The Excited Baryon Spectrum: What have we learned?

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Abstract. One of the most striking phenomenon of quantum chromodynamics (QCD) is the formation of the nucleon out of massless gluons and almost massless quarks. This system of confined quarks and gluons serves as the basic constituent of ordinary baryonic matter and exhibits the characteristic spectra of excited states, which are sensitive to the details of quark confinement. Complementary to nucleon structure studies in deep inelastic scattering experiments, nucleon excitations provide the unique opportunity to explore the many aspects of non-perturbative QCD. The last few years have seen significant progress toward the mapping of the nucleon spectrum. The rapidly growing database of high-quality experimental results on exclusive meson photo- and electroproduction on the nucleon from experimental facilities around the world now allows the hadron spectroscopy community to determine the scattering amplitudes of the underlying reactions more accurately and to identify nucleon resonance contributions with minimal model dependence. At Jefferson Laboratory (JLab), the excited baryon program now continues in the 12-GeV era with the successful data-taking of the GlueX experiment. Part of the GlueX scientific program is to search for and study the poorly-known multi-strange baryons which will provide an important missing link between the light- and the heavy-flavor baryons.

INTRODUCTION

A better understanding of the nucleon as a bound state of quarks and gluons as well as the spectrum and internal structure of excited baryons remains a fundamental challenge and goal in hadronic physics. Many years of studying excited baryons have demonstrated that the mass spectra of these states are clearly organized according to their quark flavor content, spin, and parity. Baryons are known to be fermions and thus, they obey the Pauli principle. Assuming that the baryon structure is described in terms of three symmetric quark degrees of freedom, the total wave function

$$|qqq\rangle_A = |\text{color}\rangle_A \times |\text{space, spin, flavor}\rangle_S \tag{1}$$

must be antisymmetric under the interchange of any two equal-mass quarks. Since all observed hadrons are color singlets, the color component of the wave function must be completely antisymmetric. Within the framework of the traditional quark model, the total baryon spin has two possible values. The three quark spins ($s = \frac{1}{2}$) can yield a total baryon spin of either $S = \frac{1}{2}$ or $S = \frac{3}{2}$. The latter configuration yields a completely symmetric spin wave function, whereas the $S = \frac{1}{2}$ state exhibits a mixed symmetry. The flavor and spin can be combined in an approximate spin-flavor SU(6), where the multiplets are

$$\mathbf{6} \otimes \mathbf{6} \otimes \mathbf{6} = \mathbf{56}_S \oplus \mathbf{70}_M \oplus \mathbf{70}_M \oplus \mathbf{20}_A\,. \tag{2}$$

These can be decomposed into flavor SU(3) multiplets

$$\mathbf{56} = {}^4\mathbf{10} \oplus {}^2\mathbf{8} \tag{3}$$

$$\mathbf{70} = {}^2\mathbf{10} \oplus {}^4\mathbf{8} \oplus {}^2\mathbf{8} \oplus {}^2\mathbf{1} \tag{4}$$

$$\mathbf{20} = {}^2\mathbf{8} \oplus {}^4\mathbf{1}\,, \tag{5}$$

where the superscript $(2S+1)$ gives the spin for each particle in the SU(3) multiplet. The proton and neutron belong to the ground-state **56**, in which the orbital angular momentum between any pair of quarks is zero. They are members of the octet with spin and parity $J^P = \frac{1}{2}^+$. On the contrary, the non-strange Δ resonance is a member of the decuplet with spin and parity $J^P = \frac{3}{2}^+$. The wave functions of the **70** and **20** require some excitation of the spatial part to make the overall non-color (spin × space × flavor) component of the wave function symmetric. Orbital motion is accounted for by classifying states in $\text{SU}(6) \otimes \text{O}(3)$ supermultiplets, with the O(3) group describing the orbital motion.

