2.6 Bound States of N's and Ξ's

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Abstract

Experimental information on the spectrum, structure, and decays of strangeness -2 Cascade baryons is sparse compared to non-strange and strangeness -1 baryons. It is argued that an experimental program at Jefferson Lab using the photo-production and the GlueX detector to study the physics of Cascades is of considerable interest, since it is likely that the lightest Cascade baryons of a given spin and parity are relatively narrow. If this is verified in an experiment, this would confirm the flavor independence of the confining interaction that is assumed in models. These narrow widths may also make it possible to measure the isospin-symmetry violating mass splittings in a spatially-excited baryon for the first time. Copious data for excited strangeness -1 baryons will be collected along with the data for Cascade baryons in such an experimental program. Photo-production reactions which can be used to study excited Cascade baryons are described, and simulations made to understand the production of a ground-state and an excited-state Cascade baryon in the GlueX experiment are discussed, along with possible sources of background.

1. **Introduction**

The spectrum of multi-strange hyperons is poorly known, with only a few resonances whose existence is well established. Among the doubly-strange states, the two ground-state Cascades, the octet member Ξ and the decuplet member $\Xi^*(1530)$, have four-star status in the RPP [1], with only four other three-star candidates. On the other hand, more than 20 N^* and Δ^* resonances are rated with at least three stars by the Particle Data Group (PDG). Of the six Ξ states that have at least three-star ratings, only two are listed with weak experimental evidence for their spin-parity (J^P) quantum numbers: $\Xi(1530)\,\frac{3}{2}^+$ [2], $\Xi(1820)\,\frac{3}{2}^-$ [3]. All other J^P assignments are based on quark-model predictions.

Flavor SU(3) symmetry predicts as many Ξ resonances as N^* and Δ^* states combined, suggesting that many more Cascade resonances remain undiscovered. The three lightest quarks, u, d, and s, have 27 possible flavor combinations: $3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8' \oplus 10$ and each multiplet is identified by its spin and parity, J^P. Flavor SU(3) 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, although the symmetry is known to be broken by the strange-light quark mass difference. The octets consist of N^*, Λ^*, Σ^*, and Ξ^* states. 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 also expect for every

Δ^* state to find a decuplet Ξ^* with similar properties. In a simple quark model picture, the strange states will fit into multiplets which correspond to those of the $u,\ d$ sector. However, it could be that the dynamics of the excited baryons differ from those of the lower-lying states; for example, the pattern of their decays may be systematically different. Parity doublets may appear in some sectors with increasing mass. Should we expect doubly-strange baryons with properties similar to those of the $\Lambda(1405)$ with $J^P = 1/2^-$ and the Roper N^* with $J^P = 1/2^+$, which do not fit easily the conventional picture of three quarks in the baryon? The dependence of the physics of these unusual states on the number of strange quarks is of crucial importance to our understanding of them, which motivates the collection of a significant database on multi-strange baryons.

2. Ξ **Spectrum and Decays**

The Ξ hyperons have the doubly-strange quark content $|ssu\rangle$ and $|ssd\rangle$. An interesting feature of the Ξ spectrum is that there are fewer degeneracies than in the light-quark baryon spectrum. If the confining potential is independent of quark flavor, the energy of spatial excitations of a given pair of quarks will be inversely proportional to their reduced mass. If all three quark masses are the same, the excitation energy of either of the two relative coordinates will be the same, which will lead to degeneracies in the excitation spectrum. However, with two strange quarks and one light quark, the excitation energy of the relative coordinate of the strange quark pair is smaller. This means that the lightest excitations in each partial wave are between the two strange quarks, and that the degeneracy between excitations of the two relative coordinates is lifted. The spectrum of Ξ baryons calculated using the relativized quark model [4] along with information about Ξ states extracted from experiment is shown in Figure 1. A comparison of results from this model for the masses of non-strange and strangeness -1 baryons with those extracted from experimental data makes it likely that the lowest-mass positive-parity excited Ξ^* states are lower than shown in Fig. 1, and that the spectrum of negative-parity excited states should have larger splittings.

