Measurement of beam asymmetry for $\pi^- \Delta^{++}$ photoproduction on the proton at $E_{\gamma} = 8.5$ GeV

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We report a measurement of the $\pi^-$ photoproduction beam asymmetry for the reaction $\vec{\gamma} p \to \pi^- \Delta^{++}$ using data from the GlueX experiment in the photon beam energy range 8.2–8.8 GeV. The asymmetry $\Sigma$ is measured as a function of four-momentum transfer $t$ to the $\Delta^{++}$ and compared to...
I. INTRODUCTION

Determining the types of mesons that emerge from quantum chromodynamics (QCD) is a critical experimental input to our understanding of how QCD generates the properties of hadrons [1]. The GLUEX experiment at Jefferson Lab provides a unique opportunity to search for non-\( q\bar{q}\) mesons and, by using a linearly polarized photon beam, study their production dynamics in addition to their decay properties. The GLUEX photon beam energy of 8-9 GeV is in a regime where photoproduction of hadrons can be described by \( t\)-channel exchange processes [2], and the properties of exchanged Reggeons can be constrained by experimental data. In particular, the linear polarization of the beam allows one to distinguish between exchange of particles with natural \((P(1)^J = 1)\) and unnatural \((P(1)^J = -1)\) parity [3,4]. Ultimately, this gives insight into the coupling of the produced meson and the photon to particular sets of Reggeons. This knowledge of production mechanisms for known mesons can be leveraged in the future search for exotic hybrid mesons using GLUEX data.

Measurements that constrain production mechanisms at photon beam energies relevant for the GLUEX experiment are sparse. Recent measurements on the photoproduction of pseudoscalar mesons [5-7] have begun to provide insight into into production mechanisms. In particular, this reaction requires charge exchange, allowing us to probe pion exchange and the significance of higher-order corrections to one-pion exchange at low momentum transfer. Constraining production mechanisms of conventional mesons may aid in the search for and study of unconventional mesons. This is the first measurement of the process at this energy.

II. EXPERIMENTAL APPARATUS

The GLUEX experiment utilizes the 12 GeV Continuous Electron Beam Accelerator Facility (CEBAF) to produce a beam of linearly polarized photons via coherent bremsstrahlung radiation on a thin (50 \( \mu \)m) diamond wafer [19]. Measuring the momentum of the electron after radiation using a hodoscope allows the energy of the radiated photon to be determined with a resolution of 10 MeV in the beam energy range of interest. By orienting the radiator, one may tune the coherent bremsstrahlung peak energy and direction of linear polarization. Four data sets of approximately equal statistics were collected with the coherent bremsstrahlung enhancement in the 8.2–8.8 GeV region and polarization oriented in four directions relative to the laboratory floor plane: -45°, 0°, 45°, and 90°. We group these independent data sets in pairs of orthogonal orientations and refer to them as ‘0/90’ or ‘-45/45’, each of which is used to make a measurement of the observable of interest. Within each set we label the 0 and -45 as \( | \) and the 90 and 45 as \( \perp \).

Beam photons travel 75 m from the radiator and pass through a 5 mm diameter collimator to enhance the polarization, as coherent bremsstrahlung photons are preferentially produced at small angles with respect to the beam axis. A downstream 75 \( \mu \)m beryllium converter allows for photon beam flux and polarization measurements. Flux is measured from \( e^+e^- \) pair production measured in a pair spectrometer (PS) [20]. Polarization is measured via detection of the recoil atomic electron of the triplet production process in the triplet polarimeter (TPOL) [21]. The azimuthal angle of this electron is sensitive to the photon polarization plane. The photon polarization is measured independently for each polarization direction as a function of \( E_\gamma \), with polarization values up to 40\%, as shown in Fig. 1. The statistical uncertainty in polarization is determined by the number of triplet production events detected. The systematic uncertainty of the instrument is 1.5\%.