In addition to spin-flavor multiplets, it is convenient to classify baryons into bands according to the harmonic oscillator model with equal quanta of excitation, $N = 0, 1, 2, \ldots$. Each band consists of a number of supermultiplets, specified by $(\mathbf{D}, L^P_N)$, where $\mathbf{D}$ is the dimensionality of the SU(6) representation, L is the total quark orbital angular

TABLE I. Tentative assignments of the known light baryons to the lowest-lying SU(6) $\otimes$ O(3) singlets and octets. States marked with † are merely educated guesses because the evidence for their existence is either poor or they can be assigned to other multiplets. A hyphen indicates that the state does not exist, an empty space that it is missing. For the higher multiplets, Nx gives the number of expected states. Star assignments given in red indicate the changes in the baryon listings maintained by the Particle Data Group (PDG) in the Review of Particle Physics (RPP) between 2004 [1] and 2018 [2].

N	(D, L_N^P)	S	J^P	Octet Members					Singlets
0	$(56, 0_0^+)$	1/2	$1/2^+$	$N(939)$	$\ast\ast\ast\ast$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	–
1	$(70, 1_1^-)$	1/2	$1/2^-$	$N(1535)$	$\ast\ast\ast\ast$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(1690)$	$\Lambda(1405)$
			$3/2^-$	$N(1520)$	$\ast\ast\ast\ast$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
		3/2	$1/2^-$	$N(1650)$	$\ast\ast\ast\ast$	$\Lambda(1800)$	$\Sigma(1750)$		–
			$3/2^-$	$N(1700)$	$\ast\ast\ast$				–
			$5/2^-$	$N(1675)$	$\ast\ast\ast\ast$	$\Lambda(1830)$	$\Sigma(1775)$		–
2	$(56, 0_2^+)$	1/2	$1/2^+$	$N(1440)$	$\ast\ast\ast\ast$	$\Lambda(1600)$	$\Sigma(1660)$		–
	$(70, 0_2^+)$	1/2	$1/2^+$	$N(1710)$	$\ast\ast\ast\ast$	$\Lambda(1810)^\dagger$	$\Sigma(1770)^\dagger$		
		3/2	$3/2^+$						–
	$(56, 2_2^+)$	1/2	$3/2^+$	$N(1720)^\dagger$	$\ast\ast\ast\ast$	$\Lambda(1890)^\dagger$	$\Sigma(1840)^\dagger$		–
			$5/2^+$	$N(1680)$	$\ast\ast\ast\ast$	$\Lambda(1820)^\dagger$	$\Sigma(1915)^\dagger$		–
	$(70, 2_2^+)$	1/2	$3/2^+$						
			$5/2^+$	$N(1860)$	$\ast\ast$				
		3/2	$1/2^+$	$N(1880)$	$\ast\ast\ast$			–	
			$3/2^+$	$N(1900)^\dagger$	$\ast\ast\ast\ast$		$\Sigma(2080)^\dagger$		–
			$5/2^+$	$N(2000)$	$\ast\ast$	$\Lambda(2110)^\dagger$	$\Sigma(2070)^\dagger$		–
			$7/2^+$	$N(1990)$	$\ast\ast$	$\Lambda(2020)$	$\Sigma(2030)^\dagger$		–
	$(20, 1_2^+)$	1/2	$1/2^+$	$N(2100)^\dagger$	$\ast\ast\ast$				
			$3/2^+$	$N(2040)^\dagger$	$\ast$				
			$5/2^+$	–		–	–	–	
3	$(56, 1_3^-)$	1/2	$1/2^-$	$N(1895)^\dagger$	$\ast\ast\ast\ast$				–
			$3/2^-$	$N(1875)^\dagger$	$\ast\ast\ast$		$\Sigma(1940)^\dagger$		–
	$(70, 1_3^-)$			5 x					
	$(70, 1_3^-)$			5 x					
	$(20, 1_3^-)$	1/2		2 x					
	$(70, 2_3^-)$			6 x					
	$(56, 3_3^-)$	1/2		2 x					–
	$(70, 3_3^-)$	1/2	$7/2^-$	$N(2190)^\dagger$	$\ast\ast\ast\ast$	$\Lambda(2100)^\dagger$			
		3/2	$9/2^-$	$N(2250)$	$\ast\ast\ast\ast$				
	$(20, 3_3^-)$	1/2		2 x					
4			$9/2^+$	$N(2220)$	$\ast\ast\ast\ast$	$\Lambda(2350)$			
5			$11/2^-$	$N(2600)$	$\ast\ast\ast$				

