N* Physics with Meson Photoproduction at CLAS

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An overview is given of the progress in baryon spectroscopy from the CLAS experimental programme. A range of photoproduction measurements have been carried out, which include the extraction of several polarization observables for different reaction channels. The results so far show that these data can be very useful in the search for evidence for new resonant states. A large amount of data is yet to be published form the programme.

KEYWORDS: baryon, spectroscopy, meson, photoproduction

1. Introduction

Over thirty years ago, in a review of baryon spectroscopy [1], it was asserted that

> ... it is probably no exaggeration to say that we now have essentially *all* the experimental data relevant to the low-energy baryon spectrum, that we are *ever* likely to obtain.

Thankfully, this has proved to be overly pessimistic. A glance at the number of states listed as three- or four star in the Reviews of Particle Physics from 2004 [2] and 2014 [3] shows that in the 10-year period, a small number of new states have been identified, although most of the new states identified have come from the heavy flavour sector (see table I).

Table I. Numbers of 3- and 4-star baryon states listed in the Reviews of Particle Physics [2, 3].

Baryon	2004	2014
$N^\star$	15	17
Δ	10	10
Λ	14	14
Σ	12	12
Ξ	7	9
Ω	2	2
other	14	27

Nevertheless, this survey shows that progress is being made, which inevitably relies on advances in experimental and theoretical technologies. But the process is not yet completed. Most variants of the quark model predict more states than have as yet been identified. These predictions have been given strong support from the recent results from lattice QCD such as those from the Hadron Spectrum Collaboration [4], which indicate in broad terms that the spectra derived from lattice calculations share many similar features with quark models, including the number of expected states.

It is something not far short of an embarrassment that our knowledge of the low energy baryon spectrum is incomplete. Would it have been possible for the development of quantum electrodynamics if knowledge of atomic spectra had been incomplete?

2. Experimental Programme at CLAS

The CEBAF Large Acceptance Spectrometer (CLAS) [5] was the centrepiece of Hall B at Jefferson Lab until its last experimental run finished in June 2012. A diagram of the detector is shown in figure 1.

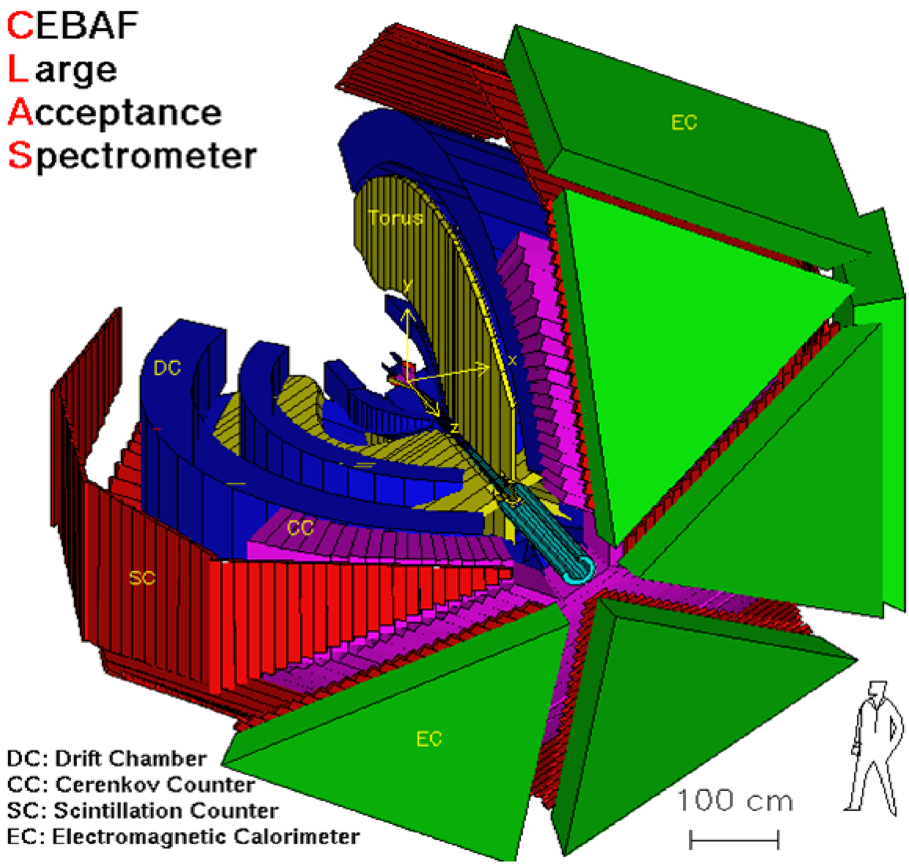

Fig. 1. Diagram of the CLAS detector [5].

