CASCADE PHYSICS: A NEW WINDOW ON BARYON SPECTROSCOPY

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The Ξ , or Cascade, hyperons have the unique features of double strangeness and narrow widths. Typically, $\Gamma_{\Xi^*} \sim 10 - 20$ MeV, which is 5–30 times narrower than N^* , Δ , Λ , or Σ states. These features, combined with its isospin of $1/2$, make possible a wide-ranging program centered on the physics of the cascade hyperon and its excited states using the photoproduction reaction $\gamma p \rightarrow K^+ K^+ \Xi^-$. The photoproduction cross section is large enough to consider a coarse survey of cascade-proton scattering. We present the physics motivations for a systematic study of the Cascade hyperons, showing recent results from the CLAS Collaboration, and describe recent developments within the physics community to identify the possibilities for future work in this field.

1. Introduction

The structure and dynamics of the nucleon and its excited states has been the subject of much inquiry since the discovery of the Δ in the early 1950's. Despite over fifty years of research, there are still many questions left unanswered. More to the point, it is becoming increasingly difficult to make further progress due to the nature of the work involved. Typically, research into nucleon structure entails acquiring a large data set using data from several experiments which must then be subjected to a detailed computer analysis; not only can we not find new states by looking at simple spectra, we cannot even improve our knowledge of the existing states. Because the states in the excited N^* spectrum are broad and overlapping, the details of the individual states can only be determined via a partial-wave analysis.

To alleviate this situation, we would ideally search for a particle that does not have the problematic large width of the excited nucleon, and yet has properties similar to those of the nucleon. Such a particle would open a "new window" on baryon spectroscopy, in that it could provide a complementary approach to the study of the excited baryons.

$SU(3)$ flavor symmetry

Indication of where we might find such a particle is provided by the flavor symmetry of $SU(3)$, $SU(3)_F$. This is due to our ability to separate the QCD lagrangian into two parts: $\mathcal{L}_{QCD} = \mathcal{L}_0 + \mathcal{L}_m$. The first part, $\mathcal{L}_0$, depends only on the quark and gluon fields, and has no mass dependence. The entire mass dependence lies in the second part, $\mathcal{L}_m$. To the extent that we can treat the mass term as a perturbation (i.e., if the quark masses are small in comparison to the baryon masses), we find that $\mathcal{L}_0$ sets the mass scale for a given $SU(3)_F$ multiplet. In this limit, the masses of the baryons are degenerate; $\mathcal{L}_m$ breaks this symmetry, setting the mass splitting within each multiplet, leading to the multiplet structure we are familiar with.

$SU(3)_F$ symmetry is observed experimentally in the properties of the baryons. Static properties, such as the masses of the baryons, are found to obey this symmetry in that the mass difference $\Delta m[\Lambda(1600)_{\frac{1}{2}}^{++} - \Lambda(1115)_{\frac{1}{2}}^{++}]$ is very similar to the mass difference $\Delta m[N(1440)_{\frac{1}{2}}^{++} - N(939)_{\frac{1}{2}}^{++}]$. Additionally, the dynamic properties of the baryons exhibit $SU(3)_F$ symmetry, as shown both by the similarity of the near-threshold cross sections for the processes $\pi^- p \rightarrow \eta n$ and $K^- p \rightarrow \eta \Lambda^1$ and by the similarity in the Dalitz plots for the processes $\pi^- p \rightarrow \pi^0 \pi^0 n$ and $K^- p \rightarrow \pi^0 \pi^0 \Lambda$.^{2,3}

Given this evidence for the usefulness of $SU(3)_F$ symmetry, we turn to the baryon multiplets. Each multiplet is identified by its spin and parity J^P . $SU(3)_F$ symmetry implies that the members of the multiplets differ only in their quark makeup, and that the basic properties of the baryons should be similar. The octets consist of a N^* , Λ^* , Σ^* , and a Ξ^* state. We thus expect that for every N^* state, there should be a corresponding Ξ^* state with similar properties. Additionally, since the decuplets consist of Δ^* , Σ^* , Ξ^* , and Ω^* states, we expect to find a decuplet Ξ^* with properties similar to every Δ^* state. This observation forms the basis of our program in Cascade physics.

3. The Cascade: Gross features

While the higher mass and double strangeness of the Ξ^* 's make them harder to produce in the laboratory than their N^* and Δ^* cousins, this same double strangeness contributes to their narrow width, which makes isolating one cascade from another a realistic possibility. The cascades thus provide a complementary approach to the study of N^* physics.

