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Lagrangian densities, where the parameters for resonant states into \( J^P \) are constructed according to the same scheme—effective coupling terms. It should be noted that the various models which are presently used are constructed during the last decade [15–23]. It should be noted that the various models which are presently used are constructed according to the same scheme—effective Lagrangian densities, where the parameters for resonant production have been studied at SLAC [13] and in the context of the Gerasimov-Drell-Hearn sum rule at MAMI [14].

On the theoretical side, some experience has been gained during the last decade [15–23]. It should be noted that the various models which are presently used are constructed according to the same scheme—effective Lagrangian densities, where the parameters for resonant production an important tool in the investigation of the structure of the nucleon.

The study of the baryon spectrum provides an avenue to a deeper understanding of the strong interaction, since the properties of the excited states of baryons reflect the dynamics and relevant degrees of freedom within them. Many nucleon resonances in the mass region above 1.6 GeV decay predominantly through either \( \pi N \) or \( \rho N \) intermediate states into \( \pi \pi N \) final states (see the Particle Data Group review [1]). Resonances predicted by symmetric quark models, but not observed in the \( \pi N \) channel (the so-called “missing” resonances), are predicted to lie in the region of \( W > 1.8 \text{ GeV} \) [2]. This makes electromagnetic double-pion production an important tool in the investigation of the structure of the nucleon.

To date, a rather large amount of unpolarized cross-section measurements of double-pion photoproduction and electroproduction on the proton have been reported by several collaborations [3–12]. However, the database collected for polarization observables remains quite sparse. Polarization degrees of freedom in charged double-pion production have been studied at SLAC [13] and in the context of the Gerasimov-Drell-Hearn sum rule at MAMI [14].

In this Letter, we report the first comprehensive measurement of the beam-helicity asymmetry [24]

\[
I_\gamma = \frac{1}{P_\gamma} \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}
\]

in the \( \gamma p \rightarrow p \pi^+ \pi^- \) reaction, for energies \( W \) between 1.35 and 2.30 GeV in the center of mass, where the photon beam is circularly polarized and neither target nor recoil polarization is specified. \( P_\gamma \) is the degree of circular polarization of the photon and \( \sigma^\pm \) are the cross sections for the two photon-helicity states \( \lambda_\gamma = \pm 1 \). Here, we give a brief overview of our data and demonstrate, by means of a phenomenological model, the sensitivity of this observable to the dynamics of the reaction.

Beam-helicity asymmetries for the two-pion-photoproduction reaction \( \gamma p \rightarrow p \pi^+ \pi^- \) have been studied for the first time in the resonance region for center-of-mass energies between 1.35 and 2.30 GeV. The experiment was performed at Jefferson Lab with the CEBAF Large Acceptance Spectrometer using circularly polarized tagged photons incident on an unpolarized hydrogen target. Beam-helicity-dependent angular distributions of the final-state particles were measured. The large cross-section asymmetries exhibit strong sensitivity to the kinematics and dynamics of the reaction. The data are compared with the results of various phenomenological model calculations, and show that these models currently do not provide an adequate description for the behavior of this new observable.

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The experiment was performed in Hall B at the Thomas Jefferson National Accelerator Facility (Jefferson Lab). Longitudinally polarized electrons with an energy $E_0 = 2.445$ GeV were incident on a thin radiator. The beam polarization was routinely monitored during data taking by a Möller polarimeter and was, on average, 0.67. A photon tagger system [25] was used to tag photons in the energy range between 0.5 and 2.3 GeV, with an energy resolution of 0.1% $E_0$. The degree of circular polarization of the photon beam is proportional to the electron-beam polarization and is a monotonic function of the ratio of the photon and incident electron energies [26]. The degree of photon-beam polarization varied from $= 0.16$ at the lowest photon energy up to $= 0.66$ at the highest energy. The photon-helicity state changes with the electron-beam helicity, which was flipped pseudorandomly at a rate of 30 Hz. The collimated photon beam irradiated an 18 cm thick liquid-hydrogen target. The final-state hadrons were identified using time-of-flight information from plastic scintillators located about 5 m from the target. The four-momentum vectors of the particles were reconstructed from their tracks in the toroidal magnetic field of the spectrometer and by particle identification using time-of-flight information from plastic scintillators.