momentum, and P is the parity. The first-excitation band contains only one supermultiplet, $(\mathbf{70},\, 1_1^-)$, corresponding to states with one unit of orbital angular momentum and negative parity, whereas the second-excitation band contains already five supermultiplets corresponding to states with positive parity and either two units of angular momentum that can couple to $L = 0, 1, 2$, giving the supermultiplets $(\mathbf{70},\, 0_2^+)$, $(\mathbf{20},\, 1_2^+)$, $(\mathbf{70},\, 2_2^+)$, respectively, or one unit of radial excitation, $(\mathbf{56},\, 2_2^+)$. Table I shows the tentative assignments of the known light baryons [2] to the lowest-lying SU(6) $\otimes$ O(3) singlets and octets. In the second excitation band, two $3/2^+$ states with masses below 2 GeV seem to be missing. Moreover, the status of the $(\mathbf{20},\, 1_2^+)$ is questionable. The $N(2100)\, 1/2^+$ can also be assigned to the fourth excitation band leaving this supermultiplet entirely empty since no Λ, Σ, or Ξ candidates have been observed either.

The recent advances in lattice gauge theory and the availability of large-scale computing technology make it possible for the first time to complement traditional model approaches with numerical solutions of QCD. Spin-parity assignments for excited states have even been successfully worked out by some groups, but a calculation of the physical excited baryon spectrum is still a tough challenge with present computing power. The used pion masses are still large in these calculations, with $m_\pi \gtrsim 400$ MeV, but a rich spectrum of excited states has been observed, and the low-lying states of some lattice-QCD calculations, e.g. those of [3], have the same quantum numbers as the states in models based on three symmetric quark degrees of freedom with wave functions based on the irreducible representations of $\mathrm{SU}(6)\otimes\mathrm{O}(3)$. The good qualitative agreement may be somewhat surprising since the connection between the relevant quark degrees of freedom, the constituent or dressed quarks, and those of the QCD Lagrangian is not well understood. However, the lattice-QCD results appear to answer the long-standing question in hadron spectroscopy of whether the large number of excited baryons predicted by constituent quark models, but experimentally not observed, is realized in nature. In recent years, further hints for additional, hitherto unobserved baryon resonances have also come from a different direction. Supplementing the conventional hadron resonance gas (HRG) models with additional, experimentally uncharted strange hadrons predicted by quark model calculations, and observed in lattice-QCD spectrum calculations, leads to a good description of strange hadron thermodynamics below the QCD crossover from deconfined quark-gluon to color-confined matter [4].

The plethora of new results from experiments using electromagnetic probes has inspired attempts to compare the pattern of observed baryon resonances with predictions from "traditional" models, but also with predictions from models generating baryons dynamically from meson-nucleon scattering amplitudes or with results from models that restore the chiral symmetry at high excitation energies. A fascinating new connection between nuclear physics and string theory has been developed in recent years – called the AdS/QCD correspondence, see e.g. [5]. Such an alternative description of QCD could provide new procedures to calculate many observables more efficiently. A direct comparison of the predicted mass spectra from AdS/QCD with experimental findings in hadron spectroscopy has become possible and significant efforts have been invested to better understand this exciting connection.

The search for new excited baryons

Several new excited nucleon states have been proposed based on the recent high-statistics photoproduction data [2]. Table II shows the group of six additional nucleon resonances now listed by the Particle Data Group and their evidence in various decay modes. The addition of the $N(1880)\,1/2^+$ state is particularly interesting since the four states, $N(1880)\,1/2^+$, $N(1900)\,3/2^+$, $N(2000)\,5/2^+$, $N(1990)\,7/2^+$, are now considered to form a quartet of nucleon resonances with spin 3/2 and to be members of the $(\mathbf{70}, 2^+_2)$ supermultiplet. A summary of the progress toward understanding the baryon spectrum is given in Refs. [6, 7].