In the absence of configuration mixing and in a spectator decay model, Ξ states with the relative coordinate of the strange-quark pair excited cannot decay to the ground state Ξ and a pion, because of orthogonality of the part of the spatial wave function between the two strange quarks in the initial excited state and in the final ground state. Having instead to decay to final states that include Kaons rules out the decay channel with the largest phase space for the lightest states in each partial wave, substantially reducing their widths [5]. This selection rule is modified by (configuration) mixing in the wave function; however, color-magnetic hyperfine mixing is weaker in Ξ states because this interaction is smaller between quarks of larger masses. The flavor-spin [SU(6)] coupling constants at the decay vertices for $N,\ \Delta \to N\pi,\ \Delta\pi$ are significantly larger than those for $\Xi,\ \Xi^* \to \Xi\pi,\ \Xi^*\pi$ decays [6], which also reduces these widths. The result is that the well known lower-mass resonances have widths Γ_{Ξ^*} of about 10 - 20 MeV, which is 5 - 30 times narrower than is typical for N^*, Δ, Λ, and Σ states.

The first excited state with nucleon quantum numbers, the Roper resonance at 1440 MeV, is interesting because its low mass is hard to explain in models containing only three quarks. It is likely that this is because the pole position of this resonance is shifted because of strong coupling to the $N\pi\pi$ channel, which also contributes to its large width of about 350 MeV. Ex-

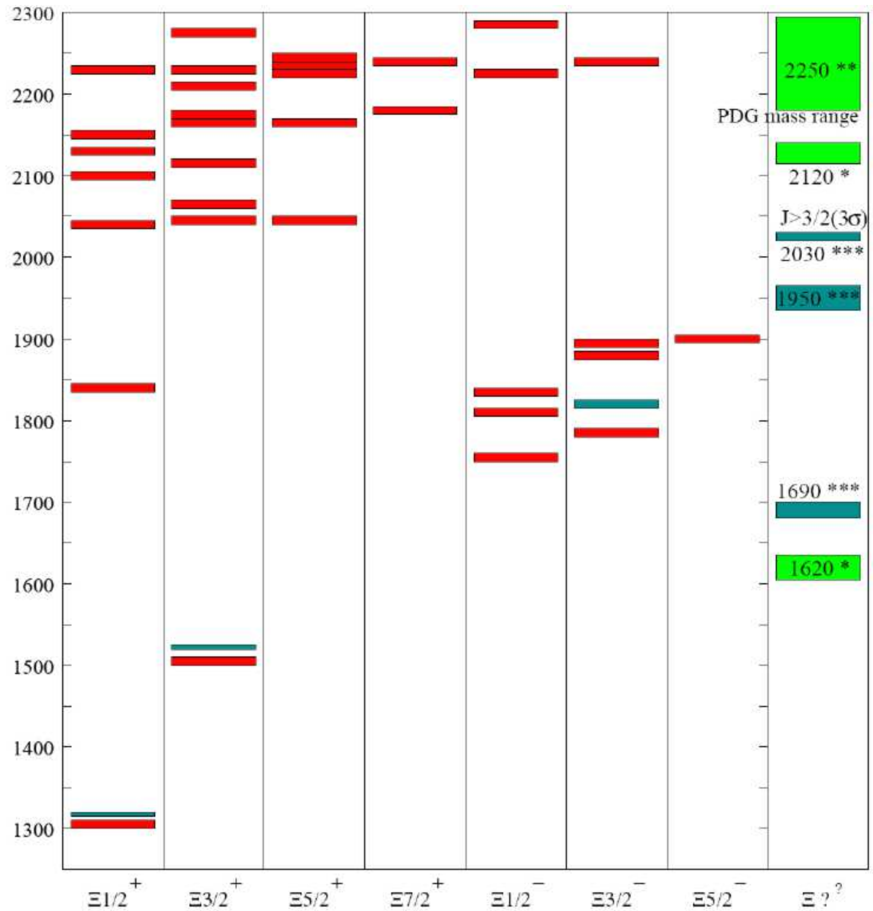

Figure 1: Relativized model spectrum of Ξ baryons [4] below 2300 MeV (red bars) compared to masses extracted from experiment and their uncertainties (dark green bars for well known states, light green bars for tentative states). Experimental states with undetermined spins and/or parities are placed in the last column on the right.

traction of its properties from partial-wave analysis of πN scattering and photo-production data is made difficult by a complicated pole structure and by the presence of a second nucleon resonance with $J^P = \frac{1}{2}^+$ at 1710 MeV with a width of roughly 100 MeV. The equivalent Ξ^* state should be quite narrow and so be relatively easy to separate from the next $\Xi^* \, \frac{1}{2}^+$, which itself should be relatively narrow, and from the lightest negative-parity excitations, which are also relatively narrow.