Figure 1 shows the widths of all the N^* and Ξ^* states in the RPP.⁴

Fig. 1. The widths of all the N^* (circles) and Ξ^* (stars) states from the RPP⁴ plotted against their mass.

As seen in the figure, the Cascade hyperons are much narrower than the nucleons. An explanation for this narrowness was first given by Riska,⁵ and is related to the number of light quarks in the baryon. Specifically, the width is proportional to the square of the number of light quarks, hence we expect to find the ratio $\Gamma_{N^*, \Delta^*} : \Gamma_{\Lambda^*, \Sigma^*} : \Gamma_{\Xi^*} \approx 9 : 4 : 1$. This prediction agrees very well with experiment. An alternative explanation for narrow Cascades, based on their structure and decay modes, is given by Capstick.⁶

Because the Cascades are narrow, we can get at least a first glimpse at their properties by inspection of a simple spectrum, either of an invariant mass plot in an experiment that detects the decay products of the Cascade (e.g. $\Xi^- \rightarrow \pi^- \Lambda$, followed by $\Lambda \rightarrow \pi^- p$), or in a missing mass spectrum, such as that from a process such as $K^- p \rightarrow K^+ X(\Xi^-)$.

4. Cascade Production

The bulk of the data that has been collected on the Cascades has used the process $K^-p \rightarrow K^+\Xi^-$. This process would be an excellent choice, as the cross section is relatively large. There are, however, currently no suitable kaon beams available, and other means must be found.

The process we have chosen is the photoproduction process $\gamma p \rightarrow K^+K^+\Xi^-$. The simplest analysis involves detecting the two positive kaons, and inferring the Cascade in the missing mass. This reaction has the advantage that below 1.6 GeV, there is no physics background. This process may be used without modification to study the entire Ξ^- spectrum. To study the neutral Ξ^0 states, we may use the process $\gamma p \rightarrow K^+K^+\pi^-\Xi^0$.

Hall B at Jefferson Laboratory is suitable for this work. The CLAS detector can be used to detect the multiple charged particles in the final state with good efficiency, and the tagged photon beam has both excellent resolution and intensity. Recent results from the CLAS collaboration indicate that the cross section for Ξ^- photoproduction is both sufficiently large and clean enough for a program in Cascade physics.⁷ Figure 2 shows two missing mass spectra from the original CLAS publication. In Fig. 2a, the ground-state $\Xi^-(1321)$ is clearly seen; using a phase-space model to calculate the acceptance, a cross section of $3.5 \pm 0.5(stat.) \pm 1.0(syst.)$ is obtained. High-statistics work with CLAS data has already begun, and is being reported on at this workshop.⁸ These results imply the production of several thousand ground-state Ξ^- per week, which is sufficient to consider a program built around the physics of the Cascade.

5. Cascade Physics Program

There are many different topics that may be addressed with a dedicated program in Cascade physics. A few are listed below.

5.1. Search for missing/Study of known Ξ states

The RPP lists 22 N^* states, of which 14 have either three or four stars (a somewhat arbitrary criterion used here to indicate that they are "well-established").⁴ Similarly, it lists 22 Δ^* states, of which 10 are well-established. By contrast, there are only eleven Ξ^* states listed, of which only six are well-established. This implies, from our earlier discussion, that there are somewhere between 13-33 Ξ states that have not yet been found.

Finding the missing Ξ states is of great importance to our understanding of baryon structure. As previously mentioned, $SU(3)_F$ symmetry requires

Fig. 2. The missing mass m_X in the process $\gamma p \rightarrow K^+ K^+ X$ from measurements at CLAS.⁷ The plots have not been corrected for detector acceptance. a) $3.2 < E_\gamma < 3.9$ GeV; b) $3.0 < E_\gamma < 5.2$ GeV. The ground-state $\Xi^-(1321)$ is clearly seen in both plots; the signal-to-background ratio for the low-energy data set exceeds 10:1. In b), we see evidence for the photoproduction of the first excited state, the $\Xi^-(1530)$.

the existence of these states; if they do not exist, then our model of baryon structure is fundamentally flawed.

We may use our knowledge of the other baryons to guide our search for new Ξ states. For instance, the RPP lists three baryons that decay primarily via the emission of an η : the $N(1535)\frac{1}{2}^-$, the $\Lambda(1670)\frac{1}{2}^-$, and the $\Sigma(1750)\frac{1}{2}^-$. Based on this, Tuan has predicted the existence of a $\Xi(1870)\frac{1}{2}^-$ that decays in large part to $\Xi(1321)\eta$.⁹ Finding such a state would suggest that these baryons belong in the same octet.

