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SUITABILITY OF A NEW CALORIMETER FOR EXOTIC MESON SEARCHES

Craig Bookwalter, Alexander Ostrovidov, and Paul Eugenio

ABSTRACT

Exotic mesons, particles that have quantum numbers that are inaccessible to conventional quark-model mesons, are predicted by quantum chromodynamics (QCD), but past experiments seeking to identify exotic candidates have produced controversial results. The HyCLAS experiment (E04005) at Thomas Jefferson National Accelerator Facility (TJNAF) proposes the use of the Continuous Electron Beam Accelerator Facility (CEBAF) Large Acceptance Spectrometer (CLAS) in Hall B to study the photoproduction of exotic mesons. However, the base detector package at CLAS is not ideal for observing and measuring neutral particles, particularly at forward angles. The Deeply Virtual Compton Scattering (DVCS) experiment at TJNAF has commissioned a new calorimeter for detecting small-angle photons, but studies must be performed to determine its suitability for a meson spectroscopy experiment. The $\eta\pi$ system has been under especial scrutiny in the community as a source for potential exotics, so the new calorimeter's ability at reconstructing these resonances must be evaluated. To achieve this, the invariant mass of showers in the calorimeter are reconstructed. Also, two electroproduction reaction channels analogous to photoproduction channels of interest to HyCLAS are examined in DVCS data. It is found that, while not ideal, the new calorimeter will allow access to additional reaction channels, and its inclusion in HyCLAS is warranted. Results in basic shower reconstruction show that the calorimeter has good efficiency in resolving π° decays, but its η reconstruction is not as strong. When examining $ep \rightarrow ep\pi^\circ\eta$, preliminary reconstruction of the $\eta\pi^\circ$ system shows faint signals in the a0(980) region. In the $ep \rightarrow e\, n\, \pi^+\, \eta$ channel, preliminary reconstruction of the $\eta\pi^+$ system gave good signals in the a0(980) and a2(1320) regions, but statistics were poor. While more analyses are necessary to improve statistics and remove background, these preliminary results support the claim that the DVCS calorimeter will be a valuable addition to CLAS for upcoming exotic meson searches in photoproduction.

INTRODUCTION

Theory

In the early 1960s, the search for the elementary constituents of matter was at an impasse. Physicists, expecting to find a small number of tiny elemental particles making up protons and neutrons, were in fact finding an extraordinary number of unique particles in their scattering experiments. In response to this, Murray Gell-Mann and George Zweig independently formulated the quark model, an organization of the "particle zoo", by postulating that most of the particles were composed of different configurations of two or three elementary particles called quarks. Gell-Mann's Eightfold Way organized the mesons (two-quark particles) and baryons (three-quark particles) into two octets and one decuplet. Using these organizing principles, Gell-Mann predicted the existence of an as yet unseen particle, the Ω^-, which was later detected by a group at Brookhaven National Laboratory. The quark model was a great success and it reinvigorated the fields of nuclear and elementary particle physics [1].

Soon, a theory governing the behavior of quarks was produced. Quarks were described by an additional quantum number, known as color charge. The color charge itself was mediated by particles known as gluons which possessed their own color charge. These interactions would be observed as the strong force. This theory of colored quarks and gluons was called quantum chromodynamics

(QCD). Development of QCD continues today. One of its predictions is that new hadronic matter should exist outside the predictions of the quark model of Gell-Mann and Zweig. These new particles would be identified by their quantum numbers, or J^{PC}, where J is the total angular momentum, P is the parity, and C is the charge conjugation. For an ordinary meson composed of a quark and an antiquark, with orbital angular momentum L and total spin S, J^{PC} is calculated as follows:

$$J = S + L$$

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

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

Given this prescription, the following $q\bar{q}$ states are allowed:

$$J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 1^{--}, 2^{-+}, 2^{--}, 2^{++} \ldots$$

Any states with J^{PC} different from those allowed by the quark model are manifestly exotic and if experimentalists can identify them they will have validated a prediction of QCD. One should note that other exotic states exist with ordinary J^{PC}, but experimentalists have focused on those with exotic J^{PC} since those will be the easiest to identify [2].

