The Search for Exotic Mesons in $\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$
with CLAS at Jefferson Lab

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Abstract.
In addition to ordinary $q\bar{q}$ pairs, quantum chromodynamics (QCD) permits many other possibilities in meson spectra, such as gluonic hybrids, glueballs, and tetraquarks. Experimental discovery and study of these exotic states provides insight on the nonperturbative regime of QCD. Over the past twenty years, some searches for exotic mesons have met with controversial results, especially those obtained in the three-pion system. Prior theoretical work indicates that in photoproduction one should find gluonic hybrids at significantly enhanced levels compared to that found in pion production. To that end, the CLAS g12 run was recently completed at Jefferson Lab, using a liquid hydrogen target and tagged photons from a 5.71 GeV electron beam. The CLAS experimental apparatus was modified to maximize forward acceptance for peripheral production of mesons. The resulting data contains the world’s largest $3\pi$ photoproduction dataset, with $\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$ events numbering in the millions. Early results describing the data quality, kinematics, and dynamics will be shown.

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INTRODUCTION

In the quark model’s original form, mesons are built from quark-antiquark pairs. Assuming mesons to be built of two spin-$\frac{1}{2}$ objects places constraints on their quantum numbers. Namely, the spin, parity, and C-parity must obey the following prescriptions:

$$J = L + S$$
$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$

Following this prescription, one finds that $q\bar{q}$ states must obey the following:

$$J^{PC}_{q\bar{q}} = 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 1^{++}, 2^{--}, 2^{-+}, 2^{++}, (\ldots)$$

However, quantum chromodynamics (QCD) makes no such restriction on the composition of mesons. Due to the self-interacting nature of the gluon, it is possible to produce $q\bar{q}g$ states, multiquark states, or states composed entirely of glue (glueballs). These states which are forbidden by the quark model but permitted by QCD are called exotic, and some of these states can be easily identified by their non-$q\bar{q}$ quantum numbers,

$$J^{PC}_{\text{exotic}} = 0^{--}, 0^{+-}, 1^{--}, 2^{+-}, (\ldots)$$
Other exotic mesons share $J^{PC}$ with quark model states, and are thus harder to identify. In both cases, studying these non-$q\bar{q}$ states and mapping out their spectra is fundamental to understanding the nature of the strong interaction.

Experimental efforts to discover exotic mesons have a rich and diverse history; especially controversial was the observation of a $J^{PC} = 1^{-+}$ state at 1600 MeV in $\pi^- p \rightarrow \pi^+ \pi^- \pi^- p$ in the E852 experiment at Brookhaven National Lab[1],[2]. This claim was later disputed by a group of E852 collaborators with a coupled-channel analysis of $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ and $\pi^- p \rightarrow \pi^- \pi^0 \pi^0 p$ data [3]. Recently, the COMPASS collaboration at CERN has acquired large pion production dataset in $\pi^- +^{208}\text{Pb} \rightarrow \pi^- \pi^- \pi^+ p$ channel, and preliminary results of a partial wave analysis on a sample of 420K low-$t'$ events show evidence for a $1^{-+}$ exotic state at 1660 MeV [4]. COMPASS is currently analyzing a much larger dataset of $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ events with the aim to continue the study of the $\pi_1(1600)$ exotic candidate.

To date, the lion’s share of experimental study of exotics has been in pion production, but theoretical work indicates that photon beams may be able to produce exotics in abundance. The flux-tube model of Isgur and Paton [5] has been central to the theoretical development in the study of gluonic hybrids, and the vector character of the photon is optimal for elevating the gluonic flux-tube to an excited state, possibly producing hybrids in proportions equal to that of the $a_2(1320)$ [6]. Additionally, calculations on the lattice in the charmonium regime show a strong photocoupling for $c\bar{c}$ hybrids[7], promising copious hybrid photoproduction in the light quark sector.

The GlueX experiment at Jefferson Lab will be the definitive exotic meson spectroscopy experiment but its commissioning comes at present in 2013. In the meantime, members of the CLAS collaboration in Hall B at Jefferson Lab have completed two photoproduction experiments to look for light exotics.

**THE CLAS DETECTOR**

Meson spectroscopy with CLAS has presented unique challenges, as CLAS was designed first and foremost as a baryon spectrometer. Roughly spherical and divided axially into six independent sectors of detector systems, the acceptance of CLAS is optimized for decays occurring in the middle lab angles (see Figure 1). Exotic meson spectroscopy is largely focussed on small lab angle, low-$t$ physics, and CLAS has limited acceptance in this region. Small modifications such as moving the target upstream and reducing the field of the CLAS torus can mitigate these concerns to some degree. Detector acceptance plays a crucial role in understanding the results of any partial-wave analysis, and for CLAS this is especially true when competing with experimental apparatus designed for the purpose of meson spectroscopy.

$$\gamma p \rightarrow \pi^+ \pi^+ \pi^- n \text{ IN G12}$$

The first photoproduction experiment in Hall B dedicated to exotic meson spectroscopy was E99-005, which obtained a limited amount of data in 2001 as a member of the
g6c rungroup. About 250K $\gamma p \rightarrow \pi^+\pi^+\pi^-n$ events were obtained, but with significant backgrounds from $\Delta$ and $N^*$ baryons. Selections of low-$t$ and small angle events to remove this background reduced the sample to 83K events. A partial-wave analysis was performed but demonstrated only that the $\pi_1(1600)$ does not appear on an equal footing with the $a_2(1320)$ – with only 83K events it could not rule it out the same level as in pion production.

These results would be greatly improved by more statistics and so the HyCLAS experiment was proposed in 2004 and completed in 2008, acquiring a high-statistics photoproduction dataset with CLAS for meson spectroscopy. Now with events numbering in the millions, the $\gamma p \rightarrow \pi^+\pi^+\pi^-n$ channel can be examined in much more detail.

Preliminary analyses on a significant fraction of the data show a strong signal for the $a_2(1320)$ in the $3\pi$ mass spectrum, as well as signals for the $\rho(770)$ and $f_2(1270)$ isobars in the Dalitz plot (see Figure 2).

Especially important will be the study of the baryon background present in g12 data, strategies for its removal, and the systematic uncertainties introduced by its removal. Background in $\gamma p \rightarrow \pi^+\pi^+\pi^-n$ at CLAS is mostly $\Delta$ baryons, but other $N^*$ states are present as seen in Figure 3. If removal of the baryon background introduces unacceptable biases into the events that remain, another opportunity exists. Modern partial-wave analysis frameworks have evolved to be formalism-agnostic, and that may allow us to write our amplitudes in a formalism that permits the inclusion the baryon resonances as well.
FIGURE 2. Dalitz plots of 21% of the g12 dataset, with their associated regions in 3π mass highlighted.

Presently, the g12 dataset is in full reconstruction, and will be complete soon, at which time, analysis will begin in earnest with background studies and event selection.

FIGURE 3. $n\pi$ mass vs against $\pi^+\pi^+\pi^-$ mass for 21% of the g12 dataset; note signals for the $\Delta^- (1232)$ (left) and for an unknown $N^*$ resonance at 1.7 GeV/c$^2$ (right).
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REFERENCES