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Study of hyperons with CLAS and CLAS12

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Abstract

Hadron spectroscopy and baryon spectroscopy in particular represents a large part of the experimental program with CLAS at Jefferson Lab. Within this program a substantial amount of data on hyperon production and properties has been accumulated. This includes photo- and electro-production of Λ and Σ hyperons and their excited states and also Ξ hyperons. Some of the highlights of this program will be presented together with plans to extend this program with CLAS12 after CEBAF upgrade to 12 GeV.

Keywords: baryon spectroscopy, hyperons, photoproduction

1. Introduction

Light baryon spectroscopy is one of the exciting and challenging topics in medium energy hadron physics. Even nucleon excitations, N^*s and Δs still pose many open questions. Initially, most of the information on these excitations came primarily from partial wave analysis of data from πN scattering. Recently, these data have been supplemented by a large amount of information from pion electro- and photoproduction experiments. Yet, in spite of extensive studies spanning decades, many of the baryon resonances are still not well established and their parameters (i.e., mass, width, and couplings to various decay modes) are poorly known. Much of this is due to the complexity of the nucleon resonance spectrum, with many broad, overlapping resonances. While traditional theoretical approaches have highlighted a semi-empirical approach to understanding the process as proceeding through a multitude of s-channel resonances, t-channel processes, and non-resonant background, more recently attention has turned to approaches based on the underlying constituent quarks. An extensive review of the quark models of baryon masses and decays can be found in Ref. [1]. Most recently lattice QCD is making significant progress in calculations of baryon spectrum [2]. While these quark approaches are more fundamental and hold great promise, all of them predict many more resonances than have been observed, leading to the so-called "missing resonance" problem. One possible reason why they were not observed because they may have small coupling to the πN. At the same time they may have strong coupling to other final states ηN, $\eta' N$, $2\pi N$, and also final states which include strange hyperons. While the significant amount of the meson photoproduction cross section measurements became available in recent years, these data alone cannot give an unambiguous answer about resonances. Since in pseudoscalar meson photoproduction there are three objects with spin involved: incident photon, target nucleon and recoil baryon. Therefore the process is descried by four spin dependent complex amplitudes. Total number of single and double polarization observables is sixteen. In order to be able to extract the amplitude of the process without any assumption one needs to measure at least eight carefully chosen single and double polarization observables. We know significantly less about the spectrum of hyperons, especially about double and triple strange baryons.

Studies of strange and non-strange baryons constitutes significant fraction of experimental program in the experimental Hall B of Jefferson Lab. In this report we discuss photproduction of Λ hyperons, properties of its first excited state Λ(1405). Then we discuss pohotoproduction of cascade hyperons and future plans with upgraded CLAS12.

2. Experimental Hall-B

Experimetal Hall-B at Jefferson Lab provides a unique set of instruments for these experiments. One instrument is the CLAS [3], a large acceptance spectrometer which allows detection of particles in a wide range of θ and ϕ. The other instrument is a broad-range photon tagging facility [4] with the recent addition of the ability to produce linearly-polarized photon beams through coherent bremsstrahlung. The last but not least component essential for the double polarization experiments is a polarized target.

The Hall B photon tagger [4] covers a range in photon energies from 20 to 95% of the incident electron beam energy. Unpolarized, circularly polarized and linearly polarized tagged photon beams are presently available. With a polarized electron beam incident on the bremsstrahlung radiator, a circularly polarized photon beam can be produced. The degree of circular polarization of the photon beam depends on the ratio $k = E_\gamma / E_e$. The magnitude of $P_\odot$ ranges from 60% to 99% of the incident electron beam polarization P_e for photon energies E_γ between 50% and 95% of the incident electron energy. CEBAF accelerator routinely delivers electron beam with polarization of 85% and higher. A linearly polarized photon beam is produced by the coherent bremsstrahlung technique, using an oriented diamond crystal as a radiator. The degree of polarization is a function of the fractional photon beam energy and collimation and can reach 80% to 90%. With linearly polarized photons, over 80% of the photon flux is confined to a 200-MeV wide energy interval.

