Meson Production Experiments with Electromagnetic Beams using CLAS

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Abstract

The CEBAF Large Acceptance Spectrometer (CLAS) started taking production data in February, 1998. It is capable of taking data for many reactions simultaneously with moderate resolution. Spectrometer properties and running conditions are presented. Data has been taken for a variety of conditions with polarized and unpolarized beam and target. Preliminary results of the initial experiments are shown and discussed.

INTRODUCTION

The CEBAF Large Acceptance Spectrometer (CLAS) is presently taking data at a very large rate with essentially all of the initial complement of detectors functioning at design specifications. A primary CLAS goal of interest to this conference is the study of \( N^* \) resonances for masses less than about 2.5 GeV. Since these states couple with various strengths to a large number of open inelastic channels, a multi-faceted detector is required. By covering about 80% of 4\( \pi \) solid angle for single particles, many reactions can be studied simultaneously. The measured reactions have common systematic errors, correcting a significant problem in previous \( N^* \) analyses. Presently accepted \( N^* \) properties are determined almost solely from experiments using pion beams. Thus, the new experiments will be sensitive to \( N^* \) states that couple weakly to \( \pi N \). A more complete description of the apparatus can be found in the published talk of Bernhard Mecking[1]. Another review of CLAS was given by Volker Burkert[2].

The physics of \( N^* \)s with CLAS is the study of nonstrange and strange baryons, i.e. \( N^*, \Delta, \Lambda, \) and \( \Sigma \) baryons. The first identification of \( \Xi \) baryons in CLAS photoproduction events has recently been reported. These states decay to \( \pi N, \eta N, \pi\pi N, \omega N, K\Lambda, K\Sigma, \) and many other final states. Targets of liquid hydrogen, deuterium, ammonia (NH\(_3\)), \(^3\)He, \(^4\)He, carbon and iron have been run with real and virtual photons using 1.5-5.5 GeV electron beams. By running at a luminosity of \( 10^{34} \text{cm}^{-2}\text{s}^{-1} \), data on a large variety of reactions are being accumulated at an instantaneous event rate of about 2.5 kHz. After the first year of data taking, we have approximately equaled the number of events taken before CLAS for reactions accessible with traditional small solid angle spectrometers and greatly exceeded it for more complicated reactions.

PDG lists about 40 \( N^* \) states with a variety of quantum numbers and varying degrees of certainty. Presently, a good qualitative understanding of many properties of these states using various versions of the Constituent Quark Model (CQM) exists. However, this has not yet been linked to QCD in any formal way and presently does not account for the meson cloud. Although full QCD calculations on the lattice are believed to include all effects correctly, efforts to date have been limited to the quenched (no \( g \rightarrow q\bar{q} \) approximation. Recent improvements in numerical techniques and in computing power have been very impressive and significant results are expected.

Limitations in previous data are very clear when extracting resonance properties. The main problem is to turn the experimental observables first into partial wave amplitudes (which carry the strength for each reaction in a particular value of angular momentum and parity), then into the resonant part of the amplitude. Resonances are then found as poles or Breit-Wigner masses and widths. The latter step has more model dependence; a review of that situation can be found in[3]. The new experiments hope to provide significant new information on two general fronts- the spectra of states and their photocoupling amplitudes for \( \gamma N \rightarrow N^* \) as a function of \( Q^2 \). A significant prediction of the CQM is that many \( N^* \) states are yet to be found, the so-called “missing states”. For example, the CQM predicts 22 nonstrange \( L=2 \) excitations, but only about 10-12 have been identified. There is an additional possibility that hybrid baryons will have a sufficiently different electromagnetic response that they will stand out from the normal baryons. The incident photon causes...
a transition from the nucleon ground state (proton and neutron) to the various excited states. The dominant excitation mechanism is often through the s channel (see Fig. 1).

![Fig. 1. Excitation of a resonance via s channel. Empirical studies show this to be the dominant reaction mechanism for many final states, but u and t channel processes must be included for a fully correct model. Each event must be kinematically complete. The typical CLAS electroproduction experiment bins events in $Q^2$ and $W$ (virtual photon mass and invariant mass of the intermediate state) and $\theta^*$ and $\phi^*$ (the decay angles of the meson in the rest frame of the intermediate state.)](image)