A schematic view of the reaction, together with angle definitions, is shown in Fig. 1. A total of $3 \times 10^7$ $p\pi^+\pi^-$ events were accumulated for both helicity states $N^\pm$. Experimental values of the helicity asymmetry were then obtained as

$$
J^\theta_{\text{exp}} = \frac{1}{P_\gamma} \frac{N^+ / \alpha^+ - N^- / \alpha^-}{N^+ / \alpha^+ + N^- / \alpha^-},
$$

where $\alpha^+ = \frac{1}{2}(1 + a_c)$ accounts for helicity-dependent differences in the luminosity due to a small electron-beam-charge asymmetry $a_c = 0.0044$. The value of $a_c$ was determined from helicity asymmetries in single-pion photoproduction data that were obtained simultaneously with the double-pion photoproduction data. Any observed asymmetry in this reaction is instrumental [28]. The experimental asymmetries have not been corrected for the CLAS acceptance. In order to allow for an analysis as model independent as possible, the data are compared with event-weighted mean values of asymmetries from model calculations [29]. The determination of these mean values

![FIG. 1. Angle definitions for the circularly polarized real-photon reaction $\gamma p \rightarrow p\pi^+\pi^-$; $\theta_{cm}$ is defined in the overall center-of-mass frame, and $\theta$ and $\phi$ are defined as the $\pi^+$ polar and azimuthal angles in the rest frame of the $\pi^+\pi^-$ system with the $z$ direction along the total momentum of the $\pi^+\pi^-$ system (helicity frame).](image)

![FIG. 2. Angular distributions for selected center-of-mass energy bins (each with $\Delta W = 50$ MeV) of the cross-section asymmetry for the $\gamma p \rightarrow p\pi^+\pi^-$ reaction. The data are integrated over the detector acceptance. The statistical uncertainties are mostly smaller than the symbol size. The solid and dotted curves are the results from model calculations by Mokeev et al. [19–21] (for $1.45$ GeV $\leq W \leq 1.80$ GeV) with relative phases of 0 and $\pi$ between the background- and $\pi\Delta$-subchannel amplitudes, respectively. The dashed curves show results of calculations by Fix and Arenhövel [23] (for $W \leq 1.70$ GeV).](image)
of the invariant mass
the results of Mokeev
are more differential than those of Fig. 2 is given in Fig. 3.

Figure 2 shows ϕ angular distributions of the helicity
asymmetry for various selected 50 MeV-wide center-of-
mass energy bins between W = 1.40 and 2.30 GeV.

The data are integrated over the full CLAS acceptance. The
analysis shows large asymmetries which change mark-
edly with W up to 1.80 GeV; thereafter they remain rather
stable. The asymmetries are odd functions of ϕ and vanish
for coplanar kinematics (ϕ = 0 and 180°), as expected
from parity conservation [24]. The large number of ob-
served $\bar{p} p \rightarrow p \pi^+ \pi^-$ events allows for a confident analy-
sis of the data in selected kinematic regions, making it
possible to tune the different parts of the production am-
plitude independently. An example of distributions which
are more differential than those of Fig. 2 is given in Fig. 3.
The data at W = 1.50 GeV are divided into nine bins in the
invariant mass $M(p\pi^+)$. The data in Figs. 2 and 3 are compared with results of
available phenomenological models. In the approach by
Mokeev et al. (solid curves), double-charged-pion photoproduction and electroproduction are described by a set of
quasi-two-body mechanisms with unstable particles in the
intermediate states: $\pi\Delta$, $\rho N$, $\pi N(1520)$, $\pi N(1680)$, and
$\pi\Delta(1600)$ and with subsequent decays to the $\pi^+\pi^- p$ final
state [19–21]. Residual direct $\pi^+\pi^- p$ mechanisms are parametrized by exchange diagrams [21]. The first two
quasi-two-body channels mentioned above are described
by a coherent sum of s-channel $N^*$ contributions and non-
resonant mechanisms [19]. All well established resonances
with observed double-pion decays are included, plus
$\Delta(1600)$, $N(1700)$, $N(1710)$, and a new state, $N(1720)$
with $J^P = 3/2^+$, possibly observed in CLAS double-
pion data [9]. $N^*$ and nonresonant parameters are fitted
to the CLAS cross-section data for virtual-photon double-
charged-pion production [9]. The model provides a good
description of all available CLAS cross-section and world
data on double-pion photoproduction and electroproduc-
tion at $W < 1.9$ GeV and $Q^2 < 1.5$ GeV$^2$.

