HADRON SPECTROSCOPY AT CLAS

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Meson photoproduction was studied at the CEBAF Large Acceptance Spectrometer (CLAS) utilizing a 5.5 GeV/c photon beam incident on a hydrogen target. Here we report on the partial wave analyses (PWA) performed on the exclusive final states $\pi^+\pi^+\pi^-n$ and $K^+K^-\pi^+n$. In addition, CLAS has data on the final state $\pi^+\pi^0\pi^-p$ which will be reported in the near future. The analysis of the $\pi^+\pi^+\pi^-$ system shows clearly the $a_2(1320)$, as well as evidence for the $a_1(1260)$ and the $\pi_2(1670)$. The $\pi_1(1600)$, previously observed in π^-p interactions, is seen very weakly here. In the $K^+K^-\pi^+n$ channel there is evidence for the $\Theta^+(1540)$ $S = +1$ baryon pentaquark. The PWA of this system gives an excellent description of the background which rules out mesonic reflection as a source of the signal.

Keywords: Meson; pentaquark; hadron structure.

1. Exotic Spectroscopy

Almost all known mesons have structure consistent with a bound quark and anti-quark. Similarly, baryon states consist of 3 bound quarks. However, the current understanding of Quantum Chromodynamics (QCD) does not preclude more complex hadronic structures, for example $qq\bar{q}\bar{q}$ and mesons with gluonic excitations in the meson spectrum, and baryons containing an additional $q\bar{q}$ pair in the baryon sector. If such states exist, one would expect so-called spin-parity exotic mesons, that is mesons with J^{PC} quantum numbers disallowed by the naive quark model ($J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}$, etc.). In the baryon sector one would expect so-called flavor exotics, for example baryons with strangeness +1.

The $J^{PC} = 1^{-+}$ exotic meson has received considerable attention; it is predicted to be one of the lightest hybrid mesons, and has characteristic decay properties. Flux-tube model^{1,2} and lattice-gauge^{3,4,5} calculations suggest the mass of the lowest lying state should be around 1900 MeV/c², while earlier bag model calculations suggest a lower mass near 1500 MeV/c² (Ref. 6). The principal decay channels should be $b_1\pi$ and $f_1\pi^1$, but the $\rho\pi$ decay mode may also be substantial^{7,8,9}.

Recent experiments have displayed substantive evidence for $J^{PC} = 1^{-+}$ isovector (π_1) mesons. The $\pi_1(1400)$ was seen in the decay channel $\eta\pi^{10,11,12}$, and a $\pi_1(1600)$ was seen in $\rho\pi^{13}$, $\eta'\pi^{14}$, and $f_1\pi^{15}$. The latter analysis also reported

a third π_1 state near 2000 MeV/c². It has been suggested that due to the vector nature of the photon, photo-production may be a source of spin-parity exotic mesons¹⁶.

The reactions $\gamma p \rightarrow p\pi^+\pi^+\pi^-$ and $\gamma p \rightarrow n\pi^+K^+K^-$ were studied at the Thomas Jefferson National Accelerator Facility. The events were measured in the Cebaf Large Acceptance Spectrometer (CLAS)¹⁷ using a tagged bremsstrahlung photon beam incident on an 18 cm. liquid hydrogen target. The trigger was a tagged photon in the energy range 4.8 to 5.5 GeV together with two sectors of the CLAS time-of-flight system reporting hits. A total of 1.2 billion events were recorded with a raw integrated luminosity of 2.7 pb⁻¹.

2. $\pi^+\pi^-\pi^-$

For the analysis of this channel all three charged pions were detected in the CLAS drift chambers. Beam energy, event spatial vertex, and vertex timing cuts were made to reject background. Fig. 1(a) shows the missing mass spectrum of the $\pi^+\pi^+\pi^-$ system after these cuts. Three-pion photoproduction events were selected by cutting around the peak near the neutron mass. A kinematic fit was performed to improve the mass resolution and to remove background. The primary background in these events is due to baryon resonance production, for example, $\gamma p \rightarrow f_2(1270)\Delta/N^*$, where the baryon resonance decays to $n\pi^+$. To suppress these events, the most judicious cut was to eliminate events where the laboratory angle of either π^+ was more than 30 degrees. Events were selected with $0.4 > -t$ (GeV/c)² to select peripheral meson production. The $n\pi^+$ spectra is shown in Figure 2 with various cuts. After all of these cuts 83K events remained. The three-pion and two-pion invariant mass distributions are shown in Fig. 1(b-d). In the three-pion mass distribution the $a_2(1320)$ is clearly seen, as well as higher mass peak near 1600 MeV/c². In the $\pi^+\pi^-$ mass distributions, the $\rho(770)$ is seen, as well as the $f_2(1270)$.

