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

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Differential cross sections and photon-beam asymmetries for the $\vec{\gamma}p \to \pi^+ n$ reaction have been measured for $0.6 < \cos\theta_\pi < 1$ and $E_\gamma = 1.5$–2.95 GeV at SPring-8/LEPS. The cross sections monotonically decrease as the photon beam energy increases for $0.6 < \cos\theta_\pi < 0.9$. However, the energy 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 different, which may be due to a nucleon or Δ resonance. The present cross sections agree well with the previous cross sections measured by other groups and show forward peaking, suggesting significant t-channel contributions in this kinematical region. The asymmetries are found to be positive, which can be explained by ρ exchange in the t channel. Large positive asymmetries in the small-$|t|$ region, where the ρ-exchange contribution becomes small, could be explained by introducing π-exchange interference with the s channel.

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I. INTRODUCTION

Photoproduction of mesons is of special importance in the search for missing nucleon resonances. In quark models, there exist more nucleon resonances than have been experimentally observed so far [1]. Since the nucleon resonances have relatively wide widths and are overlapping in mass, it is necessary to establish new resonances by performing partial-wave analyses based on rich physics observables over wide angular and energy regions. The $\gamma p \to \pi^+ n$ reaction is one of the most basic photoproduction reactions. The $\gamma p \to \pi^+ n$ reaction has relatively large cross sections of $\sim$10 μb, which enables measurements of physics observables to clarify the reaction dynamics. The Jefferson Lab CLAS group has measured differential cross sections [2] in a wide angular region without forward and backward π^+ angles for $E_\gamma = 0.725$–2.875 GeV. Existing data at forward π^+ angles taken for $E_\gamma = 1.2$–3.0 GeV by DESY [3,4] are scarce and inadequate to search for missing resonances. Experiments at the Laser Electron Photon experiment at SPring-8 (LEPS), with a spectrometer at forward angles, are complementary to CLAS experiments and can provide valuable data for the missing resonance search.

We measured differential cross sections and photon-beam asymmetries for the $\pi^+ n$ reaction. The photon-beam asymmetries are sensitive to the existence of nucleon resonances. Basically, the asymmetries are +1 for the ρ exchange and are -1 for the π exchange in the t channel [5]. Large positive asymmetries measured by CEA, DESY, and the Stanford Linear Accelerator Center (SLAC) suggest that ρ exchange in the t channel is the dominant reaction mechanism at $E_\gamma =$ 3.0 GeV [6], 3.4 GeV [7], 12 GeV [8], and 16 GeV [9,10]. However, some theoretical models predict asymmetries with large positive values in the case of π exchange in the t channel [5,11]. The CLAS and GRAAL collaborations measured the asymmetries in a wide angular range without forward and backward π^+ angles for $E_\gamma = 1.102$–1.862 GeV [12] and $E_\gamma = 0.8$–1.5 GeV [13], respectively. Asymmetry data in the LEPS kinematical region are missing in the world data set.

Data at higher energies in the small-$|t|$ region ($|t| <$ 1 GeV$^2/c^2$) taken by SLAC were extensively studied by using Regge models [5,14,15]. The Regge models do not work correctly near the threshold region where the s channel is dominant. It is questionable whether the Regge models work in the medium-energy region. In the case of the $\gamma p \to K^+\Lambda$ reaction, Regge-plus-resonance model calculations successfully apply the Regge model at medium energies [16,17]. The present LEPS data, which were taken in the small-$|t|$ region and over a wide energy range, are suitable for studying the applicability of the Regge models. The Mandelstam variable s dependence of the cross sections is expected to provide important information on the Regge trajectories exchanged in the t channel, as demonstrated by Refs. [18–20]. Testing the consistency between the results from the photon-beam asymmetries and the cross sections helps us understand the π^+ photoproduction reaction.

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

II. EXPERIMENT AND DATA ANALYSIS

The experiment was carried out by using the LEPS beam line [21] at the SPring-8 facility. The photon beam was produced by the laser backscattering technique using a deep-UV laser with a wavelength of 257 nm [34]. The energy range of the tagged photon beam was from 1.5 to 2.96 GeV. The laser light was linearly polarized with a typical polarization degree of 98%. The polarization of the tagged photon beams was 88% at 2.96 GeV and was 28% at 1.5 GeV. The photon beam was incident on a liquid hydrogen target (LH_2) with a length of 16 cm.