The Experiment

Unfortunately, searches for exotic mesons have resulted in controversy within the nuclear physics community. The E852 collaboration at Brookhaven National Laboratory, studying reactions like $\pi^- p \rightarrow \eta\pi^- p$, $\pi^- p \rightarrow \eta'\pi^- p$, and $\pi^- p \rightarrow \pi^+\pi^-\pi^- p$, published the first claims of exotic measurements in 1998 with two candidates, the $\pi_1(1400)$ (masses in MeV in parentheses) and the $\pi_1(1600)$ [2]. While theoretical predictions for the mass of the glueball place it within this range, the $\eta\pi$ system has isospin 1 and thus excludes glueballs from being produced [2,3]. With that in mind, both model-based and lattice QCD calculations put the lightest quark-based exotics at around 1.9GeV [4,5], significantly higher than the $\pi_1(1400)$. The $\pi_1(1600)$ is closer to the predicted mass, but the theory does not predict its observed decay to $\rho\pi$ [6].

At Thomas Jefferson National Accelerator Facility (JLab), an experimental program is underway to exhaustively study the lightest of the exotic meson candidates. In the long term, the GlueX experiment seeks to map the spectrum of light exotics in detail, but its commissioning will come only after a planned accelerator upgrade is complete [7]. In the near term, the Hy-CLAS experiment (Jefferson Lab experiment E04005) searches for light exotics using the Continuous Electron Beam Accelerator Facility (CEBAF) Large Acceptance Spectrometer (CLAS) in Hall B [8].

Unlike E852, which used a pion beam on a hydrogen target, HyCLAS (as well as GlueX) will use photon beams on hydrogen. Several theorists [9,10] predict that photoproduction will provide an ideal environment to search for exotics. In addition, the world photo production data in exotic-rich reaction channels is thin at best [11]. HyCLAS seeks to increase world data for a number of exotic-rich photoproduction reaction channels. However, the experiment is limited in the number of channels it can study by the detector configuration of CLAS.

CLAS and the Inner Calorimeter

CLAS is a spectrometer made up of six identical segments, arranged in a spherical shape around a toroidal magnet. It contains several layers of drift chambers for charged particle tracking, scintillator paddles for time-of-flight measurement, gas Çerenkov counters for particle identification, and sampling calorimeters for energy measurement [12]. Unfortunately, the design of CLAS leaves a large hole in the forward area around the beamline so peripheral production experiments such as HyCLAS lose a lot of events in the forward angles. CLAS also does not reconstruct neutral particles well at any angle, consequently, reaction channels with two or more neutrals are unobservable for the base detector package.

Fortunately, the Deeply Virtual Compton Scattering experiment at CLAS, measuring $ep \rightarrow ep\gamma$, also required small-angle detection for photons [12] and a new calorimeter was built to suit the purpose. The inner calorimeter (IC) is built from 424 lead-tungstate crystals arranged in an octagonal shape with a square hole in the center for the beam to pass. It is placed downstream of the target, directly in front of the forward hole in CLAS. Upon commissioning, it was demonstrated to have a 7MeV mass resolution at 1GeV [13].

The inclusion of this calorimeter in HyCLAS could open a significant number of new reaction channels for study, particularly the $\eta\pi$ system, notorious from its study in E852[2]. So, it is necessary

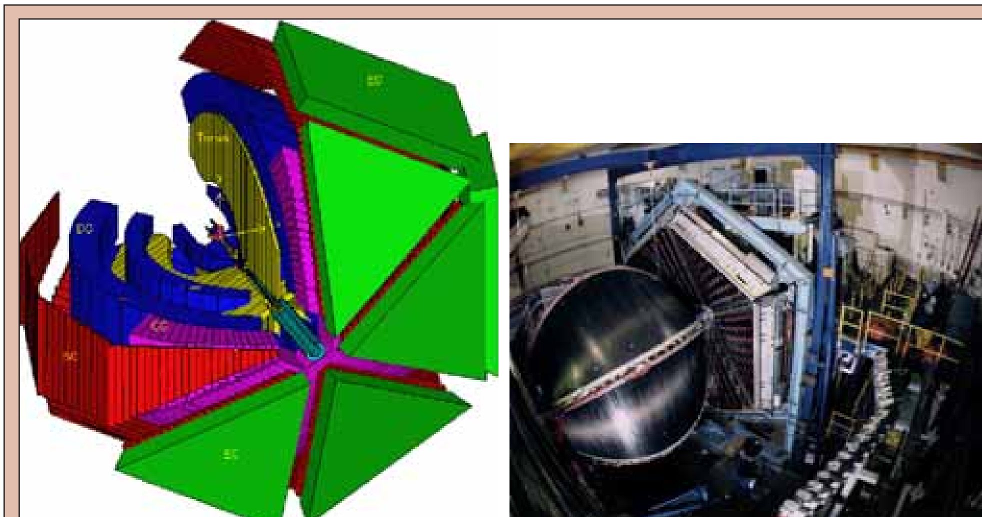

Figure 1. Left, CLAS as rendered in GEANT geometry. Right, a photo of CLAS.