In the hyperon channels, $\gamma p \to KY$ $(Y = \Lambda, \Sigma)$, precise cross section and polarization data have been obtained at Jefferson Laboratory (JLab), e. g. Refs. [8, 9, 10, 11]. The weak decay of the hyperon provides additional access to the polarization of the recoiling baryon, rendering a *complete* experiment for these reactions feasible. A partial-wave analysis (PWA) based on a large data set of photo- and pion-induced reactions performed within the Bonn-Gatchina (BnGa) PWA framework revealed the first indications for the previously poorly-established $N(1900)\,3/2^+$ resonance in photoproduction. This state was subsequently upgraded from a 2-star to a 3-star state in 2012 [12], and finally to a 4-star state by the Particle Data Group in the 2018 edition of the Review of Particle Physics (RPP) [2]. This resonance is strongly needed in the interpretation of CLAS data on the double-polarization observables C_x and C_z in $\gamma p \to K^+\Lambda$ [8], which describe the spin transfer from a circularly-polarized photon to the recoiling hyperon along and perpendicular to the beam axis in the center-of-mass frame, respectively.

TABLE II. The new nucleon resonances listed by the Particle Data Group [2].

State	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	*
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(2080)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*	*
$N(2120)$	$3/2^-$	***	***	***	**	**		**	*		*	*

The hyperon channels have also played a crucial role in the discovery of the new N^* states (Table II). The quest for new baryon states continues but in a brief summary, the goal of mapping out the N^* states in the first and second excitation bands is almost accomplished.

VECTOR MESON PHOTOPRODUCTION

The production of vector mesons in photoproduction is particularly interesting since these mesons (ρ, ω, ϕ) carry the same quantum numbers, $J^{PC} = 1^{--}$, as the photon and therefore, they are expected to play an important role in photoproduction. The Review of Particle Physics [2] clearly shows that the vector-meson decay modes have remained under-explored in recent years. However, many hitherto unobserved higher-mass N^* resonances might strongly couple to these decay modes. The study of ω-meson photoproduction is especially interesting. The photoproduction of these mesons at very high energies, $E_\gamma > 20$ GeV, can successfully be described as a diffractive process: the photon converts into a vector meson, which then scatters off the proton by the exchange of pomerons. These virtual colorless objects carry no charge and share the $J^{PC} = 0^{++}$ quantum numbers of the vacuum [13].

Close to the ω photoproduction threshold in the baryon resonance regime, N^* states strongly contribute to ω production. The isoscalar nature of the ω meson ($I = 0$) facilitates the search for nucleon resonances since the photoproduction of the ω in s-channel processes can only proceed via N^* states with $I = \frac{1}{2}$; contributions from Δ^* resonances with $I = \frac{3}{2}$ are excluded. In the CLAS $\gamma p \to p\omega$ data reported in Ref. [14], significantly non-zero target asymmetries are observed, which indicate strong s-channel resonance contributions, in agreement with the expectation from the BnGa PWA. Figure 1 shows first-time measurements of the beam-target asymmetries H (top) and P (bottom) in ω photoproduction off the proton from the CLAS Collaboration [15]. Significant non-zero values are also observed in these observables. At low energies, close to the reaction threshold, the leading partial waves have $J^P = 3/2^+$ and $5/2^+$ quantum numbers within the BnGa framework, which are identified with the $N(1720)\,3/2^+$ and the sub-threshold $N(1680)\,5/2^+$ nucleon resonances. Recent calculations that used an effective chiral Lagrangian approach [18] also found these two resonances to play a major role in ω photoproduction. In particular, the $N(1720)\,3/2^+$ was identified and observed in the beam polarization asymmetries. The $3/2^+$ partial wave is complex and multiple $3/2^+$ nucleon resonances likely contribute to the data around $W = 1.7$ - 2.1 GeV. The importance of the $3/2^+$ wave was also discussed in an earlier event-based PWA using CLAS-ω cross section data and unpolarized spin-density matrix elements alone [19]. The BnGa PWA finds indications for at least one more $3/2^+$ resonance around $W = 1.9$ GeV but more constraints provided by polarization data are needed to determine its properties.