Charged particles produced at the target were detected at forward angles by using the LEPS spectrometer. Since the main purpose of the present experiment was to detect K^{*0} decaying to K^+ and π^- with high momenta [35,36], the aerogel

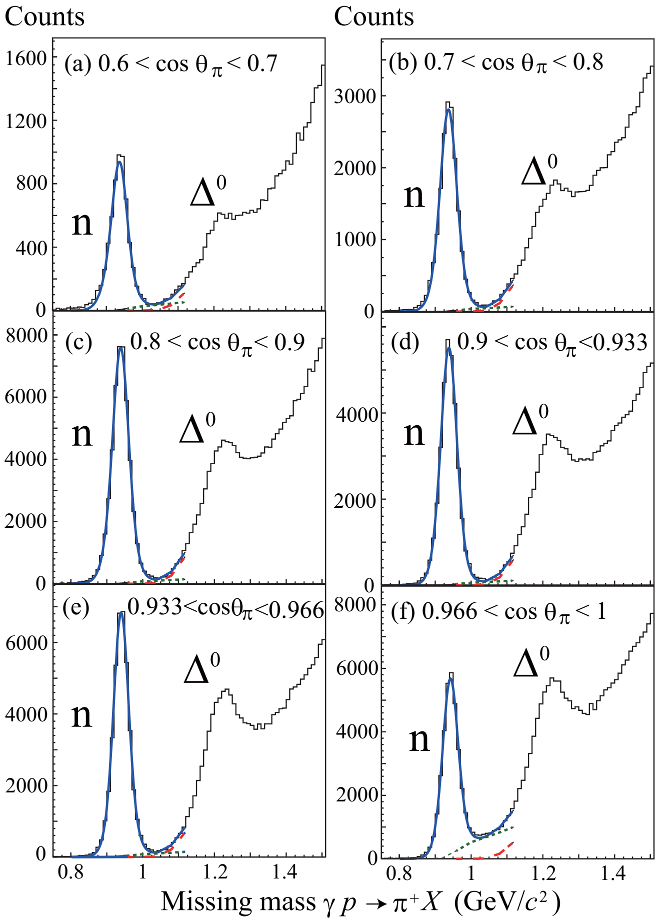

FIG. 1. Missing mass spectra for the $\gamma p \to \pi^+ X$ reaction for (a) $0.6 < \cos\theta_\pi < 0.7$, (b) $0.7 < \cos\theta_\pi < 0.8$, (c) $0.8 < \cos\theta_\pi < 0.9$, (d) $0.9 < \cos\theta_\pi < 0.933$, (e) $0.933 < \cos\theta_\pi < 0.966$, and (f) $0.966 < \cos\theta_\pi < 1$ with $E_\gamma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

Cherenkov counter was not used. Electrons and positrons were effectively vetoed by installing a plastic scintillation counter at the downstream position of the three drift chambers. The size of the scintillation counter was 40 mm in height, 185 mm in width, and 20 mm in thickness. The scintillation counter had a small hole 20 mm in height and 50 mm in width that allowed the incident γ-ray beam to pass through. The details concerning the detector configuration and the quality of particle identification are given in Refs. [21,28,36].

The π^+ meson events were identified from its measured mass within 3σ where σ is the momentum-dependent mass resolution. The events of π^+ mesons generated in the LH_2 target were selected by the z-vertex distribution, and the contamination events from the start counter placed downstream from the target are 0.3% at most.

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

III. RESULTS

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

Figure 2 shows the differential cross sections for the $\gamma p \to \pi^+ n$ reaction as a function of $\cos\theta_\pi$ in the center-of-mass frame. Systematic uncertainties of target thickness and photon flux are 1% and 3%, respectively. The cross sections increase rapidly as $\cos\theta_\pi$ approaches 1 in most of the energy regions. The angular dependence is relatively small at around $E_\gamma = 1.5$ GeV. Forward peaking of the cross sections is observed, which suggests that there are significant t-channel contributions in the reaction mechanisms for this kinematical region. In the present work, we could not confirm the sharp rising of the cross sections at very forward π^+ angles observed in the SLAC data [19].