The GLUEX spectrometer is an azimuthally symmetric...
Polarization about 1 GeV/° coverage, polar angle coverage from 11° to 120° for charged track reconstruction with uniform azimuthal cathode strip readouts. These two tracking systems allow the target volume and produce hits in the TOF or BCAL. Both detectors provide timing information used for time-of-flight measurements, which are required to be consistent with either a proton or pion hypothesis, as appropriate.

The vast majority of protons in this topology are produced at polar angles greater than 20° and with momentum lower than 1 GeV/c. In this case, energy loss dE/dx measured in the CDC is effective at further distinguishing proton and π+ candidates.

Each reconstructed event is also required to be matched to a suitable reconstructed radiating electron that is a candidate for the electron that radiated the beam photon. The momentum of this electron determines the photon energy. The CEBAF accelerator delivers the electron beam in bunches with a 4 ns period. Hit information from the ST determines the beam bunch, and a precise value of arrival time of the bunch at the target center (t_bunch) is provided by the accelerator radio-frequency clock. We require electron candidates have a time t_e such that |t_e−t_bunch| < 2 ns. Due to the hit multiplicity in the tagger, more than one electron is typically detected per event, though only one of these electrons corresponds to the beam photon that interacted downstream. To remove electrons incorrectly (“accidentally”) associated with the triggered downstream event, we also select a statistically independent sample of events that satisfy 2 ns < |t_e−t_bunch| < 18 ns. This selects additional beam bunches which, when scaled appropriately, can be used to remove the contribution of these accidentals to the analysis.

We impose several constraints to ensure the purity of the exclusive reaction of interest. First, the measured missing mass squared is required to satisfy |p_t − p_i|< 0.1 GeV² to suppress the contribution from events with undetected massive particles, where p_t and p_i are the sum of all initial and final four-momenta respectively. Then, a kinematic fit is performed, enforcing conservation of energy and momentum and a common vertex, assuming the exclusive topology γ(8.2 GeV) → π⁺π⁻p. We require that the kinematic fit χ²/NDF satisfies χ²/NDF < 8.7 to ensure that events are well-reconstructed and match the desired topology.

A number of intermediate states contribute to the reaction γ → π⁺π⁻p in addition to the desired π⁺Δ⁻⁰ channel. In particular, the topology is dominated by production of the ρ² meson. We require 1.10 GeV/c² < m_π⁺π⁻ < 2.45 GeV/c² to reduce backgrounds, particularly from ρ and Δ⁺ production. This selection removes most of the ρ² background, as shown in Fig. 2.
The differential cross section for pseudoscalar production by a polarized photon beam is related to the total cross section $\sigma_0$ by

$$\frac{d\sigma}{d\phi} = \sigma_0 \left( 1 - P \sum \cos [2(\phi - \phi_{\text{lin}})] \right),$$

where $\phi$ is the azimuthal angle of the production plane in the lab, $\phi_{\text{lin}}$ is the azimuthal angle of beam polarization in the lab, $P$ is the degree of linear polarization of the beam, and $\sum$ is the observable to be measured. By using data collected with linear polarization in orthogonal directions, the term $\Sigma$ can be isolated without explicitly determining the total cross section or any $\phi$-dependent detector acceptance.

As shown in Fig. 3(a), selecting a region of $m(\pi^+ p)$ invariant mass does not ensure a pure sample of $\Delta^{++}$ events. Previous analyses typically first select a pure sample of events, and then produce a distribution in $\Delta\phi$. (Here $\Delta\phi \equiv \phi - \phi_{\text{lin}}$ in Eq. (1).) The amplitude of the $\cos(2\Delta\phi)$ component is then extracted to obtain $\Sigma$. In what follows, we perform the steps in reverse order: we project the $\cos 2\Delta\phi$ component of all data and then isolate the $\Delta^{++}$ contribution by using the known lineshape of the $\Delta^{++}$. The technique follows from that used to determine coefficients of a Fourier expansion. One can weight individual events by $\cos(n\Delta\phi)$ and create weighted histograms in $m(\pi^+ p)$, thereby integrating over $\Delta\phi$. The bin-by-bin contents of such histograms are then proportional to the strength of the $\cos(n\Delta\phi)$ component. One can then fit these histograms, referred to later as $H_n$, to measure the $\Delta^{++}$ contribution to each, referred to as $Y_n$, with the $Y_2$ component being most sensitive to $\Sigma$.