An essential piece of the hardware for this experiment is a polarized target capable of being polarized transversely and longitudinally with a minimal amount of material in the path of outgoing charged particles. These requirement are satisfied by a frozen spin target, FROST[5]. Since in the frozen spin mode the holding field is relatively low, it is possible to design a "transparent" holding magnet with a minimal amount of material for the charged particles to traverse on their way into CLAS. Butanol was chosen as target material. The target depolarization rate was about 1% a day. This allowed us to re-polarize the target once a week and maintain an average polarization of the order of 85%.

The most recent addition to the experemental tools is HD-Ice poalrized target which allows to do measurements with polarized deuterons.

3. Hyperons and nucleon resonances

Photoproduction of strangeness off the proton leading to $K\Lambda$ and $K\Sigma$ states is a fundamental process that is part of the broader field of elementary pseudoscalar meson production. We started with cross section measurements. In addition to the cross sections for $K^+\Lambda$ [6, 7, 9] the polarization of hyperons P[6] and polarization transfer C_x/C_z were measured[8]. The same final states have been studied with linearly polarized photons incident on unpolarized target. The analysis of the data from these experiments is in its final stage.

There are several inequalities that must be satisfied by the observables available in pseudo-scalar meson photoproduction [10, 11, 12]. Artru, Richard, and Soffer [13] pointed out that for a circularly polarized beam there is a rigorous inequality

$$R^2 \equiv P^2 + C_x^2 + C_z^2 \leq 1 \tag{1}$$

among the three polarization observables, where P is the same as the measured P_{Yy}, the induced recoil polarization of the baryon. For a 100% circularly polarized photon beam, the relationship says that the magnitude of the three orthogonal polarization components may have any value up to unity. There is no *a priori* requirement that the hyperon be produced fully polarized except in the extreme forward and backward directions where orbital angular momentum plays no role. Figure 1 displays the values for R_Λ for the Λ hyperons. It is remarkable how close the magnitude of R_Λ is to its maximum possible value of +1 across all values of W and kaon angle. In other words the Λ hyperons produced in $\vec{\gamma} + p \to K^+ + \vec{\Lambda}$ with circularly polarized photons appear 100% spin polarized. Since this situation is not *required* by the kinematics of the reaction, there must be some as yet unknown dynamical origin of this phenomenon.

Once the frozen spin target became available we completed double polarization measurements with linearly and circularly polarized photons and longitudinally and transversely polarized proton target. The double polarization data are being analyzed. Due to self analyzing nature of the hyperon decays we have measured *all 16 observables* for KY final state. For non strange mesons we obtained nearly complete set of eight observables.

The double polarization measurement on the deuteron with polarized HD-Ice target were completed as well. As with a proton target we have *complete* set of observables for hyperon photoproduction. This is essential for understanding isospin structure of amplitude.

For the first time the complete measurements of meson photoproduction were performed at Jefferson Lab

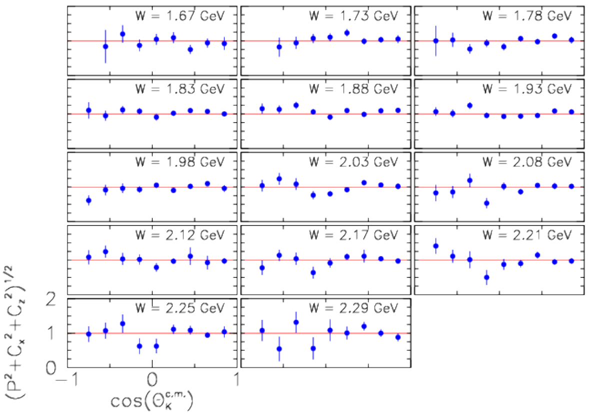

Figure 1: The magnitude of the Λ hyperon polarization observable vector $R_\Lambda = \sqrt{P^2 + C_x^2 + C_z^2}$. R_Λ is consistent with unity over all values of W and kaon angle.

with CLAS. These measurements allow model independent reconstruction of the reaction amplitude which will be used for search and study of the nucleon excitation spectrum.