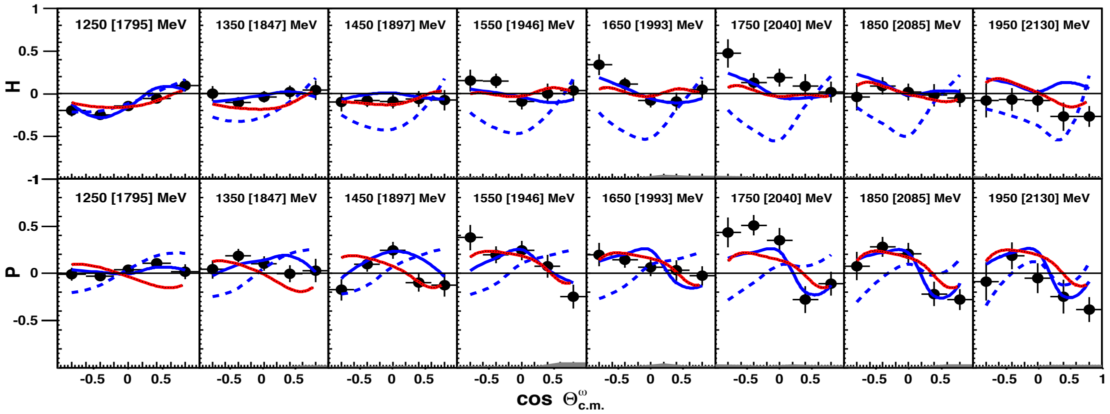

FIGURE 1. First-time measurements of the beam-target asymmetries H (top) and P (bottom) in ω photoproduction off the proton [15]. Shown are eight 100-MeV-wide energy bins (labeled as $E_\gamma[W]$) as a function of $\cos\Theta^{\omega}_{\mathrm{c.m.}}$ in the center-of-mass frame. Each data point has been assigned its statistical uncertainty, whereas the gray band at the bottom of each panel represents the absolute systematic uncertainties due to the background subtraction. The blue and red solid curves show the BnGa PWA solution and fits by Wei *et al.* [16], respectively. The blue dashed curve denotes an earlier BnGa solution [17]. Reproduced figure with permission from [15]. Copyright 2019 by the American Physical Society.