that the IC be able to reconstruct showers originating from both π° and η decays. If it can be shown that the IC can accurately reconstruct neutral pions, then one may examine the data from the DVCS experiment and look for exotics and their companions in the $\eta\pi$ reaction channels. However, any observed resonances will be from electroproduction data, since DVCS examined $ep \rightarrow ep\gamma$. Thus, HyCLAS will provide the first opportunity to examine photoproduction data with improved CLAS acceptance.

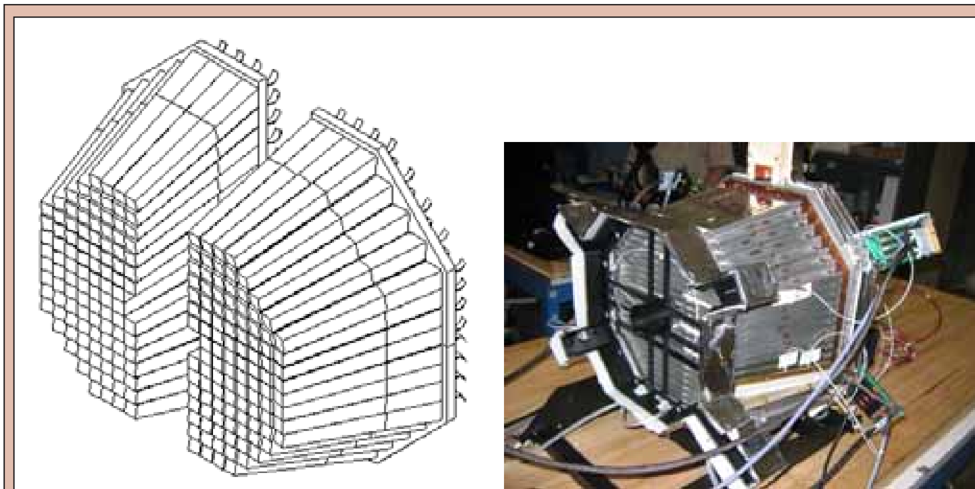

Figure 2. Left, an engineering drawing of the inner calorimeter. Right, a photograph.

METHODS OF ANALYSIS

Analysis Overview

The analyses below examined two channels similar to the systems studied in E852 and searched for exotic candidates in invariant mass spectra. The data, having already been reconstructed for the DVCS experiment, merely required the use of some in-house JLab libraries for event selection. Since the final analyses were performed using the ROOT software package [14], interesting events were transplanted into ROOT TTree format for easy access within ROOT scripts.

Reconstruction of π° and η

Evaluating the impact of the IC on the meson spectroscopy planned by HyCLAS requires examining the reconstruction of neutral pions and η mesons. Both of these particles decay primarily to 2γ, so events must have at least two showers in the IC, and the invariant mass can be reconstructed and the result plotted. An array of energy cuts on the showers in the IC are applied to determine the best cut to reduce background in further analyses. In the resulting plots, one expects to see a peak for the π° and a smaller peak for the η.

Examination of $ep \rightarrow ep\eta\pi^\circ$

After establishing the baseline characteristics of the calorimeter with the previous analysis, the first of two reaction channels is examined. Events are selected for this channel based on the following criteria:

1. an identified proton,
2. an identified electron, confirmed by examining the ratio of the energy calculated by the particle identification system and the energy reconstructed by the primary CLAS electromagnetic calorimeter,
3. two showers in the IC, each of at least 300MeV,
4. the invariant mass of the two showers is within 50MeV/c^2 of the π° mass,
5. the missing mass of the event is within 50MeV/c^2 of the η mass, and
6. the missing momentum is at least 400MeV/c.

Examining the invariant mass of the $\eta\pi^\circ$ systems of the remaining events can provide information about the masses of particles that decay to $\eta\pi^\circ$.

Examination of $ep \rightarrow en\eta\pi^+$

Another variation of the $\eta\pi$ system is the $ep \rightarrow en\eta\pi^+$channel. Events are selected by the following criteria:

1. an identified π^+,
2. an identified electron,
3. two showers of at least 300MeV in the IC,
4. the invariant of those two showers is within 100MeV/c^2 of the mass of the η,
5. the missing mass of the event is within 50MeV/c^2 of the neutron mass, and
6. the missing momentum is at least 400MeV/c.

