Search for the Photoexcitation of Exotic Mesons in the $\pi^+\pi^+\pi^-$ System

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A search for exotic mesons in the $\pi^+\pi^+\pi^-$ system photoproduced by the charge exchange reaction $\gamma p \to \pi^+\pi^+\pi^-(n)$ was carried out by the CLAS Collaboration at Jefferson Lab. A tagged-photon beam with energies in the 4.8 to 5.4 GeV range, produced through bremsstrahlung from a 5.744 GeV electron beam, was incident on a liquid-hydrogen target. A partial wave analysis was performed on a sample of 83 000 events, the highest such statistics to date in this reaction at these energies. The main objective of this study was to look for the photoproduction of an exotic $J^{PC} = 1^{-+}$ resonant state in the 1 to 2 GeV mass range. Our partial wave analysis shows production of the $a_2(1320)$ and the $\pi_2(1670)$ mesons, but no evidence for the $a_1(1260)$, nor the $\pi_1(1600)$ exotic state at the expected levels. An upper limit of 13.5 nb is determined for the exotic $\pi_1(1600)$ cross section, less than 2% of the $a_2(1320)$ production.

The self-interacting nature of the gluon within quantum chromodynamics (QCD) allows for hybrid resonant states with a $(\bar{q}qg)$ configuration, where the gluonic degree of freedom gives rise to a spectrum of additional states outside the constituent quark model (CQM). The observation of gluonic-hybrid hadrons, with an explicit excitation of this gluonic degree of freedom, will be an important test of the predicting power of QCD at intermediate energies. A signature of states beyond the CQM would be the existence of mesons with quantum numbers that cannot be attained by $(\bar{q}q)$ mesons (so-called "exotics"). In particular, the lowest lying $(\bar{q}qg)$ state is predicted to have $J^{PC} = 1^{-+}$ [1–4], and mass near 1.9 GeV. A more recent calculation on the lattice using lighter quark masses predicts a mass at 1.74 GeV [5].

Here we report on a search for exotic mesons decaying to three charged pions. This channel was chosen for its simplicity, since only a few decay channels are available to this final state. In addition, although the dominant decay mode of the lightest $J^{PC} = 1^{-+}$ state is predicted to be into an S-wave and P-wave meson, such as the $b_1(1235)\pi$ or $f_1(1285)\pi$ [6], the three-pion final state in the ρ decay channel could be non-negligible [7–9].

There is also evidence for an exotic $\pi_1(1600)$ state in the reaction $\pi^- p \to \pi^+\pi^+\pi^- p$ at 18 GeV by the Brookhaven E852 experiment [10,11]. Furthermore, the existence of the $\pi_1(1600)$ has been confirmed by the same experiment in other channels such as $\eta'\pi$ [12]. The VES Collaboration also reported an exotic signal in the $\eta'\pi^-$ channel in the same mass region [13]. However, a more recent analysis of a higher statistics sample from E852 3π data, claims to find no evidence for $\pi_1(1600)$ production [14]. All these results were obtained by pion beam experiments.

It has long been anticipated that photoproduction may be a better production mechanism for exotic mesons [6,8,15–17]. If the $\pi_1(1600)$ state couples to $\rho\pi$, then this state should also be produced with a photon beam through π exchange via the vector-meson–dominance model [18]. However, the use of photon beams as probes for exotic

meson production has not been fully explored so far, and
the existing data on multiparticle final states are sparse.
Photoproduction of mesons in multipion final states has
been reported in three previous experiments: a SLAC 40-
in. hydrogen bubble chamber experiment [19] at 4.3 GeV, a
CERN hydrogen experiment [20] between 25 and 70 GeV,
and a SLAC 1-meter hybrid bubble chamber experiment
[21,22] around 19 GeV. All of these experiments lacked the
statistics required for a full partial wave analysis (PWA).
For example, Condo *et al.* [22] showed that the three-pion
spectrum in the low-mass region (below 1.5 GeV) is domi-
nated by $a_2(1320)$ production, and found no clear evidence
for $a_1(1260)$ production. In the high-mass region (1.5 to
2 GeV), based on an angular distribution analysis, this
same group claimed evidence for a narrow state at
1.775 GeV with possible $J^{PC} = 1^{-+}, 2^{-+},$ or 3^{++} assign-
ments. From the analysis of four pion events, Ref. [20]
reported two peaks, one at the mass of the $a_2(1320)$ and
another at around 1.75 GeV, in the $\rho\pi$ state recoiling off
the proton and the remaining pion.