Reaction products are tracked by drift chambers from the target through a toroidal magnetic field. Scintillation counters measure particle time-of-flight, Čerenkov detectors allow for particle identification and electromagnetic calorimeters measure the energy of charged particles.

The programme of measurements relevant to the study of the baryon resonance spectrum is summarized in table II. This table shows the various final states that can be measured in photoproduction with CLAS, together with the observable quantities that are possible to extract. A main feature of CLAS is the capability of measuring multiple particles in the final state, although charged particles are easier to identify cleanly than neutrals.

It has to be noted that, apart from the differential cross section measurements, most of the remaining observables have yet to be published. A short summary of the findings now follows.

Table II. Observables measured in the CLAS pseudoscalar meson photoproduction programme.

Observable →	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
Final state																
Proton Targets																
$p\pi^0$	*	*	*		*	*	*	*								
$n\pi^+$	*	*	*		*	*	*	*								
$p\eta$	*	*	*		*	*	*	*								
$p\eta'$	*	*	*		*	*	*	*								
$p\omega$	*	*	*		*	*	*	*								
$p\phi$	*	*	*		*	*	*	*								
$K^+\Lambda$	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
$K^+\Sigma^0$	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
$K^0\Sigma^+$	*	*														
$K^{0\star}\Sigma^+$	*	*														
$K^{+\star}\Sigma^0$	*	*														
Neutron Targets																
$p\pi^-$	*	*			*	*	*									
$p\rho^-$	*	*			*	*	*									
$K^0\Lambda$	*	*	*	*	*	*	*				*	*	*	*	*	*
$K^0\Sigma^0$	*	*	*	*	*	*	*				*	*	*	*	*	*
$K^-\Sigma^+$	*	*			*	*	*									
$K^{0\star}\Sigma^0$	*	*														

3. Cross Section Measurements

An example of $\pi^+ n$ angular distribution of cross sections is show in figure 2. One can see that the statistical accuracy is very good, providing a tight constraint for theoretical models over the whole resonance region [6]. Progress has also been made on measurements of ω photoproduction. Figure 3 shows cross section data from [7]. Spin density matrix elements have also been extracted from those measurements.

It is not possible in the space available to show a comprehensive set of photoproduction data from CLAS. The main point to take from this is that differential cross-sections are now tied down rather nicely, and a large fraction of the photoproduction results are CLAS measurements.

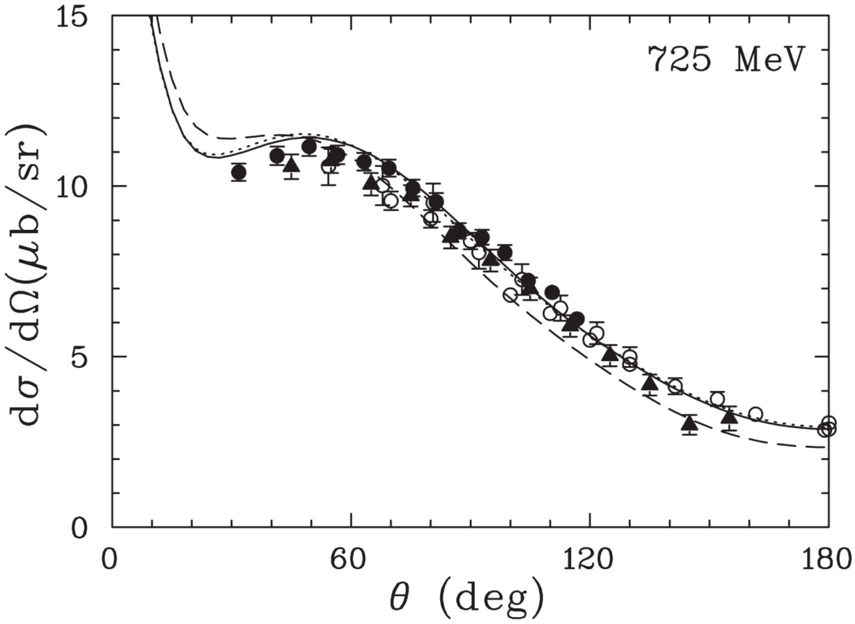

Fig. 2. Example of differential cross section results for the $\gamma p \to \pi^+ n$ reaction [6].