It is not sufficient to search for new Ξ states. Our knowledge of the Ξ^* spectrum is limited; the states we have found thus far are poorly-measured compared to the other baryon families. To improve this situation, it is

Fig. 3. Two possible mechanisms for the photoproduction of the Ξ hyperons. a) N^* excitation; b) K-exchange.

important to do a systematic survey of the known Ξ states.

An example of why this is necessary is the $\Xi(1950)$. This state has three stars, which makes it a well-established state. However, its J^P value has never been measured, and its width is anomalously large in comparison with the other Ξ states in its vicinity. Additionally, there is a large disagreement among the fourteen separate measurements as to what the mass is, ranging from about 1.90 to 1.96 GeV. The Particle Data Group summarizes by saying "...there may be more than one Ξ near this mass."⁴ A high-statistics study will help resolve the status of this state.

5.2. Ξ production mechanism

Unlike the N^* , Δ^* , Λ^* , and Σ^* states, the Ξ^* states cannot be produced directly in a reaction, but must instead be produced via some intermediate state. Two examples of possible production mechanisms are shown in Fig. 3. Fig. 3a shows an s -channel mechanism, in which the photon excites an N^* or Δ^* which decays to K^+Y^* , followed by $Y^* \rightarrow K^+\Xi^-$. Figure 3b shows another possibility, a t -channel mechanism in which the photon exchanges a kaon with the proton, which then becomes a Y^* and subsequently decays to $K^+\Xi^-$. These mechanisms will have different angular distributions and energy dependences; understanding this will require a very large data sample, along with substantial theoretical input.

5.3. Search for the Ξ^0 states

Detection of the Ξ^0 is accomplished using a reaction similar to that for the Ξ^- : $\gamma p \rightarrow K^+K^+\pi^-\Xi^0$. The π^- can come from any of the vertices in Fig. 3, so it will be difficult to isolate the production mechanism. Since the mass of the Ξ^0 must be near the mass of the associated Ξ^- , this will serve

as a strong test of the existence of any Ξ .

A topic which will greatly benefit from this study is the measurement of the mass difference Δm_q of the up and down quarks. This can be studied by looking at the mass difference $\Delta m_{N(940)}$. Other states where this can be studied are $\Delta(1232)$ and the $\Sigma(1190)$. In the Ξ sector, there are measurements of Δm_{Ξ} for both the ground state ($\Delta m_{\Xi(1321)} = +6.48 \pm 0.24$ MeV) and the first excited state ($\Delta m_{\Xi(1530)} = +3.2 \pm 0.6$ MeV). Further work will allow a test of medium modifications, as we measure this quantity as a function of J^P .

5.4. Ξ decays

The decay modes of both the charged and neutral ground-state Ξ are fairly well-known. Both decay to $\Lambda\pi$ with a branching ratio of nearly 100%. There are several weak decays that may be used to test the $\Delta S = \Delta Q$ and the $\Delta S \neq 2$ rules, and the radiative decay may be used to test chiral perturbation theory.

All of the excited Ξ^* 's decay strongly. The $\Xi(1530)$ decays primarily to $\Xi\pi$; an upper limit of 4% has been measured for the branching ratio $BR[\Xi(1530) \rightarrow \Xi\gamma]$. There is not much that can be learned by improving on this limit.

In looking at the higher-mass Ξ^* 's, the $\Xi\pi\pi$ channel opens up at 1585 MeV, the $\bar{K}\Lambda$ channel at 1608 MeV, and the $\bar{K}\Sigma$ channel at 1682 MeV. By looking at all of these decay modes simultaneously, we can improve our ability to distinguish states close to each other in mass.

5.5. Ξ J^P measurements

Although the parity of the ground-state $\Xi(1321)$ has never been measured, it is assumed to be positive. Aside from the ground state, only the $\Xi(1530)\frac{3}{2}^+$ and the $\Xi(1820)\frac{3}{2}^-$ have J^P measurements. The other eight Ξ states lack such identification (although measurements indicate that the spin of the $\Xi(2030)$ is $\geq 5/2$). This determination is an important part of the study of the Ξ spectrum; only after the J^P is measured can a state be placed within an $SU(3)_F$ multiplet.

Partial-wave techniques have not been applied to this problem, although this may change in the next few years. Instead, there are various spin tests that have been applied. These make use of the angular distributions of the decay products, and were developed in the 1960s.