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

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

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

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

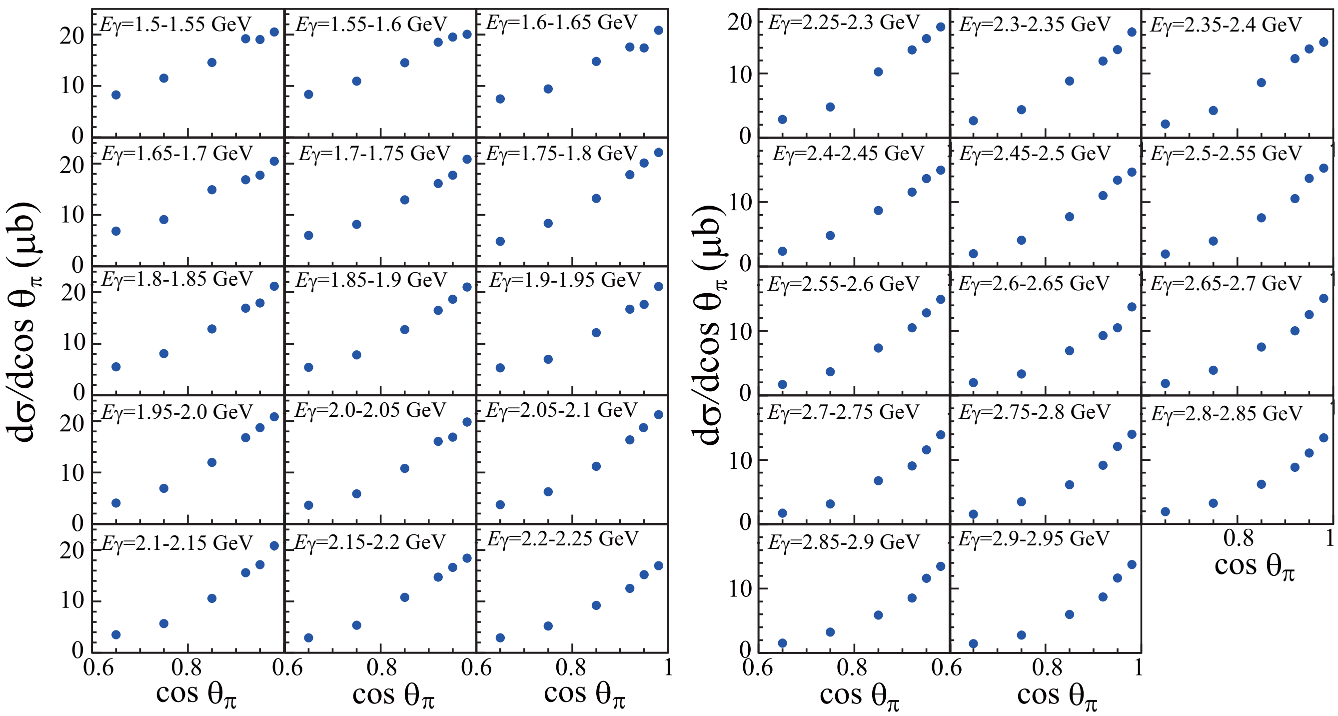

FIG. 2. Differential cross sections $d\sigma/d\cos\theta$ for the $\gamma p \to \pi^+ n$ reaction as a function of $\cos\theta_\pi$.