The transition strength for $\gamma N \rightarrow N^*$ can be determined in various helicity states using a phenomenological analysis. Since these strengths are defined as matrix elements of the electromagnetic current acting between the $N$ and the $N^*$, these results can be directly compared with any calculation of the relevant wave functions. Examples from a host of important issues include trying to measure and explain the small size of the quadrupole excitation of the $\Delta$ ($P_{33}(1232)$), i.e. the E2/M1 problem, and trying to measure and explain the properties of the Roper ($P_{11}(1440)$) resonance. A large body of data for the delta already exists; nevertheless, CLAS will still greatly add to the electroproduction database. For the Roper, the existing data is of poor quality and a significant improvement is possible in almost all reactions. Interpretation of the existing data has been interesting because the CQM has trouble fitting the mass and the photocoupling is poorly measured. In addition, models suggesting interpretations as a hybrid baryon or a meson-nucleon state rather than a predominantly three quark state have been offered.

Some of the particles in Fig. 1 are displayed as vectors. Polarized beams at Jefferson lab are very common now and there is a polarized target for protons and deuterons (ammonia). A coherent Bremsstrahlung photon beam is being installed and is expected to be tested next year followed by experiments emphasizing vector meson production. With the full coverage of the meson strong decay angles (e.g. $\phi \rightarrow K^+K^-$) and the hyperon weak decay ($\Lambda \rightarrow p\pi^0$), some polarization information about the final state can be determined. Runs with polarized and unpolarized beams and targets have been taken. The events with unpolarized beam and target are the most fully analyzed and only that data will be presented here.

**CLAS PROPERTIES**

CLAS was built by an international collaboration of physicists from about 30 universities and national labs working with Jefferson lab personnel. Experiments are run by the CLAS collaboration. CLAS has 6 almost identical sectors, each covering about 54° in $\phi$. In Fig. 2, we show an event with 2 tracks in opposite sectors. The event has been classified as $ep \rightarrow e'p\eta$ with the final state proton in the upper sector and the electron in the lower sector. The detectors are labelled.

The detectors are conventional in design, but large on a nuclear physics scale. There are a total of 35,148 drift cells that are used to track charged particles through the toroidal field. The drift chambers are divided into 34 layers of hexagonal cells. Although the resolution of each cell is about 200 $\mu$m, overall system resolution is presently about a factor of 2 larger. Time of flight resolution for the charged particles detected in the scintillators is about 140 ps for electrons. The electromagnetic calorimeter has energy resolution for photons and electrons of $\sigma_E/E \approx 0.1/\sqrt{E}$. The Cerenkov detector is run in threshold mode, so it will fire only on electrons up to pion momentum of 2.8 GeV/c. Empirical studies
have shown the Cerenkov to have efficiency larger than 99.5% in the area more than 10 cm from the edges.

![Fig. 2. Single event display of an eta electroproduction event. Various detector systems are labelled. The arcs show locations of the 3 regions of drift chambers; the dots represent drift cells where particles have deposited energy. The electron bends in the magnetic field toward the beam line, has large energy deposition in the calorimeter, and fires a Cerenkov counter. The other track is a proton. Particle identification of charged hadrons is done via time of flight to the scintillators that cover the full CLAS solid angle.](image)

In broad terms, polar angular (θ) coverage for charged hadrons is about 8-140° with moderate resolution. For electrons and photons, the range is about 20-47° due to the sizes of the Cerenkov detector and the electromagnetic calorimeter; in 2 sectors, shower counter coverage is extended to 75°. The momentum resolution is presently about 0.2% in the forward direction and increases to about 2-3% for larger θ. Presently achievable resolution is about a factor of 2 worse than design values. Each event can have charged particle tracks or neutral particles in any sector. Events with 4 charged particles have been completely reconstructed (see Table 2). Electroproduction cross sections must be binned in $Q^2$, $W$, $\theta^*$, and $\phi^*$; with the full running time allocated, this will provide an average of a few hundred events in each of about a few hundred thousand bins for the reactions with the largest cross sections. Photoproduction reactions have $Q^2=0$, no phi dependence, and in general better statistics in each bin.

Technical papers covering all CLAS detectors are submitted and some are published[4].

**CLAS RUNNING EXPERIENCE**

With CLAS, many experiments take data simultaneously. Thus, the normal nuclear physics delineation of experiments by final states is not useful. We label experiments by initial state and a wide range of final states are measured in one detector configuration. For example, the e1 run group covers all experiments with an electron beam and an unpolarized proton or neutron target. That was the first run group to take beam and most of the results shown here are from that run. The beam can be photons or electrons, polarized or unpolarized; the target can be polarized or not. To date, most runs used a liquid hydrogen target- 5 cm long for e1 and 20 cm long for g1 (unpolarized photon beam with an unpolarized hydrogen target). Table 1 lists the run groups which have taken data as of August, 1999. In each case, the trigger particle is listed in bold face. For the electron running, the trigger particle is the electron. For photon beam experiments, a charged particle in coincidence with a tagger signal triggers each event. The loose trigger is a key part of fully utilizing large acceptance. Recent run cycles have produced a few billion events each.