4. Λ(1405) properties

The nature of the $\Lambda(1405)$, and its place in the baryon spectrum has been puzzling since its discovery several decades ago. The $\Lambda(1405)$ is unique in the sense that although it is only the first excited Λ state and has relatively low excitation energy, the nature of this resonance is not well established. For the constituent quark model, the $\Lambda(1405)$ has the largest discrepancy between the model prediction and experimental mass [14]. Earlier experiments have shown a deviation of the shape of invariant mass distribution ("lineshape") of the $\Lambda(1405)$ from a simple Breit-Wigner form. On the theoretical side, all analyses agree that the closeness of the nearby $N\overline{K}$ threshold plays a role in the distortion, there is no universally accepted explanation (see [15] for a review).

Using the CLAS detector system in Hall B at Jefferson Lab, we have measured the photoproduction reaction $\gamma + p \rightarrow K^+\Lambda(1405)$ with high statistics and over different $\Sigma\pi$ decay channels. The reconstructed invariant mass distribution (lineshape) has been measured, as well as the differential cross sections for the $\Lambda(1405)$. Our results for the lineshape of the $\Lambda(1405)$ are summed over all center-of-mass kaon angles for each 100 MeV-wide energy bin we have in center-of-mass energy. Figure 2 shows the lineshape of the $\Lambda(1405)$ for each of the $\Sigma\pi$ decay channels that we have measured for $1.95 < W < 2.05$. Note that in this energy bin close

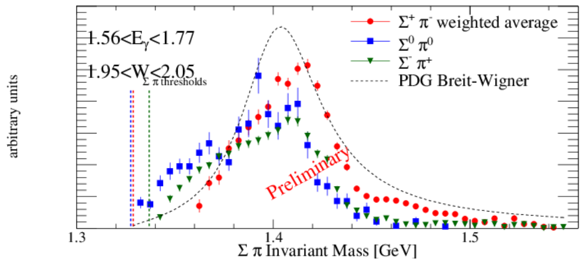

Figure 2: The $\Sigma\pi$ invariant mass spectrum measured for the $\Lambda(1405)$ for the energy range $1.95 < W < 2.05$ GeV. The different decay channels are shown as $\Sigma^+\pi^-$ (red circles), $\Sigma^0\pi^0$ (blue squares), and $\Sigma^-\pi^+$ (green triangles). An example of a relativistic Breit-Wigner function using the PDG [16] values for the $\Lambda(1405)$ mass and width are shown as the dashed line.

to the $K^+\Lambda(1405)$ threshold, we are just below the edge of the nominal K^* threshold, and the K^* has very limited kinematic influence. The lineshapes are seen to be quite different from each other, with the $\Sigma^+\pi^-$ channel peaking at a mass of $\sim$ 1420 MeV, and having a much more narrow structure than the $\Sigma^-\pi^+$ channel. This is in contrast to the theoretical prediction [17], where the $\Sigma^-\pi^+$ channel is expected to peak at a higher mass and have a narrow structure compared to the $\Sigma^+\pi^-$ channel.

5. Ξ and Ω^- hyperons

Historically, baryons with multiple strange quarks have played an important role in the development of the quark model and our understanding of the universe. The prediction and discovery of the Ω^- baryon certainly was one of the great triumphs of the quark model. However, half a century later, there has been little new information about the Ω and Ξ baryons. In fact, only two Ω states and six Ξ states are considered to be well-established, with at least three-star ratings in the PDG [16]. The production mechanism of these states is still unknown to a large extent. Typically small cross sections make the observation of the higher excited states difficult, which explains our current lack of knowledge in excited hyperon spectroscopy. Constituent quark models predict the existence of a cascade state corresponding to each N^* and Δ^* resonance. The relativised quark model with chromodynamics of Isgur and Capstick [18] predicts a total of 44 cascade states below 2.5 GeV. Current experimental verification of these predictions is badly lacking. Overall, only 6 cascade states are listed with three or four stars in [16], with only three of them have their quantum numbers J^P considered as determined (Table 1). In the past two decades, there have been no new cascade states discovered.