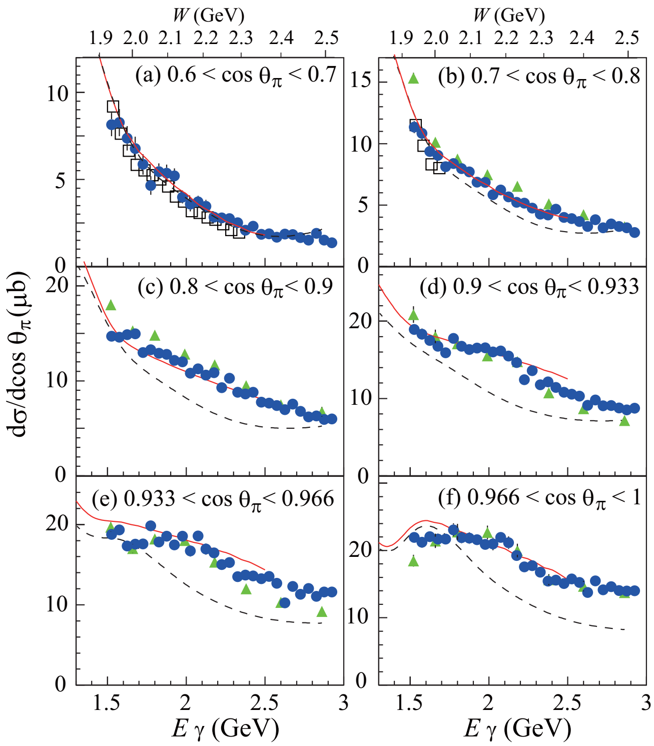

FIG. 3. Differential cross sections for the $\gamma p \to \pi^+ n$ reaction for (a) $0.6 < \cos\theta_\pi < 0.7$, (b) $0.7 < \cos\theta_\pi < 0.8$, (c) $0.8 < \cos\theta_\pi < 0.9$, (d) $0.9 < \cos\theta_\pi < 0.933$, (e) $0.933 < \cos\theta_\pi < 0.966$, and (f) $0.966 < \cos\theta_\pi < 1$ with $E_\gamma = 1.5$–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].

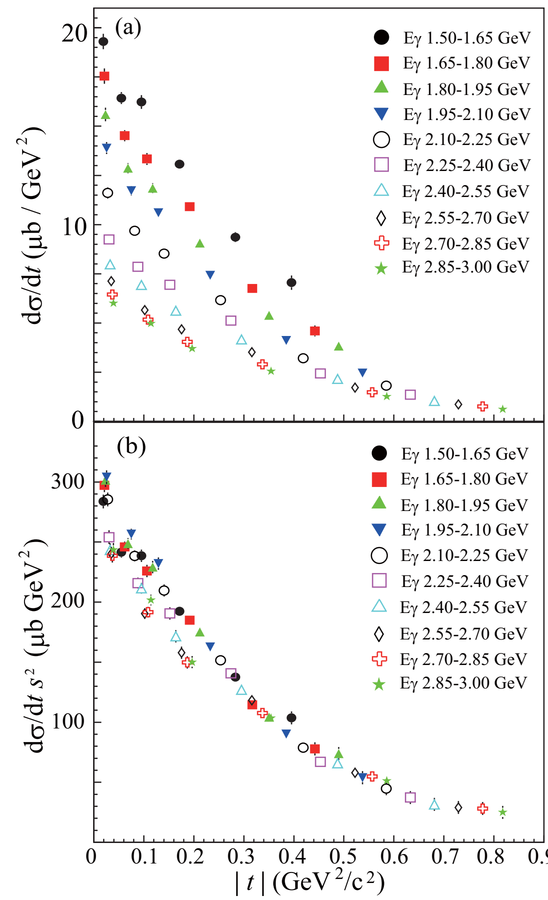

FIG. 4. (a) Differential cross sections $d\sigma/dt$ for the $\gamma p \to \pi^+ n$ reaction as a function of $|t|$. (b) Differential cross sections scaled with s^2 as a function of $|t|$.

cross sections is written as

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

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

A small energy dependence still remains in the small-$|t|$ region for $E_\gamma > 2.4$ GeV in Fig. 4(b). The assumption of $\alpha(t) \approx 0$ does not work well. Further studies are necessary to obtain effective $\alpha(t)$ values which give information on what trajectory is effective in the $\gamma p \to \pi^+ n$ reaction. Figure 5(a) shows the differential cross sections $d\sigma/dt$ for the $\gamma p \to \pi^+ n$ reaction measured by LEPS and SLAC. The cross sections were fit with the function $C(t)s^{2\alpha(t)-2}$, where $C(t)$ and $\alpha(t)$ are free parameters for each t. Each curve is a result of fitting exclusively to the SLAC data, which were measured at high energies and are considered to be dominated by t-channel contributions. The curves slightly underestimate the LEPS data.