From the surviving events the invariant mass of the $\pi^+\eta$ system is calculated and examined.

RESULTS

Reconstruction of π° and η

Basic shower reconstruction in the inner calorimeter produced excellent results for the π° and poor results for the η. Fig. 3 shows the reduction of background with energy cuts in 100MeV increments. The π° peak emerges early from the background, but even at a cut of 1GeV (when two showers each of at least 1GeV in energy are required) the η signal is not sufficient to show above background. This could be due to the small angular acceptance of the IC or, perhaps, to a large background of hadronic showers. Based on these data, a global cut of 300MeV was selected to reduce background on subsequent analyses.

ep → *ep*$\eta\pi^\circ$

One might expect the best-quality results to come from this channel, due to the high efficiency of the inner calorimeter in its detection of π°. However, the effect of the background has been difficult to overcome, as Fig. 4 demonstrates. The $\eta\pi$ invariant mass plot displays some recognition of the α_0(980) in the appropriate place, but more studies will be required to be certain of its presence. Judgment should be withheld on the identity of the obvious peak at 800MeV/c^2 until background is reduced. In addition, if one looks at the missing mass in Figure 4, there is no obvious η feature and a large portion of events are simply ep → epπ° (zero missing mass). There are a large number of these events so they are removed during analysis to allow an appropriate scale to plot the desired physics.

ep → *en*$\eta\pi^+$

The ep → en$\eta\pi^+$channel was expected to be more difficult, since events were required to have a reconstructed η in the IC. Despite suffering from low statistics, preliminary results show cleaner signals for relevant mesons than for the ep → ep$\eta\pi^\circ$channel. Examining the $\eta\pi$ effective mass plot in Figure 5, the two peaks in question are seen, one near the α_0(980), and the other near the α_2(1320). Those results come with a caveat, as demonstrated by the other plot in Fig. 5, which shows the missing mass. One may notice the lack of a neutron peak in these data background is still high at this stage, therefore these results are still preliminary. However, the peaks in the $\eta\pi$ invariant mass still seem to imply that there is a neutron under that background.

CONCLUSIONS

The lack of robust η reconstruction is disappointing, but the added acceptance of π° is welcome. The sighting of the α_0(980) and α_2(1320)mesons, while tentative, gives cause for excitement, since in photoproduction the π^1 exotic and the α_2 should be produced in similar numbers [10]. Additional studies are being conducted to remove the substantial background, but hardware solutions have also been proposed. A charged-particle hodoscope to identify charged particles entering the calorimeter and masquerading ad photons will further reduce background. Even though these results are preliminary, it seems clear that the IC will provide a decided benefit to the HyCLAS effort to study exotic meson spectroscopy.