The present experiment was performed at Jefferson
Laboratory during the 2001 running period of CLAS.
Details of the design and operation of CLAS and its
components may be found in Ref. [23] and references
within. The experiment ran with a fixed electron beam
energy of 5.744 GeV. A tagged-photon beam, with a flux
of 5×10^7 photons/s produced via bremsstrahlung from a
3×10^{-4} radiation lengths radiator, was incident on a
liquid-hydrogen target contained in a cylindrical cell
18 cm in length. The running conditions were optimized
for meson production recoiling off a neutron: the CLAS
torus magnet field was reduced to half its maximum cur-
rent, and the target pulled back 1 m from the nominal
center of CLAS position. Only events with tracks coming
from the target material that were in time within 1 ns with a
beam photon with energy between 4.8 and 5.4 GeV were
selected.

The three pions in the reaction $\gamma p \to \pi^+ \pi^+ \pi^- n$ were
identified by the time-of-flight detector, and the neutron
was identified through missing mass (Fig. 1). The recon-
structed mass of the neutron was 942.2 MeV with a width
of 25.1 MeV. As shown in Figs. 2(a) and 2(b), the various
$n\pi$ invariant mass spectra show clear production of baryon
resonances recoiling off a two-pion system, consistent with
the process shown in Fig. 3(b). The $n\pi^-$ invariant mass
[Fig. 2(a)] shows a peak at the mass of the $\Delta(1232)$, while
the $n\pi^+$ effective mass distribution [Fig. 2(b)] shows
enhancements around the mass of $N^*(1520/1535)$ and
$N^*(1650/1675/1680)$, with a smaller contribution from
$\Delta(1232)$ production.

The observed squared four-momentum transfer distribu-
tion $-t$ between the incoming photon beam and the pro-
duced three-pion system follows an exponential of the
form $f(t) = ae^{-b|t|}$. This form is consistent with peripheral
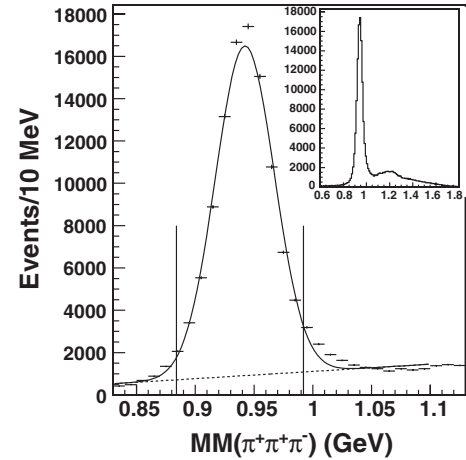production of the three-pion system recoiling off the neu-

FIG. 1. Missing mass of the three-pion system. The distribu-
tion was fit to a Gaussian plus a linear background (solid curve).
The inset shows a wider scale. The region between the vertical
lines at 0.884 and 0.992 GeV identified the neutron.

tron and is consistent with the production mechanism
shown in Fig. 3(a). For the exponential slope constant b,
we obtained a fitted value of 3.02 GeV^{-2}. To enrich the
sample of peripheral events, we required $|t| \leq 0.4$ GeV^2.
To further enhance the mesonic sample relative to the
baryonic background, only events with forward-going
π^+'s $[\theta_{\text{Lab}}(\pi^+) \leq 30°]$ were selected. This requirement,
as determined from simulation, is necessary to remove
most of the baryonic background without significantly
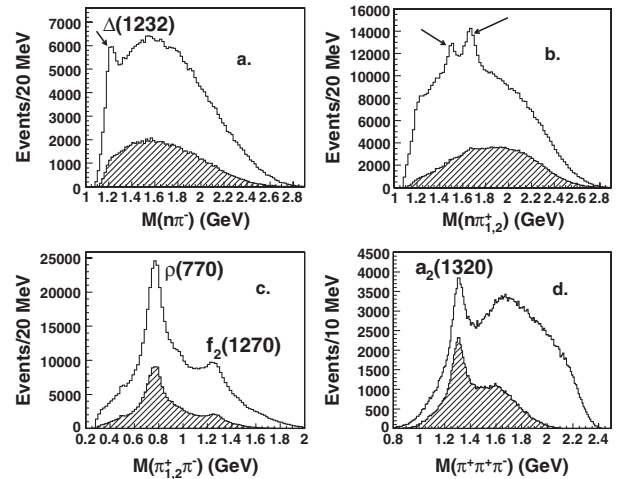affecting the mesonic sample. After all the former selec-