These features render possible a wide-ranging program to study the physics of the Cascade hyperon and its excited states. The study of these hyperons has focused until recently on their production in K^-p reactions, although some Ξ^* states were found using high-energy hyperon beams. Photo-production appears to be a very promising alternative. Results from earlier Kaon-beam experiments indicate that it is possible to produce the Ξ ground state through the decay of high-mass Y^* states [7–9]. It is therefore possible to produce Cascade resonances through t-channel photo-production of hyperon resonances using the photo-production reaction $\gamma p \to KK\,\Xi^{(*)}$. The CLAS collaboration investigated this reaction [10], but no signicant signal for an excited Cascade state was observed, other than that of the decuplet ground state $\Xi(1530)$. The absence of higher-mass signals is very likely due to the low photon energies available to these experiments and the limited acceptance of the CLAS detector. Equipped with a Kaon-identification system, the GlueX experiment will be well suited to search for and study excited Ξ resonances.

To summarize, it would be interesting to see in a Cascade physics program at Jefferson Lab the lightest excited Ξ^* states of a given spin and parity J^P decoupling from the $\Xi\pi$ channel, confirming the flavor independence of confinement. Measurements of the isospin-symmetry violating mass splittings ($\Xi^{*-} - \Xi^{*0}$) in spatially excited Cascade states are also possible, for the first time in a spatially-excited hadron. Currently, mass splittings like $n - p$ or $\Delta^0 - \Delta^{++}$ are only available for the octet and decuplet ground states, but are hard to measure in excited $N,\ \Delta$ and $\Sigma,\ \Sigma^*$ states, which are broad. The lightest Cascade baryons are expected to be narrower, and measuring the $\Xi^- - \Xi^0$ splitting of spatially-excited Ξ states remains a strong possibility. Such measurements would allow an interesting probe of excited-hadron structure, and would provide important input for quark models which explain the isospin-symmetry violating mass splittings by the effects of the difference of the u- and d-quark masses and of the electromagnetic interactions between the quarks.

3. Ξ **Searches using the GlueX Experiment**

The Cascade octet ground states (Ξ^0, Ξ^-) can be studied in the GlueX experiment *via* exclusive t-channel (meson exchange) processes in the reactions

$$\gamma p \to K\,Y^* \to K^+\,(\,\Xi^-\,K^+\,),\ K^+\,(\,\Xi^0\,K^0\,),\ K^0\,(\,\Xi^0\,K^+\,)\,. \tag{1}$$

The production of such two-body systems involving a Ξ particle also allows the study of highly-excited Λ^* and Σ^* states. Initially, the Ξ octet ground states (Ξ^0 and Ξ^-) will be challenging to study via exclusive t-channel (meson exchange) production. The typical final states have kinematics for which the baseline GlueX detector has very low acceptance due to the high-momentum forward-going Kaon and the relatively low-momentum pions produced in the Ξ decay. However, the production of the Ξ decuplet ground state, $\Xi(1530)$, and other Ξ^* states decaying to $\Xi\pi$ results in a lower momentum Kaon at the upper vertex, and heavier Ξ states produce higher momentum pions in their decays.

The Cascade decuplet ground state, $\Xi(1530)$, and other excited Cascades can be searched for and studied in the reactions

$$\gamma p \to K\,Y^* \to K^+\,(\,\Xi\,\pi\,)\,K^0,\ K^+\,(\,\Xi\,\pi\,)\,K^+,\ K^0\,(\,\$ \tag{2}$$

The lightest excited Ξ states of a given spin and parity J^P are expected to decouple from $\Xi\pi$ and can be searched for and studied in the reactions

$$\gamma p \to K\,Y^* \to K^+\,(\,K\Lambda\,)_{\Xi^{-*}}\,K^+,\ K^+\,(\,K\Lambda\,)_{\Xi^{0*}}\,K^0,\ K^0\,(\,K\Lambda\,)_{\Xi^{0*}}\,K^+\,, \tag{3}$$

$$\gamma p \to K\,Y^* \to K^+\,(\,K\Sigma\,)_{\Xi^{-*}}\,K^+,\ K^+\,(\,K\Sigma\,)_{\Xi^{0*}}\,K^0,\ K^0\,(\,K\Sigma\,)_{\Xi^{0*}}\,K^+\,. \tag{4}$$