Results also have been obtained by Fix and Arenhövel
using the model described in [23]. They use an effective
Lagrangian approach with Born and resonance diagrams at
the tree level. The model includes the nucleon, the
$\Delta(1232)$, $N(1440)$, $N(1520)$, $N(1535)$, $N(1680)$,
$\Delta(1620)$, $N(1675)$, and $N(1720)$ resonances, as well as
the $\sigma$ and $\rho$ mesons. The corresponding results are shown in Figs. 2 and 3 as dashed curves. For completeness, we
note that the recent work of Roca [18] shows our prelimi-
nary data [30] in the framework of the Valencia model for
double-pion photoproduction.

Although both models had previously provided a good
description of unpolarized cross sections, neither of the
models is able to provide a reasonable description of the
beam-asymmetry data over the entire kinematic range
covered in this experiment. Even though the model predic-
tions agree remarkably well for certain conditions (see,
e.g., the dashed curves in Fig. 3), for other conditions they
are much worse and sometimes even out of phase entirely.

As is noted above, the main theoretical challenge for
double-pion photoproduction lies in the fact that several
subprocesses may contribute, even though any given indi-
vidual contribution may be small. In this connection, the
polarization measurements should be very helpful in sepa-
rating the individual terms. The particular sensitivity of
the beam asymmetry to interference effects among various
amplitudes is illustrated in Fig. 2. The dotted curves show
results of calculations by Mokeev et al. with a relative phase of $\pi$ between the background- and $\pi\Delta$ subchannel
amplitudes. The access to interference effects permit a
cleaner separation of background and resonances. This in
turn makes it possible to make more reliable statements
about the existence and properties of nucleon resonances.

Figure 4 shows the helicity asymmetry as a function of
the invariant mass $M(p\pi^-\pi^+)$ for two different values of $W$
and a fixed value of $\phi$.

This is a typical case. The most interesting features of
these data are the changes that occur as $M(p\pi^-\pi^+)$ traverses
the $\Delta(1232)$ resonance. At $W = 1.55$ GeV, a maximum is
seen in the region of this resonance. We see a similar trend
in the region of the higher-mass resonances around
1.60 GeV for $W = 1.95$ GeV. This hints at the way in
which the helicity asymmetry (along with other polarization
observables) could be used in studies of baryon spec-
troscopy. Of particular interest is the study of sequential
decays of resonances, such as $N(1520) \rightarrow \pi\Delta \rightarrow \pi\pi N$, or

FIG. 3. Helicity asymmetries at $W = 1.50$ GeV for nine bins
of the invariant mass $M(p\pi^+)$, as indicated. The solid curves are
the results of Mokeev et al. [19–21]. The dashed curves show
results of calculations by Fix and Arenhövel [23].

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Here, the moderate values of the curves are the results of Mokeev [2] predicted to lie [2]. The energy range where yet-unobserved resonances are pre-

\[ N(1700) \rightarrow \pi N(1520) \rightarrow \pi \pi N, \] 

which can be studied at moderate values of \( W \) from 1.5 to 1.9 GeV; see Ref. [10]. Here, the \( p \)-production channel is also open. This is the energy range where yet-unobserved resonances are predicted to lie [2].

In summary, we have given a brief overview of our \( \gamma p \rightarrow p \pi^+ \pi^- \) data, and we have demonstrated, by means of phenomenological models, the sensitivity of this helicity-asymmetry observable to the dynamics of the reaction. The large amount of high-quality data that we have obtained opens the path for a series of further investigations. Obvious next steps are (1) a better theoretical understanding of the reaction and (2) an attempt to describe simultaneously our polarized double-charged pion photoproduction data and other CLAS data obtained with unpolarized real [11] and virtual [9] photons.

We see, even from the small sample of data shown here, that existing theoretical models have severe shortcomings in the description of the beam-helicity asymmetries. In the region of overlapping nucleon resonances (and uncontrolled backgrounds), it clearly will be a challenge to any theoretical model to describe this new observable that depends so sensitively on the interferences between them. Yet, without a proper understanding of the \( \pi \pi N \) channel the problem of the missing resonances is unlikely to be resolved.

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[29] The mean value \( \langle F_0 \rangle \) of model asymmetries in a kinematical bin is given by \( F_0 = \sum P_{x_i} P_{y_i} \), where the sum runs over all \( N \) events observed in that bin; \( P_{x_i} \) is the calculated beam polarization at the corresponding \( W \) and \( I^0 \) is the model asymmetry for the kinematics of each of those events.