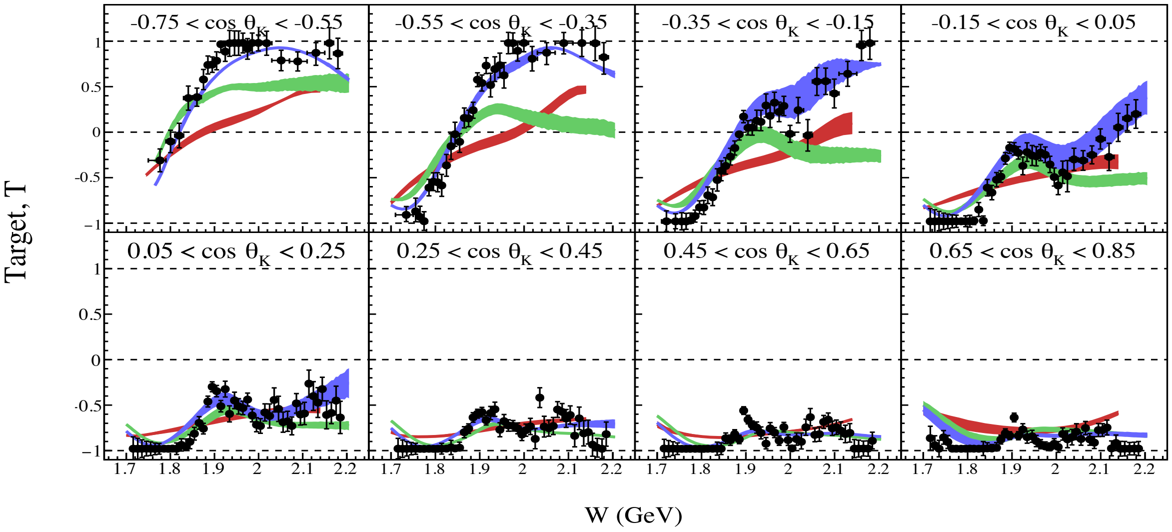

FIGURE 2. The energy dependence of the target asymmetry, T, for the reaction $\vec{\gamma} p \to K \vec{\Lambda}$ [11]. Red curves - ANL-Osaka predictions from coupled-channels calculations [20]; Green curves - predictions from the 2014 solution of the BnGa partial wave analysis [21]; Blue curves - BnGa calculations after a re-fit including the present data, which include additional $N^*(3/2^+)$ and $N^*(5/2^+)$ resonances. The bands associated with each colored curve represent one standard deviation in calculations within the kaon angular range labeled in the sub-plots. Reproduced figure with permission from [11]. Copyright 2016 by the American Physical Society.

Toward higher energies, the t-channel contributions increase in strength and in the case of the Σ asymmetry, the linear-beam polarization allows for the separation of natural- from unnatural-parity exchange processes. The BnGa group has found that pomeron-exchange dominates over the smaller π-exchange across the analyzed energy range. Further N^*-resonance contributions are required to describe the data at and above center-of-mass energies of $W =$ 2 GeV. The $1/2^-$, $3/2^-$, and $5/2^+$ partial waves also play a significant role in the PWA solution. In addition to the $N(1680)\,5/2^+$ close to the threshold, a further structure around $W = 2$ GeV is observed, which is identified with the $N(2000)\,5/2^+$ state. The latter is listed as a 2-star state in the RPP [2] and has been considered a missing baryon resonance.

OPEN STRANGENESS PHOTOPRODUCTION

The production of open or associated strangeness in photon-induced reactions is sensitive to the underlying dynamics of the nucleon's quark structure since an $s\bar{s}$ quark-antiquark pair must be created. Kaon electromagnetic production experiments can be thought of as producing nonstrange baryons in the s channel, which subsequently decay into a strange baryon and a strange meson. The strange quark plays a unique role in particle and nuclear physics. As a degree of freedom in the description of light hadrons, it is not quite as light as the u and the d quark for expansions based on chiral symmetry to work, nor is it heavy enough for it to be treated in heavy-quark effective approaches. The strange quark was also important in the development of the Standard Model, as hadrons containing strange quarks were the first to manifest flavor-changing neutral currents and CP violation.

Predictions in a quark-pair creation model [22] or a collective string-like 3-quark model [23] revealed substantial decay branches of baryon resonances into the $K\Lambda$ and $K\Sigma$ channels. Kaon-production experiments will therefore be an important tool to establish or disprove so-called *missing* baryon resonances and thus to determine the relevant degrees of freedom of quark models. Figure 2 for example shows the target asymmetry for the reaction $\vec{\gamma} p \to K \vec{\Lambda}$ using linearly-polarized incident photons [11]. Additional $N^*(3/2^+)$ and $N^*(5/2^+)$ resonances were needed in a BnGa re-fit of the data.