**FIRST LOOK AT RESULTS**

At this stage of analysis, a few reactions are well understood and reasonably close to publication. However, there are no final results of cross sections presently available. A sampling of distributions will be shown here.
Table 1. Summary of the first 1.5 years of CLAS data-taking. Each run group takes data for many reactions. Polarized beam has become common at the lab. An arrow over a particle shows that it was significantly polarized.

| run group reaction, trigger particle in bold |
|---------------------------------------------|
| Feb-Mar, 98 e1 $e p \rightarrow e' X$ |
| May-June, 98 g1 $\gamma p \rightarrow cX$ (c=charged hadron) |
| June, 98 g6 $\gamma p \rightarrow ccX$ |
| July, 98 g1 $\vec{\gamma} p \rightarrow cX$ |
| Aug-Dec, 98 eg1 $\vec{e} p \rightarrow e' X$ |
| Jan-Apr, 99 e1 $\vec{e} p \rightarrow e' X$ |
| Apr-May, 99 e2 $\vec{e} A \rightarrow e' X$ (A= $^{3,4}$He,$^{12}$C,Fe) |
| July, 99 g6 $\gamma p \rightarrow ccX, \phi \rightarrow f_0\gamma$ |
| Aug, 99 g2 $\gamma d \rightarrow cX$ |

The acceptance of CLAS is shown in Fig. 3 through the distribution of $\pi^+$ seen in a small fraction of the first e1 run. Traditional spectrometers detect particles over a few degrees in $\theta$ and $\phi$. Here, acceptance falls off at small values of $\theta$ due to support structures close to the beam line. The 6 bands of missing events are due to the gaps between sectors filled by the magnet coils and detector supports. These fixed gaps are the major elements in the acceptance calculation. The detailed form of the acceptance depends on the value and sign of the magnetic field. These events were taken with 2.4 GeV beam, normal field (electrons bending toward the beam line), and field value of 60% of full strength (2250 A).

Fig. 3. Preliminary analysis of the distribution of $\pi^+$ in the lab from part of the first e1 run.

Angular Distribution of $\pi^+$
CLAS 2.4 GeV Data

Fig. 4 provides a broad, preliminary look at the physics to be measured with CLAS. We show $W$ distributions for 4 GeV beam energy and proton target. Final states were identified through missing mass techniques. The $Q^2$ of these events ranges between 1 and 3 (GeV/c)$^2$. Even though no corrections have been applied and only a simple background subtraction was used, the distributions are quite similar to the final cross sections. The well-known 3 resonance regions are seen, peaked at $W \sim 1.2, 1.5,$ and $1.75$ GeV. However, the peaks are in different places and have different strengths in the various reactions because each broad peak is a sum of contributions from a few underlying states. The reactions in the upper figures show strength in a variety of resonances; a detailed partial wave analysis will be required to get strengths individual states. Both $\eta$ and $\omega$ distributions have a peak near
Table 2. Reactions identified in CLAS data as of October, 1999. The number of particles detected is also given. Elastic scattering and \( \pi^+\pi^- \) production events have been very valuable for calibration and efficiency measurements because they are overdetermined.

| Reaction                  | Events | \( \gamma \rightarrow \pi \) Events |
|---------------------------|--------|-------------------------------------|
| \( ep \rightarrow ep \)   | 1,2    |                                     |
| \( ep \rightarrow e'p\pi^0 \) | 2      | \( \gamma \rightarrow \pi \) 1     |
| \( ep \rightarrow e'n\pi^+ \) | 2      | \( \gamma \rightarrow \pi \) 1     |
| \( ep \rightarrow e'p\eta \) | 2      | \( \gamma \rightarrow \pi \) 1     |
| \( ep \rightarrow e'\Lambda K^+ \) | 2      | \( \gamma \rightarrow \pi \) 1     |
| \( ep \rightarrow e'\Sigma K^+ \) | 2      | \( \gamma \rightarrow \pi \) 1     |
| \( ep \rightarrow e'p\omega \) | 3      | \( \gamma \rightarrow \pi \) 2     |
| \( ep \rightarrow e'p\phi \) | 3      | \( \gamma \rightarrow \pi \) 2     |
| \( ep \rightarrow e'p\pi^+\pi^- \) | 3,4    | \( \gamma \rightarrow \pi \) 2.3   |
| \( ep \rightarrow e'p\eta' \) | 4      | \( \gamma \rightarrow \pi \) 3     |
| \( ep \rightarrow e'p\eta\pi^+\pi^- \) | 4      | \( \gamma \rightarrow \pi \) 2     |
| \( ep \rightarrow e'\Lambda(1520)K^+ \) | 3      | \( \gamma \rightarrow \pi \) 2     |
| \( ep \rightarrow e'\Lambda^0K^+\pi^- \) | 3      | \( \gamma \rightarrow \pi \) 2     |
| \( ep \rightarrow e'\Lambda^0K^*0 \) | 3      | \( \gamma \rightarrow \pi \) 2     |