A partial wave analysis (PWA) was performed on this sample of 83K events to identify spin-parity meson states. The data were binned into intervals of 40 MeV/c² in the three-pion mass. Independent partial wave analyzes were performed in each mass bin, and the isobar model was used to distinguish intermediate resonance decays. The ρ , the $f_2(1270)$, and an S-wave $\pi\pi$ (σ) were candidate isobars. Partial waves were fitted as isospin eigenstates, with G-parity, isospin, and C-parity well defined. States were also defined as eigenstates of reflection through the production plane. An extended maximum likelihood was performed with the rank of the three-pion meson resonance spin-density matrix limited to 1. Detector acceptance was included through the probability normalization.

Partial waves with total angular momentum $J \leq 4$ and $M \leq 1$, where M is the projection of J along the beam direction in the three-pion rest frame. A procedure was developed where many different waves were used in various fits, and small resulting waves were rejected systematically. Two different sets of waves were utilized in two different mass ranges: 1.0-1.4 GeV/c², and 1.4-2.0 GeV/c². In the

Fig. 1. Distributions for (a) missing mass squared, and (b) $\pi^+\pi^+\pi^-$ mass with various cuts. (c) The mass distribution of $\pi_1^+\pi^-$, where π_1 indicates the higher momentum π^+ . (d) The mass distribution of $\pi_2^+\pi^-$, where π_2 is the lower momentum π^+ .

Fig. 2. $n\pi^+$ invariant mass distributions. (a) $n\pi^+_{fast}$ effective mass. (b) $n\pi^+_{slow}$ effective mass.

$\pi^+\pi^+\pi^-$ mass	J^{PC}	m^ϵ	L	Isobar	# Waves
1.0 – 1.4 GeV 23 waves (complex amplitudes) 46 parameters	0^{-+}	0^+	0	σ	1
	0^{-+}	0^+	0	$f_0(980)$	1
	0^{-+}	0^+	1	$\rho(770)$	1
	1^{++}	$0^+, 1^\pm$	0,2	$\rho(770)$	6
	1^{-+}	$0^-, 1^\pm$	1	$\rho(770)$	3
	2^{++}	$0^-, 1^\pm, 2^\pm$	2	$\rho(770)$	5
	2^{-+}	$0^+, 1^\pm, 2^\pm$	1	$\rho(770)$	5
	Flat bg				
1.4 – 2.0 GeV 44 waves 88 parameters	0^{-+}	0^+	0	σ	1
	0^{-+}	0^+	0	$f_0(980)$	1
	0^{-+}	0^+	1	$\rho(770)$	1
	1^{++}	$0^+, 1^\pm$	0,2	$\rho(770)$	6
	1^{-+}	$0^-, 1^\pm$	1	$\rho(770)$	3
	2^{++}	$0^-, 1^\pm, 2^\pm$	2	$\rho(770)$	5
	2^{-+}	$0^+, 1^\pm, 2^\pm$	1,3	$\rho(770)$	10
	2^{-+}	$0^+, 1^\pm, 2^\pm$	0,2	$f_2(1270)$	10
	3^{++}	$0^-, 1^\pm$	2	$\rho(770)$	3
	4^{++}	$0^+, 1^\pm$	3	$f_2(1270)$	3
	Flat bg				

Fig. 3. Waves included in the partial wave analysis.

low mass region the $f_0(980)$, $\pi\pi$ S-wave (σ), and ρ isobars were allowed, above 1.4 GeV/ c^2 the $f_2(1270)$ was also included. The wave sets used in the analysis are shown in Fig. 3.

Some of the prominent waves in the preliminary partial wave analysis are shown in Fig. 4. The $a_2(1320)$ is clearly seen in photoproduction, and there is evidence for the $a_1(1260)$ being produced via a charge-exchange mechanism. At higher mass, there is a signal for the $\pi_2(1670)$. The exotic $\pi_1(1600)$ is not being produced copiously here, but there is some evidence of a signal which is being further investigated.

3. $K^+K^-\pi^+n$

A baryon with strangeness $S = +1$ must have exotic structure. Diakonov, Petrov and Polyakov¹⁸ have predicted a spin $\frac{1}{2}$ $S = 0$ isosinglet baryon with a mass near 1530 MeV/ c^2 within a chiral soliton model. Pentaquark baryons have also been considered in quark models¹⁹ and lattice QCD²⁰.