Practically, one must use orthogonal orientations of the beam polarization to cancel detector acceptance in the formulation of $\Sigma$. The full prescription for implementing this technique is documented in Refs. [31, 33].

Following this prescription, we define a set of weighted invariant mass $m(\pi^+ p)$ histograms for each separate orientation of polarization $H_n^{\perp/\parallel}$, each with accidental beam photon candidates subtracted as described above. Data in 0/90 orientations are given an event-by-event weighting of $\cos(n\phi)$, while $-\sin(n\phi)$ is used for data in the -45/45 orientations. The shape of the $\Delta^{++}$ in each $t$ region can be described by a relativistic Breit-Wigner function multiplied by a phase space factor $[34]$:

$$S(m) = \frac{|p|}{m} \left| \frac{A}{m_0^2 - m^2 - i\Gamma(m)} \right|^2,$$

where $A$ is a parameter determined by a maximum likelihood fit, and

$$\Gamma(m) = \Gamma_0 \left( \frac{m_0}{m} \right)^2 \left( \frac{1 + |p|^2 \sigma^2}{1 + |p_0|^2 \sigma^2} \right),$$

Here, $m$ and $p$ refer to the invariant mass of the $\pi^+ p$ system and the three-momentum of the proton (or pion) in the $\pi^+ p$ rest frame. The values of $m_0$ and $\Gamma_0$ are $\Delta^{++}$ resonance parameters obtained from Ref. [35], and $|p_0|$ is $|p|$ computed at $m = m_0$. The interaction radius $\alpha$ is taken from Ref. [36]. Thus, the signal component of the fit contains a single free parameter $A$ in the equation above. We use a fourth order Bernstein polynomial set to describe the smoothly varying background in the $m(\pi^+ p)$ spectra. By integrating the signal fit function, we extract the moment-weighted yield of $\Delta^{++}$ candidates $Y_n$ corresponding to a particular histogram $H_n$.

Following Ref. [32], $\Sigma$ can then be expressed as

$$\Sigma = \frac{Y_{\perp} - F_R Y_{\parallel}}{Y_{\perp} + Y_{\parallel} + \frac{F_R}{2} (Y_{0} + Y_{4})},$$

where $F_R = N_{\perp}/N_{\parallel}$ is the ratio of measured photon flux for data sets with orthogonal linear polarizations.
the GLUEX detector was designed to be uniform in $\phi$, this need not be assumed: any non-uniform azimuthal acceptance effects are removed by taking the difference of two orthogonal polarization directions and by including the terms $Y_{4,3}^{+}$ and $Y_{4,2}^{+}$.

In practice, rather than fit each individual histogram $H_{3,0}^{+}$ and $H_{4,0}^{+}$ to extract the $Y_{n}$, we note that the numerator and denominator in Eq. 4 are linear combinations of terms $Y_{n}$, and hence we can construct two histograms $D$ and $N$, where the contents of the $i$th mass bin for each histogram (denoted $D_{i}$ and $N_{i}$) are given by the linear combinations

$$D_{i} = \frac{P_{i}(H_{3,0}^{+} + H_{4,0}^{+})}{2} + \frac{F_{R} P_{i}}{2}(H_{0,2}^{+} + H_{4,2}^{+}), \quad (5a)$$

$$N_{i} = H_{2,0}^{+} - F_{R} H_{2,2}^{+} + D_{i}. \quad (5b)$$

Let the weighted yield of $\Delta^{++}$ events in histograms $N$ and $D$ be denoted as $Y_{N}$ and $Y_{D}$ respectively. In terms of these two quantities, the asymmetry is then given by