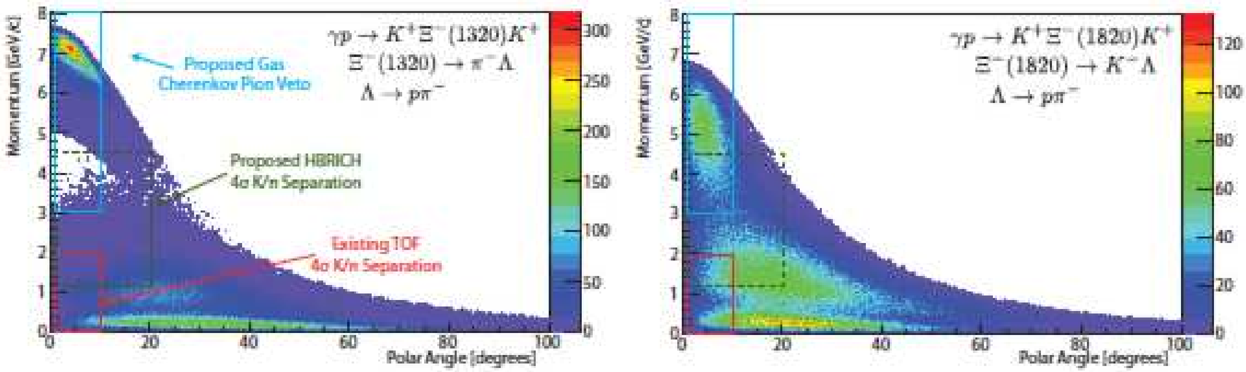

Figure 2: Generated momentum versus polar angle for all tracks in the simulated reactions (a) $\gamma p \to K^+ \Xi^-(1320) K^+$ and (b) $\gamma p \to K^+ \Xi^-(1820) K^+$. The decay of the Cascade resonance and assigments of final-state particles to observed high-density regions in phase space are described in the plots.

Our simulations and application of state-of-the-art analysis tools [11] show that background from competing hadronic reactions will be much reduced because of the unique signature provided by the two associated Kaons in photo-production, in combination with the additional information found by analyzing the weak-decay secondary vertices of ground-state strangeness -1 hyperons in the final state.

However, decays such as $Y^* \to \phi\Lambda,\ \phi\Sigma$ might contribute to the background for certain final states. Larger contributions to the background will more likely come from events with pions misidentified as Kaons, as well as other reconstruction and detector inefficiencies. To extract small Cascade signals at masses above the $\Xi(1530)$, it will therefore be important to reduce the background by kinematically reconstructing complete final states. A full exclusive reconstruction also enhances the possibility of being able to measure the J^P of these states.

We have simulated the production of the $\Xi^-(1320)$ and $\Xi^-(1820)$ resonances to better understand the kinematics of these reactions. The photo-production of the $\Xi^-(1320)$ decaying to $\pi^-\Lambda$ and of the $\Xi^-(1820)$ decaying to ΛK^- is shown in Fig. 2. These reactions results in the $K^+K^+\pi^-\pi^-p$ and $K^+K^+K^-\pi^-p$ final states, respectively. Reactions involving excited Cascades have "softer" forward-going Kaons, and there is more energy available on average to the Cascade's decay products. Both plots show three regions of high density. The upper momentum region (> 4 GeV/c) consists of forward-going K^+ tracks from the associated production of an excited hyperon. The middle momentum regions (1-2 GeV/c) are a mixture of K^-, K^+, and proton tracks, while the lower region (below 1 GeV/c) contains mostly π^- tracks. The high-momentum Kaon tracks with momenta larger than about 2.5 GeV/c cannot be identified with the current GlueX PID system. Shown in Fig. 2 in solid (red), dashed (green), and dotted (blue) are the regions of phase space where the existing time-of-flight (TOF) detector, the proposed Hadron Blind RICH (HBRICH) detector, and proposed gas Cherenkov detector provide pion/Kaon discrimination at the four standard deviation level [12].

4. **Acknowledgments**

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