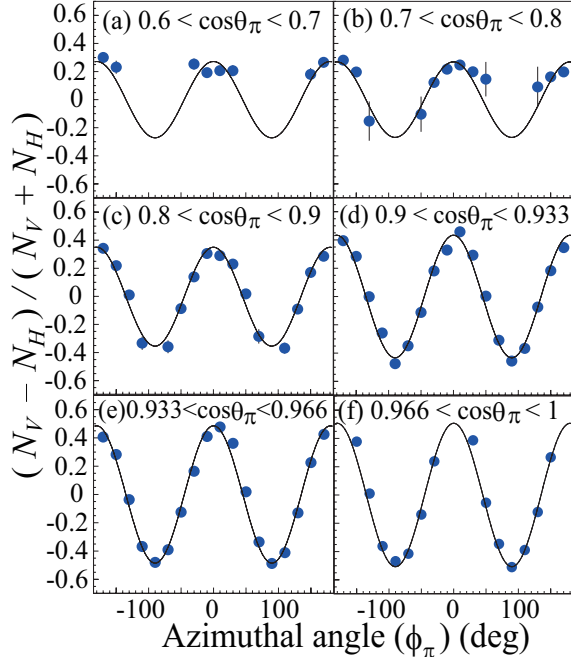


FIG. 6. The ratio $(N_V - N_H)/(N_V + N_H)$ as a function of π^+ azimuthal angle (ϕ_π) for the $\vec{\gamma}p \rightarrow \pi^+n$ reaction for (a) $0.6 < \cos \theta_\pi < 0.7$, (b) $0.7 < \cos \theta_\pi < 0.8$, (c) $0.8 < \cos \theta_\pi < 0.9$, (d) $0.9 < \cos \theta_\pi < 0.933$, (e) $0.933 < \cos \theta_\pi < 0.966$, and (f) $0.966 < \cos \theta_\pi < 1$ with $E_\gamma = 1.5\text{-}2.9$ GeV. The solid curves are the result of the fits with $P_\gamma \Sigma \cos 2\phi_\pi$.

1 target are removed. The asymmetries are positive in all the LEPS kinematical region, which
 2 can be explained by ρ -meson exchange in the t -channel.

3 The photon-beam asymmetries are small at large π^+ angles, while the asymmetries be-
 4 come large and approach unity at small π^+ angles. It is interesting that this angular depen-
 5 dence is different from the asymmetries obtained for the $\vec{\gamma}p \rightarrow K^+\Lambda$ and $K^+\Sigma^0$ reactions.
 6 The asymmetries for those two reactions become small at small K^+ angles [27]. The asym-
 7 metries for $0.9 < \cos \theta_\pi < 1$ and $E_\gamma = 1.5\text{-}2$ GeV are slightly smaller than those at higher
 8 energies. The differential cross sections also have different energy dependence in this kine-
 9 matical region as shown in Fig. 3. These results might suggest the existence of a nucleon or
 10 Δ resonance although the final conclusion should wait until a partial wave analysis is done
 11 over a wide kinematical region.

12 The agreement between the LEPS data and the CLAS data is good although the overlap
 13 of the photon energy region is limited. The SAID analysis by the George Washington
 14 University group well reproduces the present data for $0.7 < \cos \theta_\pi < 0.966$ and $E_\gamma < 2.5$ GeV.

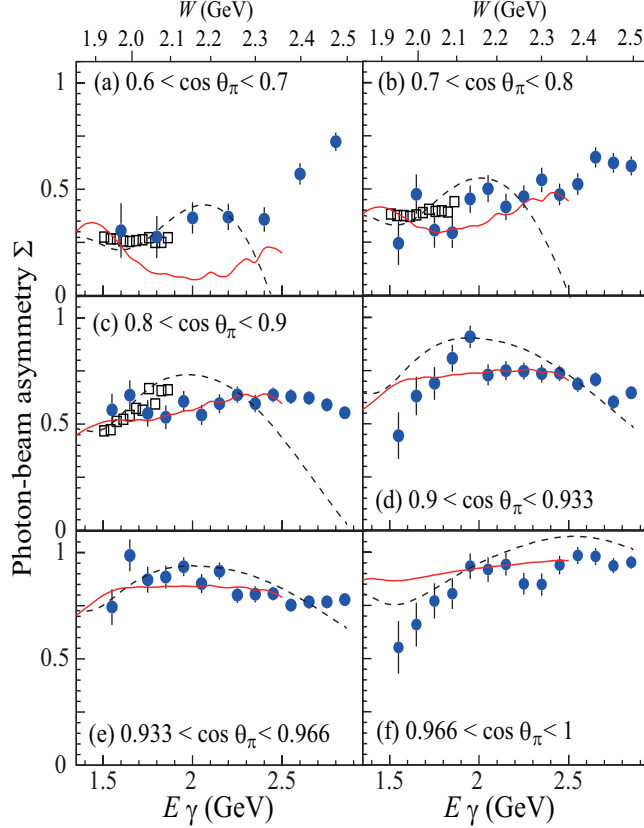


FIG. 7. Photon-beam asymmetries for the $\vec{\gamma}p \rightarrow \pi^+n$ reaction for $E_\gamma=1.5$ -2.95 GeV. The closed circles are the present LEPS data and the open squares are the CLAS data [12]. The solid curves are the results of the SAID analysis by the George Washington University group [11]. The dashed curves are the results of partial wave analysis performed by the Bonn-Gatchina group [39].