$$\Sigma = \frac{Y_{N}}{Y_{D}} - 1. \quad (6)$$

In this formulation, $Y_{N}$ and $Y_{D}$ must be positive in order to be physical. This is advantageous, as likelihood fitting techniques can then be employed. We use this method to fit the $m(\pi^{+}p)$ spectrum in the mass ranges $1.14 \text{ GeV}/c^{2} < m(\pi^{+}p) < 1.60 \text{ GeV}/c^{2}$ and $2.60 \text{ GeV}/c^{2} < m(\pi^{+}p) < 3.50 \text{ GeV}/c^{2}$, where the lower mass region contains the majority of the $\Delta^{++}$ signal and the higher mass region is used to further constrain backgrounds while avoiding $\Delta^{*}$ contributions. Figure 4 illustrates a fit to $N$ and $D$ histograms obtained over a large $t$ range to demonstrate the ability of the lineshape to describe the data at high statistical precision. Data are segmented into 16 regions of $t$, and in each region the 0/90 and -45/45 data sets provide two independent measurements of $\Sigma$.

The triply-differential cross section that describes the production of the $\Delta^{++}$ in each bin of $|t|$ can be written in terms of spin density matrix elements $\rho_{\Delta^{++}}^{M,N}$ (SDMEs). When the two angles related to the polarization of the $\Delta^{++}$ are integrated over, one obtains the expression in Eq. 1 with $\Sigma = 2[\rho_{3,3}^{1} + \rho_{11}^{1}]$, where $\rho_{\Delta^{++}}^{M,N}$ are SDMEs as defined in Ref. 37. Experimentally, the non-uniform efficiency of detecting the $\Delta^{++}$ decay results in a weighted integration over the decay phase space. This leads to a non-equal weighting of $\rho_{3,3}^{1}$ and $\rho_{11}^{1}$ and the introduction of other SDMEs that may cause the measured value of $\Sigma$ to deviate from the above expression. To correct for this bias, we use a GEANT4 [38] Monte Carlo (MC) simulation to calculate the efficiency $\epsilon$ as a function of the two decay angles in the $\Delta^{++}$ rest frame for each bin of $|t|$. We then introduce an additional event-by-event weight of $1/\epsilon$ down to a cutoff value of $\epsilon = 0.1\%$. We exclude events in regions of phase space with efficiency lower than this. Averaged over all bins of $|t|$, the effect of this weighting modifies $\Sigma$ by a magnitude of about 40\% of its total uncertainty. After this procedure, we find any residual bias to be negligible. Separately, we use MC simulation to evaluate $m(\pi^{+}p)$ and $t$ dependent modifications to the $\Delta^{++}$ lineshape, a dimension in which acceptance is uncorrelated with decay angles. We assess the systematic uncertainties in these corrections later.

To validate the statistical properties of our technique, we analyze simulated data from many toy experiments and find that our method for extracting $\Sigma$ is unbiased. We estimate the statistical uncertainty in our measurement by examining the variance of large ensembles of toy experiments modeled to match our data. With these uncertainties, the results from 0/90 and -45/45 data sets agree statistically with $\chi^{2}/\text{NDF}=0.35$ (NDF=15). We combine measurements from the independent 0/90 and -45/45 data sets, which have comparable statistical precision, by averaging the results. In constructing the uncertainty on this average, we assume that individual systematic errors in the measurement technique (detailed below) are fully correlated.