The effective $\alpha(t)$ values are shown in Fig. 5(b). The $\alpha(t)$ values obtained from the SLAC data, the LEPS and SLAC data, and the LEPS data are close to each other. The present cross sections measured for $E_\gamma = 1.5$–2.95 GeV are found to have almost the same s dependence as the SLAC data. The $\alpha(t)$ values obtained from the LEPS data are slightly smaller than those from the SLAC data for $t < -0.1$ GeV$^2/c^2$. The differences of the $\alpha(t)$ values are considered to come from the differences of reaction mechanisms between the LEPS data and the SLAC data. Differences between the LEPS data and the curves in Fig. 5(a) are about 10%–20% on average and estimated to be due to resonance contributions in the s channel. The resonance contributions are small and the t-channel contributions are dominant in the LEPS kinematical region. The application of the Regge theory to the LEPS kinematical region seems to be acceptable. The $\alpha(t)$ values range between -0.22 and 0.06. The s dependence of the cross sections at t close to 0 GeV$^2/c^2$ favors the single π trajectory, while the dependence at t close to -0.5 GeV$^2/c^2$ cannot be simply explained by the single π trajectory.

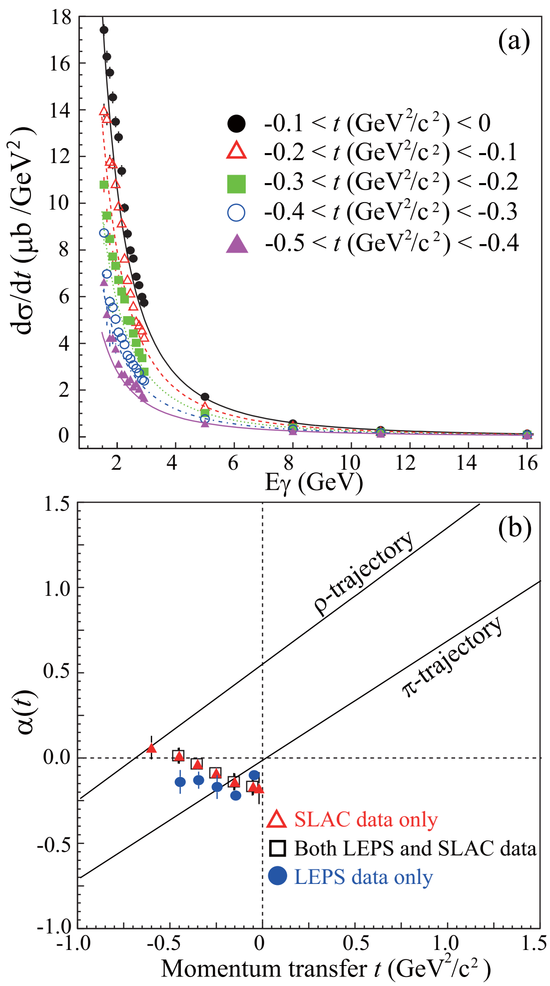

FIG. 5. (a) Differential cross sections $d\sigma/dt$ for the $\gamma p \to \pi^+ n$ reaction as a function of E_γ. The data $E_\gamma < 3.0$ GeV were measured by LEPS and the data $E_\gamma \geqslant 5$ GeV were measured by SLAC. The curves are the results of exclusive fits to the SLAC data. (b) The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