Recently many experiments have reported the observation of such a state. The first reported signal was made by the Spring8 collaboration in γC interactions, with the photon interacting with a neutron²¹. The state has a mass of 1540 MeV/ c^2 , and a width less than the experiment resolution of The CLAS collaboration has reported the same state with a photon beam incident on liquid deuterium²². Here we report

Fig. 4. Results of the preliminary partial wave analysis. (a) $J^{PC} = 1^{++}$ (a_1) wave. (b) $J^{PC} = 2^{++}$ (a_2) wave. (c) $J^{PC} = 2^{-+}$ (π_2) wave. (d) $J^{PC} = 1^{-+}$ (π_1) wave.

on a high-energy photon beam incident on liquid hydrogen at CLAS²³. The data came from three different experimental runs with different running conditions. Two runs, labeled (a) and (b) had the same geometric configuration of CLAS, but slight different beam energies. Run a had beam energies between 3.2 and 3.95 GeV, and run b had beam energy between 3.0 and 5.25 GeV. The third run, g6c has been described above. In this case, the target was moved upstream 1 meter to improve acceptance in the forward direction, and the beam energy was between 4.8 and 5.4 GeV. In addition, the CLAS torus magnet was reduced by half in order to improve the acceptance for forward negative tracks. The integrated raw luminosity for runs a and b together is 2 pb^{-1} , and for run c it was 2.7 pb^{-1} .

Events with a π^+ , K^+ and K^- in the final state, identified by tracking and time-of-flight were selected for analysis. The missing mass distribution for the reaction $\gamma p \rightarrow \pi^+ K^+ K^- X$ is shown in Fig. 5. A neutron peak is observed in each distribution. The missing mass resolution is better in runs a and b due to the lower energy and higher magnetic field for the momentum spectrometer. Exclusive events were selected by selecting events within $\pm 2\sigma$ of the neutron mass for each run individually. The resulting sample consisted of 14000 events. In order to eliminate $\phi\pi^+n$

Fig. 5. Missing mass distribution in the reaction $\gamma p \rightarrow \pi^+ K^- K^+ X$. The peak is the neutron. The four panels (clockwise) are for each of the runs a,b, and c, while d shows the combined spectrum.

events, events with a $K^+ K^-$ effective mass less than $1.060 \text{ GeV}/c^2$ were removed. Various mass distributions are shown in Fig. 6. The nK^+ effective mass shows no particular structure. Various t-channel mechanisms were considered to enhance any possible Θ^+ signal, shown in Fig. 7. The clearest signal is obtained by selecting events with $\cos(\theta_{\pi^+}^*) > 0.8$, where $\theta_{\pi^+}^*$ is the angle between the beam and the π^+ in the center-of-mass system, which corresponds to a cut on momentum transfer $-t < 0.28 \text{ GeV}/c^2$. The spectrum is shown in the inset in Fig. 8(a). As a systematic check, we varied the pion angle cut from 0.7 to 0.9 and found that in all cases the peak was clearly visible. It should be noted that for the Fig. 7(a) momentum transfer is a relevant variable, while the background to this process, eg. Fig 7(b) will have a significantly different behavior in momentum transfer, hence the reasoning of the center-of-mass angle cut, rather than the more natural momentum transfer.

The final nK^+ effective mass distribution (Fig. 8) was fitted by the sum of a Gaussian function and a background function obtained from the simulation. The fit parameters are: $N_{\Theta^+} = 41 \pm 10$, $M = 1555 \pm 1 \text{ MeV}/c^2$, and $\Gamma = 26 \pm 7 \text{ MeV}/c^2$ (FWHM), where the errors are statistical. The systematic mass scale uncertainty is estimated to be $\pm 10 \text{ MeV}/c^2$.

The fact that the angular cuts we applied enhanced the Θ^+ signal suggests the possible production of an N^*/Δ^* that decays to Θ^+ and K^- . If the Θ^+ is an isosinglet, the intermediate state can only be an N^* . The $nK^+ K^-$ invariant mass is shown in Fig. 8(b) for the events with nK^+ effective mass between 1.54 and $1.58 \text{ GeV}/c^2$. The apparent excess of events near $2.4 \text{ GeV}/c^2$ are suggestive of an

Fig. 6. Effective mass distributions for the reaction $\gamma p \rightarrow K^+ K^- \pi^+ n$. The neutron is measured by missing momentum. **a)** $K^- \pi^+$ effective mass. **b)** $K^+ K^- \pi^+$ effective mass. **c)** $n \pi^+$ effective mass. **d)** $n K^+$ effective mass.