FIG. 2. Mass spectra. (a) $n\pi^-$ invariant mass, (b) $n\pi^+$ invari-
ant mass [the left arrow indicates $N^*(1520/1535)$ resonances
and the right arrow $N^*(1650/1675/1680)$ resonances],
(c) $\pi^+\pi^-$ invariant mass, and (d) $\pi^+\pi^+\pi^-$ invariant mass.
The hatched areas are the distributions of remaining events after
the momentum transfer and π^+ laboratory angle selections. The
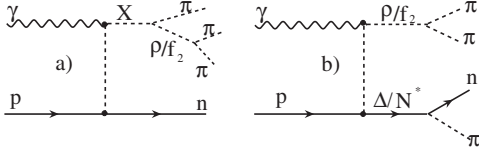histograms in (b) and (c) are filled twice for each event, once for
each π^+.

FIG. 3. (a) Peripheral meson production, (b) baryon resonance background processes.

TABLE I. Set of partial waves used in the PWA. J, P, C refers to the spin, parity, charge-conjugation of the three-pion system. m, ϵ are the spin-projection and reflectivity quantum numbers. L is the orbital angular momentum of the decay. Isobar is the intermediate meson that decays to two pions. Note: Background ("Bg") refers to an isotropic, noninterfering wave that is meant to accommodate events that are not described by the interfering waves.

$\pi^+\pi^+\pi^-$ mass	J^{PC}	m^ϵ	L	Isobar	# Waves
1.0–1.36 GeV	1^{++}	$1^\pm$	0, 2	$\rho(770)$	4
	2^{++}	$1^\pm, 2^\pm$	2	$\rho(770)$	4
13 waves	1^{-+}	$1^\pm$	1	$\rho(770)$	2
(48 parameters)	2^{-+}	$1^\pm$	1	$\rho(770)$	2
	"Bg"				1
1.36–2.0 GeV	1^{++}	$1^\pm$	0, 2	$\rho(770)$	4
	1^{++}	$1^\pm$	1	$f_2(1270)$	2
31 waves	2^{++}	$1^\pm, 2^\pm$	2	$\rho(770)$	4
(120 parameters)	1^{-+}	$1^\pm$	1	$\rho(770)$	2
	2^{-+}	$1^\pm, 2^\pm$	1	$\rho(770)$	4
	2^{-+}	$1^\pm$	3	$\rho(770)$	2
	2^{-+}	$1^\pm, 2^\pm$	0	$f_2(1270)$	4
	2^{-+}	$1^\pm$	2	$f_2(1270)$	2
	3^{++}	$1^\pm$	2	$\rho(770)$	2
	3^{++}	$1^\pm$	1	$f_2(1270)$	2
	"Bg"				1

tions were applied, about 83 000 events remained as input to the PWA.

The $\pi^+\pi^-$ invariant mass distribution, Fig. 2(c), shows enhancements at the mass of the $\rho(770)$ and $f_2(1270)$. The 3π invariant mass spectrum, Fig. 2(d), shows a clear peak around the mass of the $a_2(1320)$ meson. It also shows a broad enhancement in the 1600–1700 MeV mass region.