C. Photon-beam asymmetry

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

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

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

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

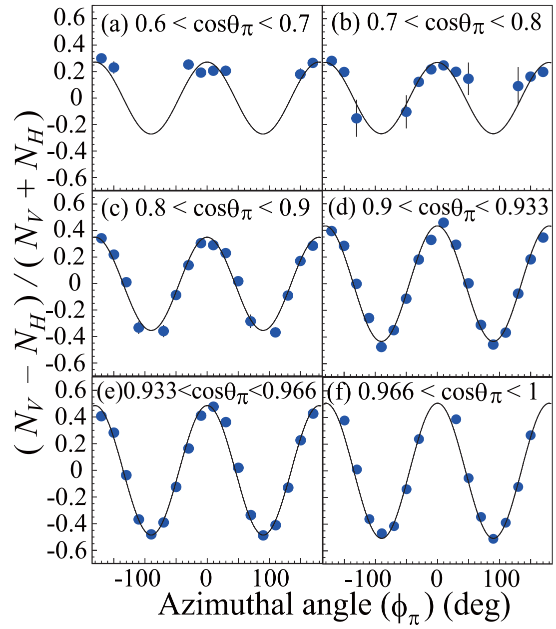

FIG. 6. The ratio $(N_V - N_H)/(N_V + N_H)$ as a function of π^+ azimuthal angle (ϕ_π) for the $\vec{\gamma} p \to \pi^+ n$ reaction for (a) $0.6 < \cos\theta_\pi < 0.7$, (b) $0.7 < \cos\theta_\pi < 0.8$, (c) $0.8 < \cos\theta_\pi < 0.9$, (d) $0.9 < \cos\theta_\pi < 0.933$, (e) $0.933 < \cos\theta_\pi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

Figure 7 shows the photon-beam asymmetries for the $\vec{\gamma} p \to \pi^+ n$ reaction. The systematic uncertainty of the measurement of the laser polarization is $\delta\Sigma = 0.02$. The effects of the positron contamination in the π^+ sample and the start counter contamination in the LH_2 target are removed. The asymmetries are positive in all the LEPS kinematical region, which can be explained by ρ-meson exchange in the t channel.

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

The agreement between the LEPS data and the CLAS data is good although the overlap of the photon energy region

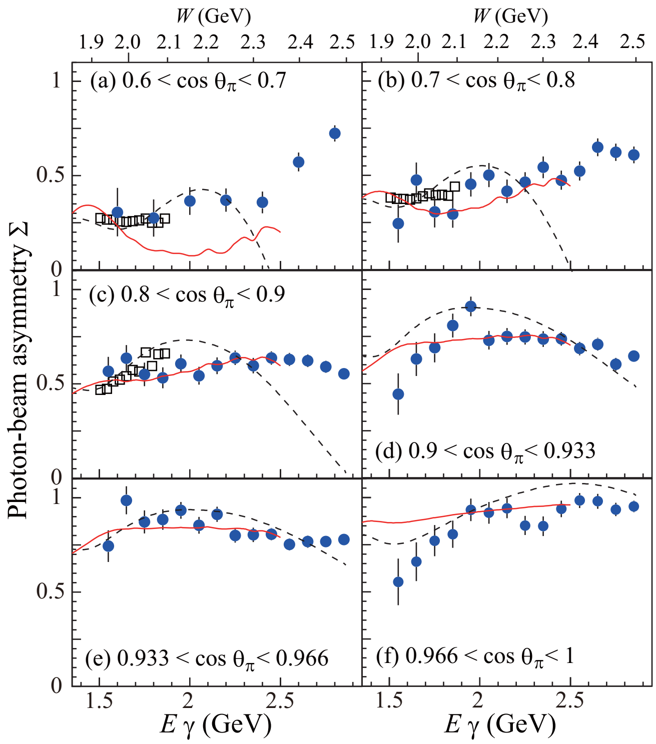

FIG. 7. Photon-beam asymmetries for the $\vec{\gamma} p \rightarrow \pi^+ n$ reaction for $E_\gamma = 1.5$–2.95 GeV. The closed circles are the present LEPS data and the open squares are the CLAS data [12]. The solid curves are the results of the SAID analysis by the George Washington University group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