Fig. 7. The diagram in (a) shows a possible production mechanism for the Θ^+ , which could be a decay product of an intermediate baryon resonance. The three diagrams in (b), (c), and (d) are background processes in the reaction $\gamma p \rightarrow \pi^+ K^- K^+(n)$. All background processes have a K^+ going in the forward direction in the center-of-mass system.

intermediate baryon state. A possible production mechanism that could contribute to the Θ^+ production is shown in Fig. 7(a). Similar processes were also theoretically

Fig. 8. (a) The nK^+ invariant mass spectrum in the reaction $\gamma p \rightarrow \pi^+ K^- K^+(n)$ with the cut $\cos \theta_{\pi^+}^* > 0.8$ and $\cos \theta_{K^+}^* < 0.6$. $\theta_{\pi^+}^*$ and $\theta_{K^+}^*$ are the angles between the π^+ and K^+ mesons and photon beam in the center-of-mass system. The background function we used in the fit was obtained from the simulation. The inset shows the nK^+ invariant mass spectrum with only the $\cos \theta_{\pi^+}^* > 0.8$ cut. (b) The nK^+K^- invariant mass spectrum calculated from the missing mass off the π^+ in the reaction $\gamma p \rightarrow \pi^+ K^- K^+(n)$ with the cuts $\cos \theta_{\pi^+}^* > 0.8$ and $\cos \theta_{K^+}^* < 0.6$. $\theta_{\pi^+}^*$ and $\theta_{K^+}^*$ are the angles between the π^+ or K^+ mesons and photon beam in the center-of-mass system. These events have $M(K^+n)$ between 1.54 and 1.58 GeV/c^2 . The shape of the background curve was obtained from the simulation as discussed in the text. The inset shows the nK^+K^- invariant mass spectrum for all events in Fig. 8(a).

Fig. 9. PWA results intensity distribution: Left panels from top to bottom: $2^- \bar{K}^{*0}$, $0^- K^{*0}(1430)$, $1^+ \bar{K}^{*0}$ and total intensities. Right panel from top to bottom: $2^- f_2(1270)$, $1^- \bar{K}^{*0}$, $0^- \bar{K}^{*0}$ and isotropic background.

considered in Ref. 24. The simulation we described previously also demonstrated that the angular cuts we applied could not generate a narrow peak in the nK^+K^- invariant mass spectrum from any of the three data runs.

The most prominent background to the Θ^+ production is t-channel production of a meson which then sequentially decays to $K^+K^-\pi^+$ as shown in Fig. 6(b).

Fig. 10. **a)** PWA prediction of the G-J angle for K^+ and π^+ compared with data. Red triangle marker is the real data, while blue circles are the prediction of the PWA results. The error bars are only statistical. Top panels are K^+ G-J angles, and bottom panels are π^+ G-J angles. **b)** PWA prediction of the invariant mass spectra compared with data. Left: with the angular cuts of with $\cos(\theta_{\pi^+}^*) > 0.8$ and $\cos(\theta_{K^+}^*) < 0$. Right: with angular cut of $\cos(\theta_{K^+}^*) < 0$ and $t'(\gamma \rightarrow \pi^+ < 1 \text{ GeV}/c^2)$. Red histogram is the real data, while blue histogram is the prediction of the PWA results. The prediction is normalized to the data outside the Θ^+ region ($1.52 < M(nK^+) < 1.6 \text{ GeV}/c^2$).

There has been a suggestion that meson resonances may reflect into the nK^+ mass spectrum, particularly under the influence of strong kinematic cuts²⁵. To this end we have performed a partial wave analysis on this channel in order to identify the predominant mesonic background in our data. From Fig. 6 it is seen that the strongest resonance state in the data is the $K^*(892)$ decaying to $K^-\pi^+$, with much less background from $f_2(1270)$ and $a_2(1320)$ decaying to K^+K^- .

In an effort to isolate pure mesonic peripheral production, a cut was made on the momentum transfer to the $K^+K^-\pi^+$: $|t'| < 0.6(\text{GeV}/c^2)^2$. In addition, a cut was made on the laboratory angle of the π^+ to suppress the background from Δ and N^* resonances decaying to $n\pi^+$ (See Fig. 7(c)). The partial wave decomposition of the significant contributions are shown in Fig. 9. There is clear evidence for two π_2 states, both the $\pi_2(1670)$ and the $\pi_2(1900)$.

Comparisons of the partial wave fit to various measured distributions are shown in Fig. 10(a). The partial wave analysis is successful in describing the mesonic background. From the measured partial wave amplitudes, a monte carlo data set can be generated, relaxing the cuts used in the analysis. From this resulting data set, applying now the cuts used in the Θ^+ analysis, as well as monte carlo simulation of the detector, the mesonic background can be described into the nK^+ mass spectrum, shown in Fig. 10(b). As can be seen, mesonic states reflecting into the nK^+ spectrum generate no bumps in this channel.

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