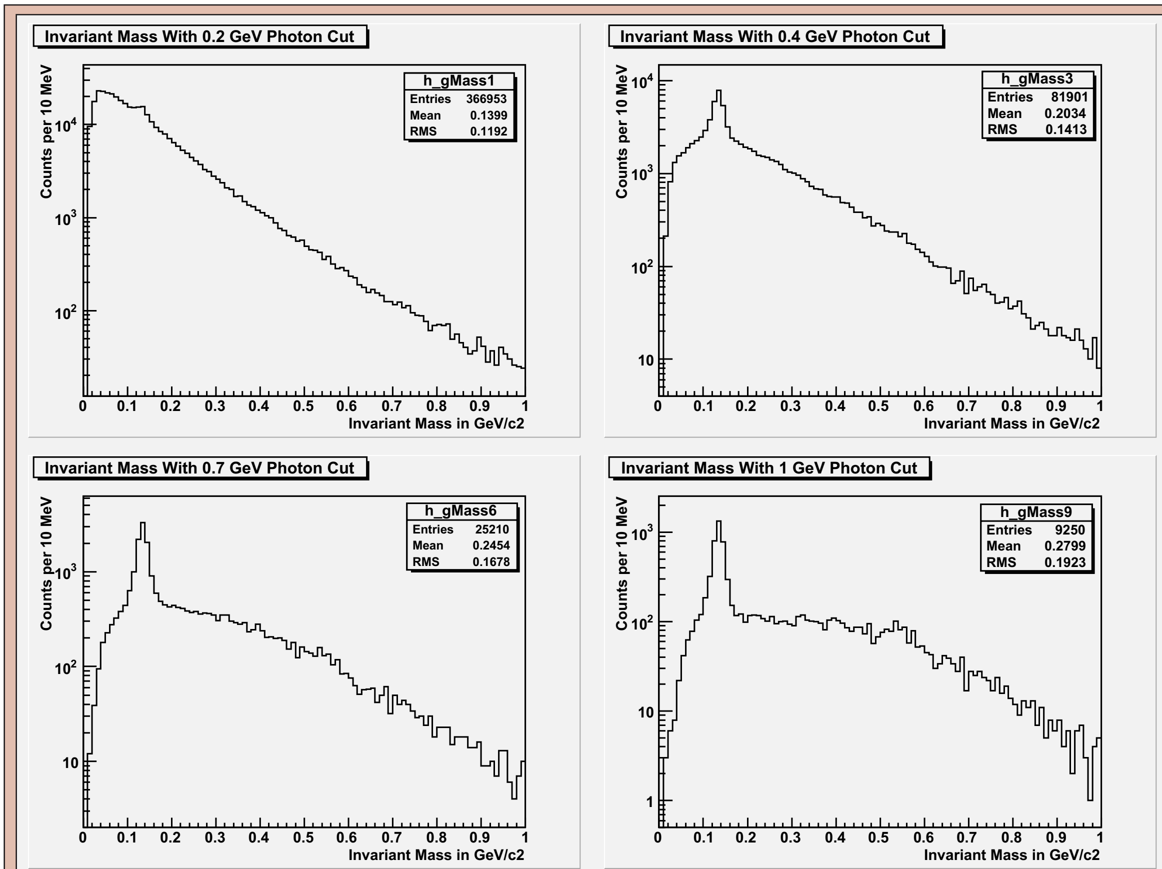

Figure 3. Effective mass of two-plus photon showers in the inner calorimeter subjected to cuts from 200MeV to 1GeV. Note the π° peak at 140MeV/c^2 and the lack of an η peak at 550MeV/c^2.

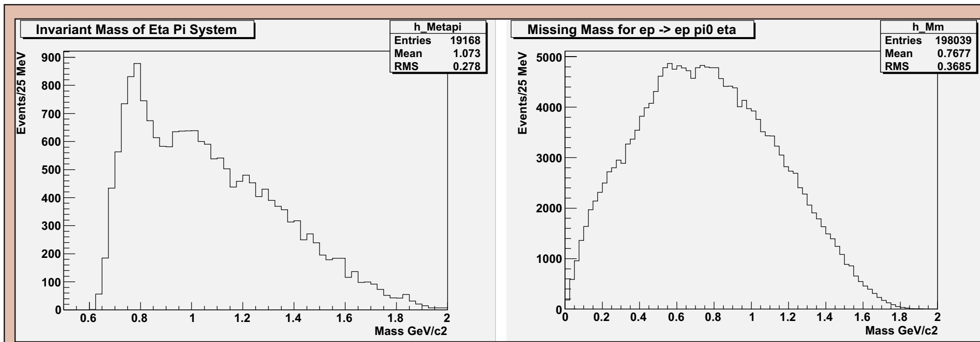

Figure 4. Data from the ep → epηπ° channel. A weak α_0(980) signal can be seen in the ηπ mass plot.

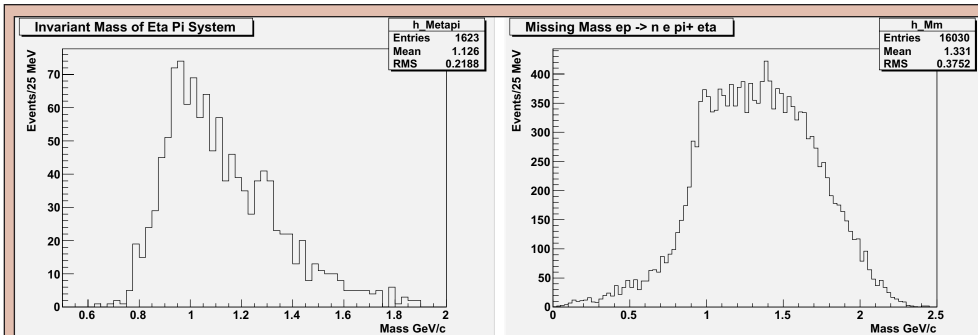

Figure 5. Data from the ep → epηπ° channel. In the plot on the left, one may notice a peak for the α_2(1320) and, possibly, a peak for the α_0(980), but further kinematical studies must be performed to confirm its existence. On the right, the missing mass of events selected as ep → epηπ$^+$ events; note the lack of a neutron peak.

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