The method of Byers and Fenster¹⁰ developed a technique to study the

decay $B^* \rightarrow B\pi$, where B^* is an excited baryon, and B has spin-1/2. This method uses the angular distribution of the decay of the B^* followed by a measurement of the polarization of the ground-state B to determine J^P of the original B^* . This method was used to measure the spin and parity of the $\Xi(1530)$.¹¹

Button-Shafer¹² extended this method to look at excited baryons that decay to a spin-3/2 baryon. This method was used to make the first estimate of the J^P of the $\Xi(1820)$, via the decay $\Xi(1820) \rightarrow \Xi(1530)\pi$.

Minnaert¹³ took this a step further, by looking at multiple decay modes for a given baryon. This method exploits the fact that the spin of the excited baryon is independent of the decay mode. This method was used to improve the confidence in the J^P determination of the $\Xi(1820)$.

The amount of data anticipated should be sufficient to provide new information on the J^P values of several of the Ξ^* states. More theoretical input is needed to define the optimal procedure for the extraction of J^P for the Cascades.

5.6. *s-d quark mass difference*

A major issue in the quark model is the values of the input parameters, for instance the quark masses. A key parameter is the mass difference between the strange and the down quarks. This mass difference is built into the various mass relations for the baryons: the Gell-Mann-Okubo relation for the octet states [$2(m_N + m_\Xi) = 3m_\Lambda + m_\Sigma$], and the Gell-Mann equal-spacing relation for the decuplet states ($m_\Sigma - m_\Delta = m_\Xi - m_\Sigma = m_\Omega - m_\Xi$). Because there are only three Cascades with reliable J^P determinations, we can only test these relations with three $SU(3)_F$ multiplets. The main question of interest here is whether the mass difference $m_s - m_d$ is the same for the excited baryons as it is for the ground-state baryons.

5.7. *Cascade-proton scattering*

There has been very little work on Cascade-proton scattering. The main reason for this is the difficulty of extracting a signal. With a dedicated program in Cascade physics, however, one can make use of the relatively long lifetime of the Ξ ($c\tau_{\Xi^-} = 4.91$ cm; $c\tau_{\Xi^0} = 8.71$ cm) in conjunction with a long target to make detailed measurements of this process. There are two main reasons why this should be pursued.

The process $\Xi^- p \rightarrow \Lambda\Lambda$ has strong implications for hypernuclear physics. One of the currently interesting lines of research is in double hy-

pernuclei, for which this process will provide much-needed input.

By comparing the process $\Xi^- p \rightarrow \Lambda \Lambda$ with the processes $\Xi^- p \rightarrow \Xi^0 n$ and $\Xi^- p \rightarrow \Lambda \Lambda \gamma$, we may be able to determine the parity of the ground-state Ξ relative to that of the nucleon.¹⁴ This would be the first such measurement of this important quantity.

There is a reasonable measurement of these cross sections at high energy from CERN¹⁵, but the data at lower energies are scarce.¹⁶⁻¹⁹ A recent result from KEK²⁰ detected two candidate $\Xi^- p \rightarrow \Xi^- p$; from this, they calculate a 90% C.L. upper limit for the elastic scattering process to be 24 mb. Using three candidate $\Xi^- p \rightarrow \Lambda \Lambda$ events, they arrive at a cross section of $4.3^{+6.3}_{-2.7}$ mb. Both measurements used an initial sample of 6000 ground-state Ξ^- 's. With a larger data sample, a correspondingly better measurement could be achieved.

6. Summary

A systematic study of the Ξ^* states represents a "new window" on baryon spectroscopy. With the new results from CLAS, we have opened the window a crack, and what we have seen so far looks very encouraging. Whether one's interests lie in the nature of the Ξ^* spectrum, in Ξ^* production mechanisms or decay modes, or in other areas such as quark-mass differences or Ξp scattering, there are many topics in this field to keep the experimentalists busy for quite some time.

On the theoretical side, there is also much to do. While the experiments are sufficiently interesting to stand on their own, the results would have much more impact if there was a body of theoretical work available to be tested. Thus far, there has been little progress made in understanding the nature of the Ξ^* states. In particular, theoretical input is urgently needed on the production models of the Ξ^* states; without this input, it is very difficult to understand detector acceptances, which in turn makes the calculation of cross sections problematic. Another possible avenue of theoretical research lies in the lattice community, as the presence of two strange quarks in the Ξ^* may ease the calculation of reliable results.

To explore these and other topics related to Cascade physics, a workshop was organized at Jefferson Laboratory in early December 2005. As of this writing, this workshop has taken place, and was very successful. Over fifty people registered for the workshop, and a white paper on the issues related to Cascade physics is in preparation. It is hoped that we can form a core group of physicists, both experimental and theoretical, to carry out and extend the program described here.

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