1 The SAID analysis underestimates the present data for $0.6 < \cos \theta_\pi < 0.7$. Calculations by
 2 the Bonn-Gatchina partial wave analysis almost reproduce the present data for $E_\gamma < 2.4$
 3 GeV. The Bonn-Gatchina calculations underestimate the present data for $\cos \theta_\pi < 0.9$ and
 4 $E_\gamma > 2.4$ GeV. The calculations are pure predictions for $E_\gamma > 2.4$ GeV.

5 The result of the ρ -exchange for the positive asymmetries seems to be in contradiction
 6 to the result obtained from the Regge model studies shown in Fig. 5 where the π -trajectory
 7 almost explains the s dependence of the cross sections $d\sigma/dt$ in the small π angles (t close to
 8 $0 \text{ GeV}^2/c^2$). The theoretical calculations given in Ref. [5, 11] predict positive photon-beam
 9 asymmetries in the case of the π -exchange. The positive asymmetries are obtained by an
 10 interference between the π -exchange in the t -channel and the s -channel resonances.

11 Figure 8 shows photon-beam asymmetries for the π^+n reaction as a function of $|t|$. The

1 asymmetries become large as $|t|$ becomes smaller. A similar $|t|$ dependence is observed at 16
 2 GeV [9]. The ρ -exchange contribution becomes small in the small $|t|$ region [5]. The forward
 3 peaking asymmetry observed in Fig. 8 cannot be explained by a ρ -exchange contribution.
 4 Large positive asymmetries in the small $|t|$ region could be due to π -exchange interference
 5 with the s -channel [5]. A final conclusion needs further advancements in theory or new data
 6 observables which can distinguish between the two contributions.

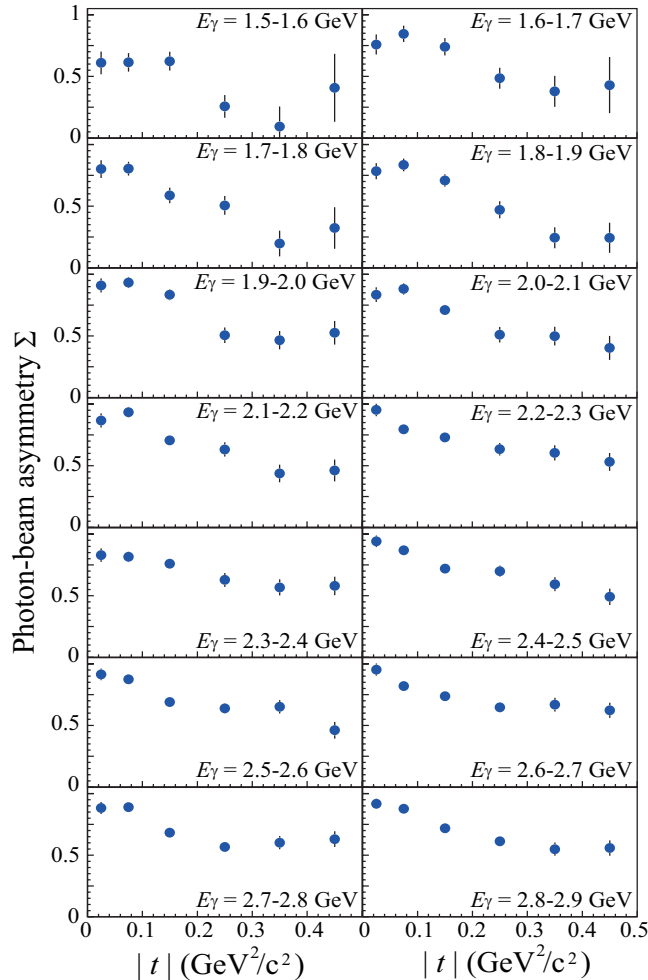


FIG. 8. Photon-beam asymmetries for the $\bar{\gamma}p \rightarrow \pi^+n$ reaction as a function of $|t|$.

8 IV. SUMMARY

9 We have carried out a photoproduction experiment observing the $\bar{\gamma}p \rightarrow \pi^+n$ reaction by
 10 using linearly polarized tagged photon beams with energies from 1.5 to 2.95 GeV. Differen-
 11 tial cross sections and photon-beam asymmetries have been measured for $0.6 < \cos \theta_\pi < 1$.

1 The differential cross sections monotonically decrease as the photon beam energy increases
2 for $0.6 < \cos \theta_\pi < 0.9$, while the cross sections are close to constant values for $E_\gamma=1.5-2.2$
3 GeV ($W=1.9-2.2$ GeV) and decrease above $E_\gamma=2.2$ GeV for $0.9 < \cos \theta_\pi < 1$. This energy
4 dependence for $E_\gamma=1.5-2.2$ GeV is inferred to be due to a nucleon or Δ resonance although
5 the final conclusion should wait for a partial wave analyses over a wider kinematical region.

6 Regge model studies on the s dependence of $d\sigma/dt$ give $\alpha(t)$ values close to the π -
7 trajectory at t close to $0 \text{ GeV}^2/c^2$. Positive asymmetries found for the $\vec{\gamma}p \rightarrow \pi^+n$ reaction
8 can be explained by ρ -exchange in the t -channel. Large positive asymmetries in the small
9 $|t|$ region could be explained by the π -exchange interference with the s -channel as suggested
10 by some theoretical calculations [5, 11]. Experimentally, we are developing a polarized HD
11 target [41] for LEPS experiments, and CLAS has already taken data with polarized bu-
12 tanol [42, 43] and HD targets [44]. Rich physics observables measured by using polarized
13 targets and polarized photon beams are expected to appear soon. Theoretically, partial wave
14 analyses using these physics observables are available. The photon-beam asymmetry is a
15 strong constraint to theoretical models. Our data will provide an important contribution to
16 advanced theoretical studies that we hope will clarify the hadron photoproduction dynamics
17 in the near future.

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