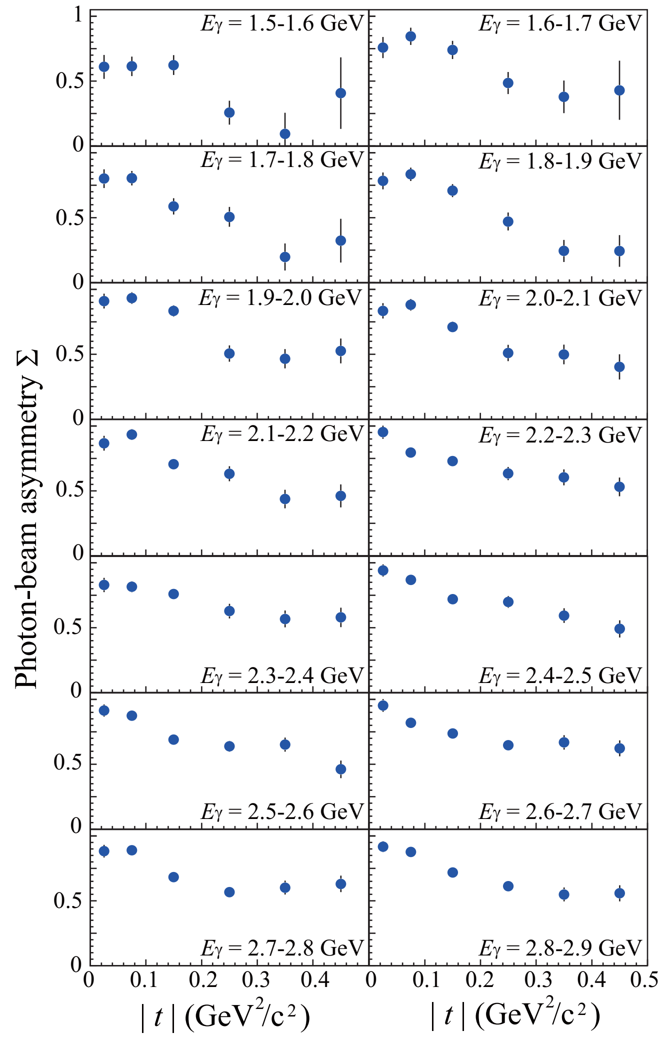

FIG. 8. Photon-beam asymmetries for the $\vec{\gamma} p \rightarrow \pi^+ n$ reaction as a function of $|t|$.

is limited. The SAID analysis by the George Washington University group well reproduces the present data for $0.7 < \cos\theta_\pi < 0.966$ and $E_\gamma < 2.5$ GeV. The SAID analysis underestimates the present data for $0.6 < \cos\theta_\pi < 0.7$. Calculations by the Bonn–Gatchina partial-wave analysis almost reproduce the present data for $E_\gamma < 2.4$ GeV. The Bonn–Gatchina calculations underestimate the present data for $\cos\theta_\pi < 0.9$ and $E_\gamma > 2.4$ GeV. The calculations are pure predictions for $E_\gamma > 2.4$ GeV.

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

Figure 8 shows photon-beam asymmetries for the $\pi^+ n$ reaction as a function of $|t|$. The asymmetries become large as $|t|$ becomes smaller. A similar $|t|$ dependence is observed at 16 GeV [9]. The ρ-exchange contribution becomes small in the small-$|t|$ region [5]. The forward-peaking asymmetry observed in Fig. 8 cannot be explained by a ρ-exchange contribution. Large positive asymmetries in the small-$|t|$ region could be due to π-exchange interference with the s channel [5]. A final conclusion needs further advancements in theory or new data observables which can distinguish between the two contributions.

IV. SUMMARY

We have carried out a photoproduction experiment observing the $\vec{\gamma} p \rightarrow \pi^+ n$ reaction by using linearly polarized tagged photon beams with energies from 1.5 to 2.95 GeV. Differential cross sections and photon-beam asymmetries have been measured for $0.6 < \cos\theta_\pi < 1$. The differential cross sections monotonically decrease as the photon beam energy increases for $0.6 < \cos\theta_\pi < 0.9$, while the cross sections are close to constant values for $E_\gamma = 1.5$–2.2 GeV ($W = 1.9$–2.2 GeV) and decrease above $E_\gamma = 2.2$ GeV for $0.9 < \cos\theta_\pi < 1$. This energy dependence for $E_\gamma = 1.5$–2.2 GeV is inferred to be due to a nucleon or Δ resonance although the final conclusion should wait for a partial-wave analysis over a wider kinematical region.

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

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