A PWA, based on the isobar model, was performed to determine the spin, parity, and charge conjugation (J^{PC}) of the three-pion system. The three-body decay of the meson was described by a sequence of two-body intermediate decays [Fig. 3(a)]. States with definite J^{PC} of the mesonic system were combined as eigenstates of reflection through the production plane (reflectivity) according to the formalism described in Refs. [24–27]. The expected number of events per mass bin were written as a sum of production and decay amplitudes. To obtain the observed number of events per bin, the acceptance of the detector was determined by normalizing to the Monte Carlo sample. The model used the same t distribution as determined from the data, and the events were simulated in a GEANT-based model of the CLAS detector. A maximum likelihood fit to each mass bin was done with a set of input partial waves. Many different sets of waves were tried during the analysis. The meson spin-density matrix was approximated by a rank 2 matrix due to limited statistics and the large number of parameters required for the fit. The rank of the spin-density matrix represents the number of independent spin components in the initial and final states necessary to describe the interaction. Parity conservation reduces the number of independent components to four.

No baryon resonance partial waves were used and an isotropic noninterfering background wave was included, which is appropriate, since the events were dominated by meson production after the kinematic selection cuts. We separated the PWA in two regions (at 1.36 GeV) to account for the different goals in the analysis (the observation of a well-known state: the $a_2(1320)$ and to determine the components of the 1600 MeV region). We limited the waves in the low-mass region because the higher orbital angular momentum (L) waves do not contribute at low mass. Below 1.36 GeV, no $f_2\pi$ wave was included as its mass is lower than the nominal threshold. Contributions from $m^\epsilon = 0^+$, 0^- waves were found to be small, and these waves are therefore not included in the final wave set. The final list of waves that provided the best stable fit is shown in Table I. The quality of the PWA fit was checked by comparing various mass and angular distributions from the observed data and the predictions of the PWA results, i.e., weighting the Monte Carlo events according to the PWA fit. Qualitatively good agreement was observed between these two sets [28].

Results from the PWA are shown in Figs. 4 and 5. The two most prominent waves are $J^{PC} = 2^{++}$ and 2^{-+} [Figs. 4(c) and 4(d)]. The $a_2(1320)$ is observed in the $(\rho\pi)_D$ wave at the expected mass and width. For the a_2 cross section, we obtained a value of $0.81 \pm 0.25 \mu b$. The uncertainty includes both detector systematics and variation of PWA results estimated by using different wave sets and starting parameters. The result is in rough agreement with the previous measurement of $1.14 \pm 0.57 \mu b$ obtained at 5.25 GeV by Ballam [29] and $1.71 \pm 0.86 \mu b$ obtained at 4.7 to 5.8 GeV by Eisenberg [30].

The $\pi_2(1670)$ is observed clearly in the $(f_2\pi)_S$ decay mode [Fig. 5(b)]. In the remaining π_2 decay modes: $(\rho\pi)_{P,F}$ [Fig. 5(a)], and $(f_2\pi)_D$, the signal looks broad and distorted in the low-mass region. This is most likely due to the incomplete set of waves in the fit, and is indicative of leakage from the a_2. Similar observations were reported by the E852 Collaboration [11,14]. In addition, due to the two different wave sets used in the two fitting regions (Table I), some instability is observed near the border of 1.36 GeV [Figs. 4(b) and 4(d)]. This should be expected as a result of incomplete wave sets. In order to perform PWA using a larger number of waves and a spin-
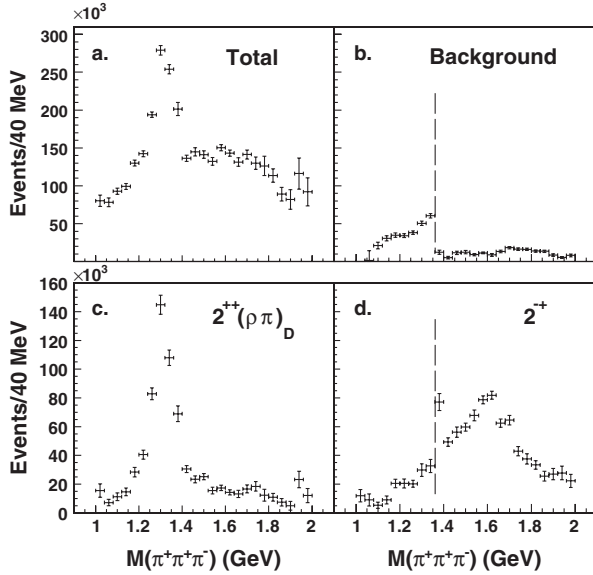
FIG. 4. PWA results: Combined intensities of waves included in the fit. The intensities shown are the sum of the intensities from both ranks of the spin-density matrix: (a) Total intensity, (b) Background intensity, (c) $2^{++}(\rho\pi)_D$ intensity, and (d) 2^{-+} total intensity. The dashed vertical line in (c) and (d) indicates the border of the two fitting regions. The drop in the isotropic, noninterfering wave ("background") at the boundary, is a consequence of the reduced wave set used at low mass.
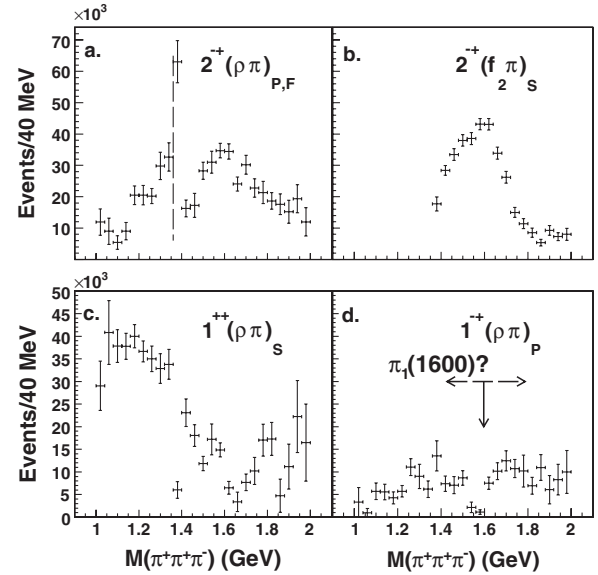