To study systematic uncertainty related to choice of fitting model, we perform additional evaluations of $\Sigma$ while independently varying: background polynomial from fourth to eighth order, choice of fit range, whether to allow individual $\Delta^{++}$ signal parameters to float, and removal of efficiency correction to the $\Delta^{++}$ lineshape. To study the systematic uncertainty related to reliance on MC-determined corrections applied to the phase space of the $\Delta^{++}$, we perform additional evaluations of $\Sigma$ by varying the efficiency cutoff and systematically deforming

Figure 4. (color online) Fit to (a) numerator $N$ and (b) denominator $D$ defined in Eqs. 5a and 5b in the extended range $0.4 \text{ (GeV}/c^{2}) < |t| < 1.4 \text{ (GeV}/c^{2})$. The $\Delta^{++}$ component is shown in green (dashed), polynomial background in blue (dotted), and total fit in red. Data are fit in the shaded regions only, the integral of the green (dashed) curve in the lower shaded region is used to determine the yields $Y_{N}$ and $Y_{D}$. 
the efficiency map. We also roughly describe Δ* contributions using a double Gaussian shape, fitting to the region of 1.14 GeV/c² < m(π⁺π⁻) < 3.50 GeV/c² as an additional study. Each fit variation produces changes that are largely uncorrelated in t and provide similar fit quality and results as the nominal scheme. It is important to note that variations in fitting scheme often affect Y_N and Y_D in the same way, which reduces the dependence of the extracted value of Σ on the fit scheme. Nevertheless, we find that systematic uncertainties are comparable to or larger than statistical uncertainties in several regions of t. Other sources of uncertainty investigated include uncertainty in flux, uncertainty in polarization due to limited triplet statistics, variations in number of beam bunches selected for accidental subtraction, varying φ_{lin} within experimental uncertainties, and choice of binning. These potential sources of systematic uncertainty are described in greater detail in Ref. [21]. The systematic uncertainty in P_n, the polarization as measured by the TPOL, produces a relative uncertainty of 1.5% on the magnitude of the measured value of Σ that is fully correlated amongst all t regions.

As an additional check, the analysis was repeated with varied selections of m(π⁺π⁻) < 1.1 GeV/c², i.e., all ρ backgrounds, were included.

The asymmetry Σ of the background can similarly be evaluated by inserting background yields to Eqs. 5a and 5b. In the mass range 1.14 GeV/c² < m(π⁺p) < 1.60 GeV/c², the background is found to have a negative asymmetry without clearly discernible t dependence.

V. DISCUSSION OF RESULTS

The results of beam asymmetry Σ for π⁻Δ^{++} photoproduction are listed in Table I and displayed in Fig. 5 with theoretical predictions at 8.5 GeV provided by Nys et al. [16] and B.-G. Yu and K.-J. Kong [17]. Several trends are apparent from the data. The asymmetry is negative in the range of approximately |t| < 0.45 (GeV/c)², demonstrating that negative naturality pion exchange is favored at smaller |t|. In the range |t| < 0.25 (GeV/c)², the asymmetry is negative and downward sloped as magnitude |t| increases. This is consistent with mixed-naturality modifications to one-pion exchange, which are sharply peaked in the forward direction. For |t| > 0.45 (GeV/c)² the asymmetry becomes positive, consistent with descriptions including positive naturality vector ρ and tensor a₂ exchanges.

We find that the model of Nys et al. describes the general shape of the asymmetry over |t|, though it predicts an overall lower value of Σ. The model by Yu and Kong appears to slightly better describe the asymmetry for |t| larger than 0.5 (GeV/c)²; however, it predicts a minimum value and upward rise at much lower |t| than observed.

In summary, we have measured the beam asymmetry Σ as a function of t for the reaction γ_p → π⁻Δ^{++} at E_γ = 8.5 GeV using data from the GLUEX experiment. These measurements are the first in this energy range and are of higher precision than and complementary to those made at higher photon beam energies [15]. In the t-channel particle exchange picture, our measurements indicate that the naturality of exchanged Reggeons changes significantly as a function of |t|, consistent with pion ex-
change at smaller $|t|$ and natural exchange processes at higher $|t|$. These results constrain models for $t$-channel photoproduction of pions, which will be useful for understanding backgrounds in both hybrid meson searches and baryon spectroscopy studies at lower energies.

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