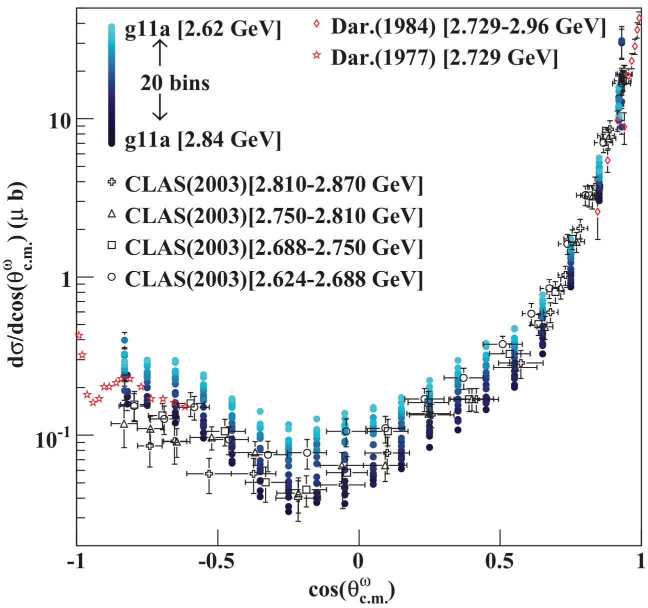

Fig. 3. Example of differential cross section results for the $\gamma p \to \omega p$ reaction [7].

4. Recoil Polarization

Whilst the accurate determination of cross sections is necessary, it is not sufficient for determining whether there is evidence for new resonant states. Figure 4 from [8] shows that with a circularly polarized photon beam, and the ability to determine the polarization of the recoiling hyperon, the double polarization observables C_x and C_z for the $\gamma p \to K^+\Lambda$ reaction can be extracted. These data were instrumental in providing evidence for new resonances, found in the analysis of [9], and reported in the 2012 Review of Particle Physics [2].

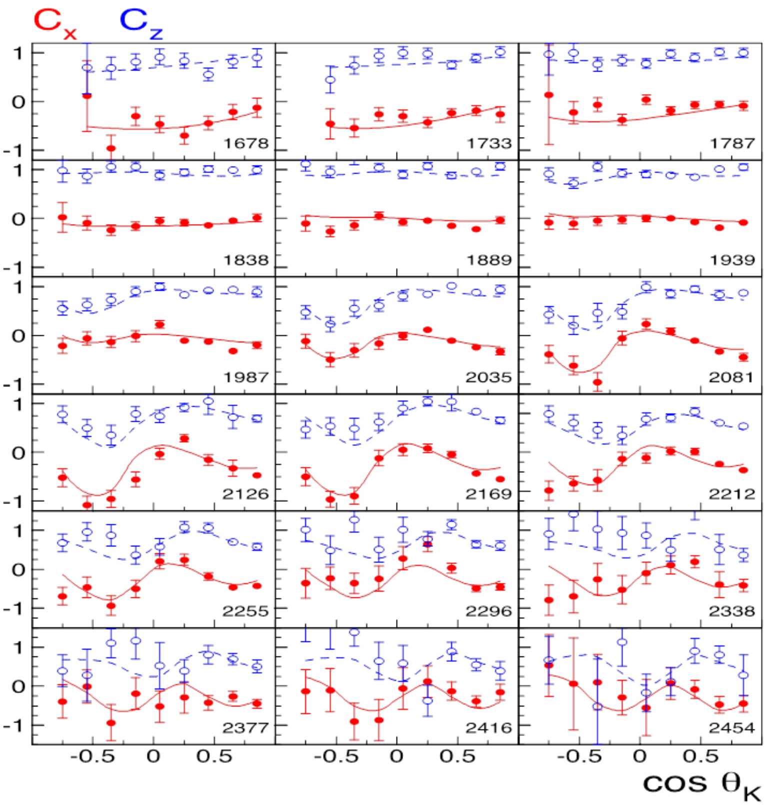

Fig. 4. Double polarization observables C_x and C_z for the $\gamma p \to K^+\Lambda$ reaction [8].