FIG. 5. Partial wave decompositions: (a) $2^{-+}(\rho\pi)_{P,F}$ (the dashed vertical line indicates the border of the two fitting regions), (b) $2^{-+}(f_2\pi)_S$, (c) $1^{++}(\rho\pi)_S$, and (d) $1^{-+}(\rho\pi)_P$ (the vertical and horizontal arrows indicate the mass and width of the $\pi_1(1600)$ as reported by Ref. [10]).

density matrix of rank 4, future higher statistics experiments are needed [31].

It is important to note that we see no clear evidence for the $a_1(1260)$ in the possible decay mode of the $(\rho\pi)_S$ wave [Fig. 5(c)]. This observation agrees with Condo *et al.* [21]. The event enhancement observed around 1.3 GeV in the noninterfering, flat background waves [Fig. 4(b)] is likely leakage coming from the a_2 and may demonstrate that the rank of the spin-density matrix is larger than 2.

We do not observe resonant structure in the exotic $1^{-+}(\rho\pi)_P$ partial wave [Fig. 5(d)]. To determine if the 1^{-+} wave was necessary to better fit our data, we compared PWA fits with and without the 1^{-+} wave using the likelihood ratio (LR) test [32,33]. Using LR statistics, we find that the PWA set of waves including the 1^{-+} wave fits the data significantly better than a model without the 1^{-+} wave. While no clear resonant structure was observed in the 1^{-+} intensity distribution [Fig. 5(d)], this distribution was used to estimate an upper limit to the $\pi_1(1600)$ cross section using the method of Helene [34]. Using the mass of 1597 MeV and the width of 340 MeV as measured by Ref. [12], we estimated an upper limit for the $\pi_1(1600)$ of 13.5 nb at a 95% confidence level, less than 2% of the $a_2(1320)$. Therefore, our results do not agree with the predicted strengths for photoproduction of a 1^{-+} gluonic-hybrid meson [6,8,15–17]. Based on Ref. [8], the $\pi_1(1600)$ is expected to be produced with a strength near 10% of the $a_2(1320)$. Reference [17] predicts a factor of 5–

10 larger ratio of exotic meson to a_2 in photoproduction than hadroproduction. This would imply the $\pi_1(1600)$ cross section to be on the order of 50% of a_2, more than 25 times higher than what we observed. It is possible that the $\pi_1(1600)$ reported by Ref. [10] is not a gluonic-hybrid meson, but rather of other nature. Alternatively, the calculated photoproduction cross section of gluonic exotic mesons might be overestimated.

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