Table 1: Well established cascade resonances [16].

State	PDG rating	Width (MeV)	J^P
$\Xi(1320)$	****		$\frac{1}{2}^+$
$\Xi(1530)$	****	9.5	$\frac{3}{2}^+$
$\Xi(1690)$	***	< 30	$\frac{1}{2}^-?$
$\Xi(1820)$	***	24	$\frac{3}{2}^-$
$\Xi(1950)$	***	60	?
$\Xi(2030)$	***	20	$\frac{5}{2}^?$

We performed measurements of cascade photoproductions with CLAS [19] The differential cross sections for the ground and the first excited state were measured. Fig. 3 shows missing mass spectrum for $\gamma p \to K^+K^+X$. One can clearly see signals from the ground and the first excited states. However, with the sensitivity of present experiment we do not see anything above.

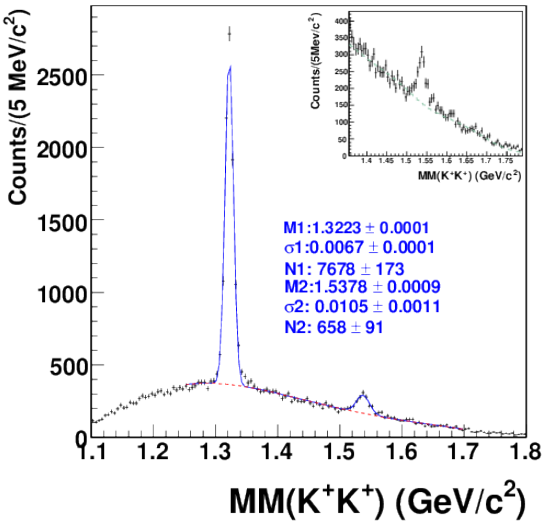

Figure 3: $MM(K^+K^+)$ distribution for $E_\gamma > 2.6$ GeV fitted with two Gaussian functions and an empirical background shape with adjustable normalization (M: mean of the Gaussian peak position, σ: width of the Gaussian signal, N: number of events in the peak); Inset:$MM(K^+K^+)$ distribution enlarged for the 1.36-1.79 GeV/c^2 region, the dashed lines show the empirical background shape from K^- events normalized to the region of 1.36-1.5 GeV/c^2.

The photoproduction of the ($S = -3$) Ω baryon requires the a total strangeness transfer $\Delta S = 3$. This is the largest possible transfer of strangeness number. The production and decay properties of this state in this environment are therefore of particular interest.

The existence of the Ω^- was first predicted in 1962, based on the quark model[1], and subsequently observed in a bubble chamber experiment[2]. Within the quark model the Ω^- is $S = -3$, spin 3/2 member of the baryon decuplet. Several experimental results find consistency with the predicted quantum numbers for the Ω^-[3]. The Ω^- production cross section has been measured using kaon beams[4] and in photoproduction with limited statistics[5].

There is no experimental data on the photoproduction of the Ω^- besides the upper limit ($\sigma_t < 17$ nb (90% C.L.)) set by the SLAC experiment [26].

Current theoretical models (by Roberts, Afanasev, and Shklyar) give a prediction of a cross section of approximatively 0.3 nb for the photoproduction of the Ω^-. Furthermore, the flavor-dependence of the non-perturbative regime might be explored from the energy-dependent cross section lineshape extraction of the photoproduced Ω^-.

CLAS12 photoproduction data would therefore provide a unique laboratory to explore the properties of Ω^- and Ω resonances.