5. Linearly Polarized Photons

With the development of linearly polarized beams [10], it is now possible to measure beam asymmetry and beam-recoil double polarization observables. Examples of beam asymmetry measurements for π^0 and π^+ photoproduction are shown in figures 5 and 6 [11]. These plots clearly show how statistically accurate the measurements are, and also indicate how the data discriminate among various model predictions.

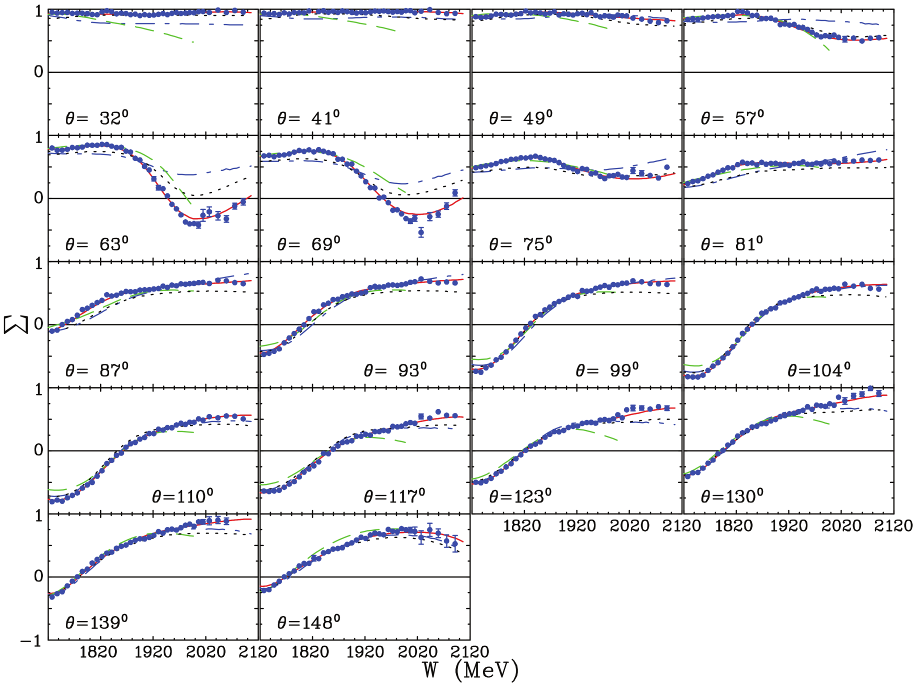

Fig. 5. Beam asymmetry Σ for the $\vec{\gamma}p \to \pi^0 p$ reaction [11].

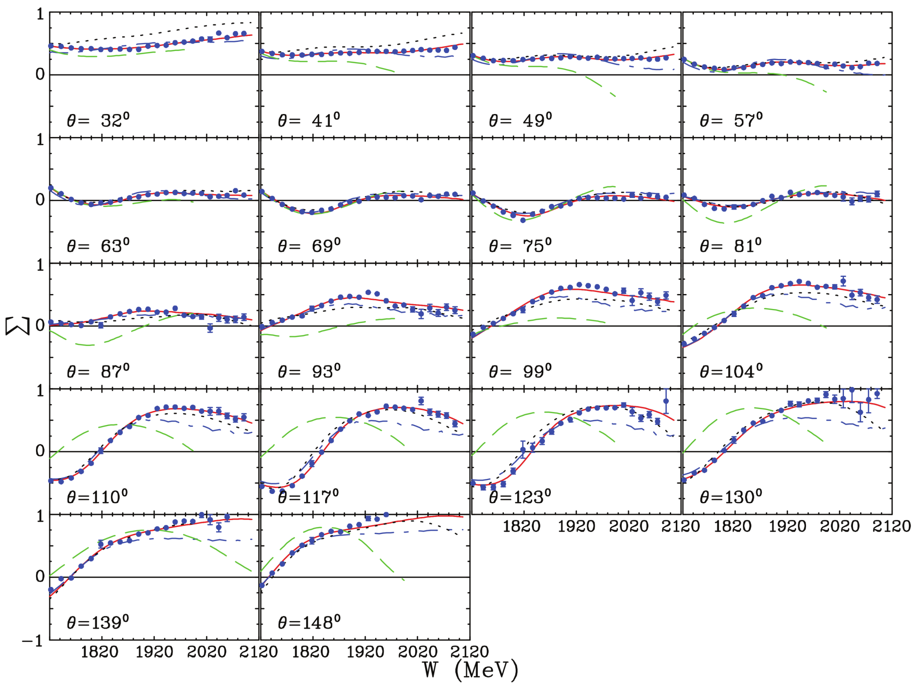

Fig. 6. Beam asymmetry Σ for the $\vec{\gamma}p \to \pi^+ n$ reaction [11].