Threshold. For \( \eta \) electroproduction, the peak is known to be largely due to excitation of a single resonance, the \( S_{11}(1535) \). These events have a largely isotropic angular distribution. Since this is the first data for \( \omega \) electroproduction that wasn’t dominated by diffractive processes, the peak is new. It is probably due to newly discovered coupling of known or new resonances to \( \omega N \) since the angular distributions have no hint of forward angle peaking close to threshold.

![Fig. 4. Preliminary analysis of W distribution for various final states from part of the first e1 run. Although no acceptance correction is applied, the acceptance in this variable is fairly flat. Sideband subtraction in the missing mass spectrum of a neutral particle is sometimes used to isolate final states.](image)

Table 2 lists the reactions that have been identified with CLAS in the g1 and e1 data sets.

Acceptance calculations are in progress and largely understood. The primary contributor to acceptance is the geometric holes shown in Fig. 3. These effects and detector
inefficiencies are accounted for in angular distributions defined in Fig. 1 ($\theta^*$ and $\phi^*$) by Monte Carlo simulations. Another important effect in experiments with an electron beam is the radiative corrections. An example of preliminary CLAS results, one of the $\phi^*$ distributions for the $e p \rightarrow e' p \eta$ experiment, is shown in Fig. 5. Previous experiments had very limited $\phi^*$ coverage; still, the angular distributions at $W \sim 1.5$ GeV over a large range in $Q^2$ were predominantly isotropic. (This means the interference response functions, $R_{LT}$ and $R_{TT}$ are small, but very poorly measured in previous experiments.) Thus, isotropic results within the $\sim \pm 10\%$ errors of previous experiments can be expected. The raw eta yields (data points in the left figure) are decidedly nonisotropic, but the acceptance correction matches its shape to give a cross section that is isotropic. The total correction factor is given as a line in the left plot. The radiative correction is about 15\% independent of angle. For these points, the acceptance is about 35-40\%; the dips come from situations when either the scattered electron or the proton tend to be in the phi gaps. A quantity proportional to the cross section $d\sigma/d\Omega^\eta_{\phi^*}$ is shown in the right plot.

Fig. 5. $\phi^*$ dependence for eta yield and correction factor (left) and preliminary cross section (right) for $e p \rightarrow e' p \eta$ at $Q^2=0.75$ (GeV/c)$^2$, $W=1.53$ GeV, $\cos(\theta^*)=-0.6$. Errors shown reflect statistical errors in the data and in the Monte Carlo acceptance calculation. Systematic errors for these points are presently estimated as less than 10\%.

SUMMARY

CLAS is now a working device. In standard running mode, data is taken at an instantaneous event rate of 2.5 kHz or about 0.5 Terabyte/day. It presently takes data for 10 months each year. The collaboration has taken data with a variety of targets and with both photon and electron beams. A few run groups have recently accumulated a few billion events each in runs of about 2 months.

At present, a significant number of reactions have been measured with statistical precision equal to or better than previous data. Some reactions are being explored for the first time. Others are being explored in kinematic regions not previously explored. Systematic errors are presently under study.

Use of polarization has become common. At the end of 1998, 2 months were devoted to runs with polarized hydrogen target and polarized electron beam. Those experiments are important for isolating specific spin parity intermediate states and for measuring an important contribution to the GDH Sum Rule at $Q^2 > 0$. A diamond crystal and goniometer are being installed for production of a transverse linearly polarized photon beam in 2000.

ACKNOWLEDGEMENTS

The author is a member of the CLAS collaboration. All results shown have been taken and approved by the collaboration. Special thanks for production of the figures used in this paper go to Stepan Stepanyan, Kui Young Kim, and Richard Thompson.

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