Our physics goals for the studies of Ω states are:

- to obtain a first measurement fo the cross section for $\gamma p \to \Omega^- K^+K^+K^0$,
- to study the reaction mechanism for Ω^- in photoproduction (note that the Ω^- is the first baryon with constituent quarks not inherited from the target proton);
- to search for other excited Ω states (only the $\Omega^-(2250)$ state is rated with at least three stars in the PDG, while neither the $\Omega(2380)^-$ nor the

[1] Gell-Mann and Neèman predicted the existence of a new baryon, the Ω^-, with $S = -3$, $J^P = 3/2^+$, and mass ~1670 MeV/c^2 [20].

[2] The Ω^- observation in 1964 at BNL triumphantly confirmed the $SU(3)_F$ model prediction. The unambiguous discovery in both the production and decay of this state was reported in Ref. [21].

[3] A first attempt to measure its quantum numbers led to the conclusion that the spin was inconsistent with 1/2 and consistent with 3/2 (see Ref. [22]). The BaBar Collaboration measured the spin of the Ω^- using $\Xi_c^0 \to \Omega^- K^+$ and $\Omega_c^0 \to \Omega^- K^+$, $\Omega^- \to \Lambda K^-$ events. Under the assumption that the charm baryons have spin 1/2, as expected from the quark model, the angular distribution of the Λ from Ω decay is consistent with spin assignment 3/2 for the Ω^- and inconsistent with all half-integer spin assignments [23].

[4] The ANL experiment measured the $K^-p \to \Omega^- X$ cross section at 6.5 GeV as $\sigma_t = 1.4 \pm 0.6$ μb [24]. The experiment SLAC E-135 measured the forward differential cross section for $K^-p \to \Omega^- X$ at 11 GeV [25].

[5] Experiment SLAC BC-073 sought Ω-photoproduction in the $\gamma p \to \Omega^- X$ reaction at 20 GeV, and provided only an upper limit of $\sigma_t < 17$ nb [26].

$\Omega(2470)^-$ have not been firmly established (Table 2).

State	PDG rating	Width (MeV)	J^P
Ω^-	****		$\frac{3}{2}^+$
$\Omega(2250)^-$	***	55 ± 18	?
$\Omega(2380)^-$	**	26 ± 23	?
$\Omega(2470)^-$	**	72 ± 33	?

Table 2: Well established Ω^- resoances [16].

Production of doubly- or triply-strange baryons by means of a photon beam (such as in the CLAS, at present, and CLAS12 and GlueX, in the future) is expected to shed light on the genesis of these states which involves the production of $s\bar{s}$ pairs from the vacuum. This significant change in baryon strangeness number from initial ($S = 0$) to final state ($S = -3, -2$) could result from direct production via vector-meson dominance or from a sequence of intermediate transitions. Inference on the production mechanisms of these states in γp collisions can be obtained from precision measurements of the cross section and invariant mass of these states.

Although the Ω and Ξ baryons photoproduction rates are small, making the excited states difficult to observed with high significance, the expected narrowness of their widths would make it easier to identify and isolate them in the laboratory. For example, the Ξ excited states are typically $5 - 10$ times narrower than their $S = 0, -1$ counterparts. While many of the Ω excited states remain unknown, it is natural to expect that they will exhibit similar features to those in the Ξ sector.

The 12 GeV Upgrade will provide an order of magnitude higher in luminosity and CLAS12 significantly better multiple-particle final states acceptance than CLAS. It is therefore expected that many aspects of Ω^- and Ξ physics can be probed at CLAS12 using the quasi-real photon beams with the forward tagger.

The CLAS12 detector is expected to record sufficient statistics to perform several essential measurements to deepen our understanding of Ω^- and Ξ states, including the cross section of the ground state Ω^- and Ξ baryons, the mass splittings of of ground and excited cascades which would deepen our understanding of the u/d quark mass difference, and the polarization of the Ξ^- baryon. The expected CLAS12 hyperon data samples would also provide spin-parity information for multiple excited cascades. Furthermore, the narrow width of cascades might be better understood from the experimental verification of decoupling of excited cascade from the $\Xi\pi$ channel.

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