6. Polarized Targets

Another advance in experimental techniques is the use of polarized targets. Data taken from experiments with the FROzen Spin Target (FROST) target have recently been published [12]. The first measurement of the polarization observable E up to $W = 2.25$ GeV has been extracted for the $\gamma p \rightarrow \pi^+ n$ reaction, and a sample of the results is shown in figure 7. This is a very nice demonstration of power of new data to influence the extraction of parameters from fits. The top line shows calculations of various models that are predictions, whilst the bottom line shows the result of refitting with the new data. This analysis is providing further evidence for new resonant states.

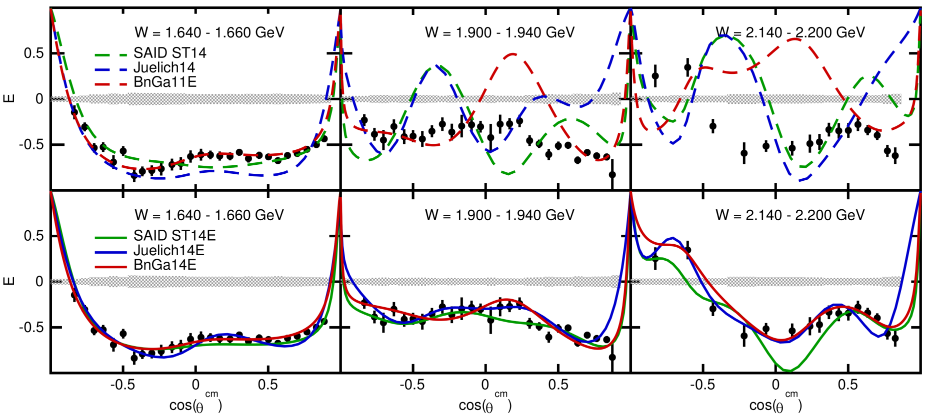

Fig. 7. Beam-target double polarization asymmetry E for the $\vec{\gamma}\vec{p} \rightarrow \pi^+ n$ reaction [12].

In principle the measurement of many observables in the $K\Lambda$ and $K\Sigma$ channels that have still to be published will allow the extraction of reaction amplitudes. This is highly desirable from a phenomenological perspective, since these could lead to fitting results with the minimum amount of ambiguity in the solutions. Much effort has been brought to bear on analyses of combinations of observables that lead to a "complete" measurement. However "completeness" is only a mathematical construct that does not take into account the finite resolution of experimental results. Amplitude extraction will ultimately only be possible through the measurement of a large set of observables with sufficient accuracy.

7. Summary and Outlook

The CLAS collaboration has now measured many photoproduction channels in the $N^\star$ resonance region, but the full impact of that programme will not be apparent for a few years. In terms of publications there is still a great deal more to come including: polarization observables from two-pion photoproduction; finalised results from linearly polarized photon beams, including kaon photoproduction; results from measurements with a deuterium target; more results from the frozen spin target (FROST) and the polarized proton/deuteron target HDIce.

The list above only really refers to experiments carried out with real photon beams. There is a wealth of other information from electroproduction measurements, both published and in the analysis phase, which has and will have significant impact on our understanding of the $N^\star$ spectrum. Other talks within this conference have presented the current status.

Further progress in the study of the low-energy baryon spectrum will require a great deal of dedicated effort to see the programme reach a satisfactory conclusion. Combining the analyses of all relevant channels in the resonance region is now seen as essential. On the theoretical side that means coupled channels analyses, which necessarily involve large-scale optimization to estimate values of coupling constants and other physical parameters.

The experimental part of this effort also needs careful management. As more observable quantities are reported from more reaction channels, one needs to ensure that they are at least self consistent (and this needs to be checked, potentially, for experiments carried out at different labs). In addition to this, it is important to ascertain whether the set of observables for specific reactions are complete *enough* for meaningful extraction of amplitudes.

To end on a positive note, we now stand at the point where a complete picture of the low-energy baryon spectrum is within reach. This is a goal that must be achieved if we are to claim understanding of the nature of strongly interacting matter. It is a great challenge, but the success of NSTAR conferences, such as this recent one, indicates that there is the will and the enthusiasm to address it.

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