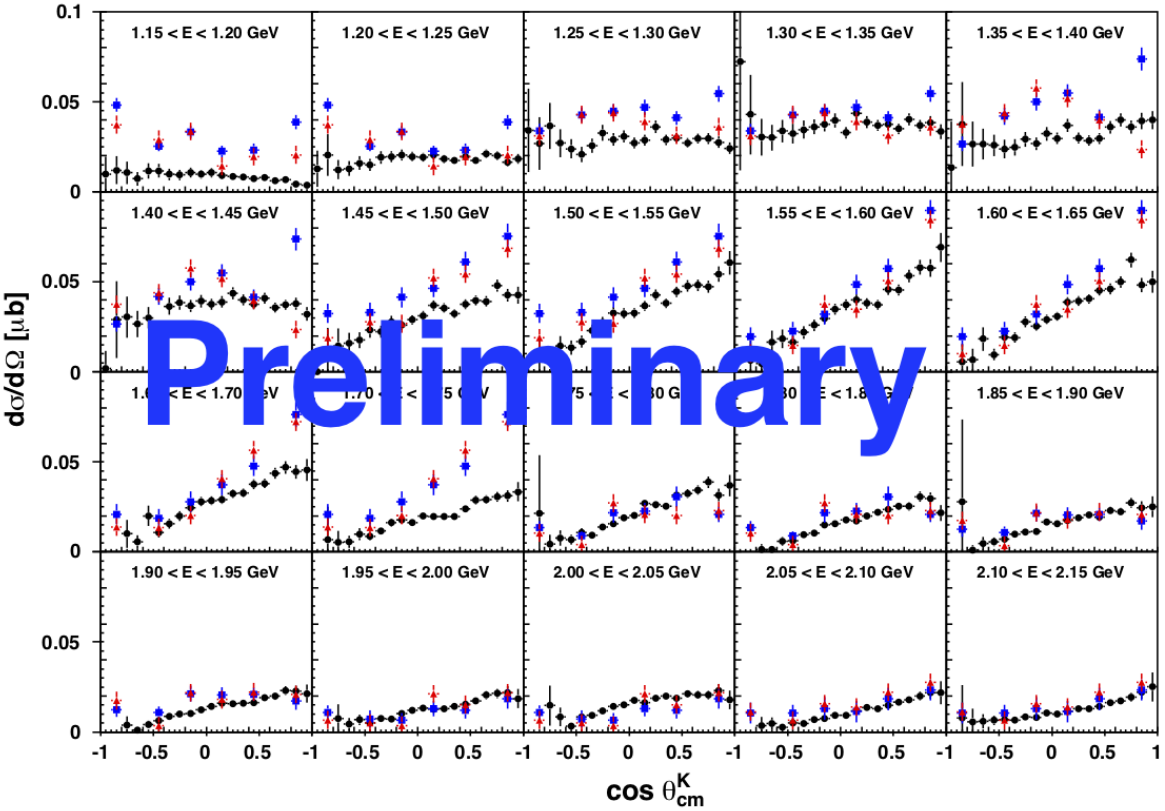

FIGURE 3. The angular distributions for the reaction $\gamma p \to K^0 \Sigma^+$. Shown in black are the recent CLAS data in comparison with earlier results from CB-ELSA [25] and CBELSA/TAPS [24].

In the $\gamma p \to K^0 \Sigma^+$ channel, the CBELSA/TAPS Collaboration recently announced the observation of a cusp-like structure in the cross section near the $K^* \Lambda/\Sigma$ thresholds [24]. This was observed as a rapid decline of the differential cross section in the energy range between 1750 MeV and 1850 MeV, changing from forward peaked to a flat angular distribution. Figure 3 shows statistically-improved (preliminary) data from the CLAS-g12 experiment in comparison with the published data from CBELSA/TAPS [24]. A smooth behavior of the cross section is observed across the 1700 - 1900 MeV energy range and the cusp-like structure is not confirmed.

The Ξ Spectrum

Experimental information on the spectrum, structure, and decays of strangeness $S = -2$ Cascade baryons is sparse compared to non-strange and strangeness $S = -1$ baryons. Among the doubly-strange states, the two ground-state Cascades, the octet member $\Xi(1320)$ and the decuplet member $\Xi^*(1530)$, have four-star status in the RPP [2], 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). And 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: $\Xi(1530)\frac{3}{2}^+$ [26], $\Xi(1820)\frac{3}{2}^-$ [27]. All other J^P assignments are based on quark-model predictions. It is strongly argued that an experimental program at Jefferson Lab using photoproduction and the GlueX detector in order 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 the relatively narrow width of the Ξ resonances is experimentally verified, this would confirm the flavor independence of the confining interaction that is assumed in models. The narrow widths may also make it possible to

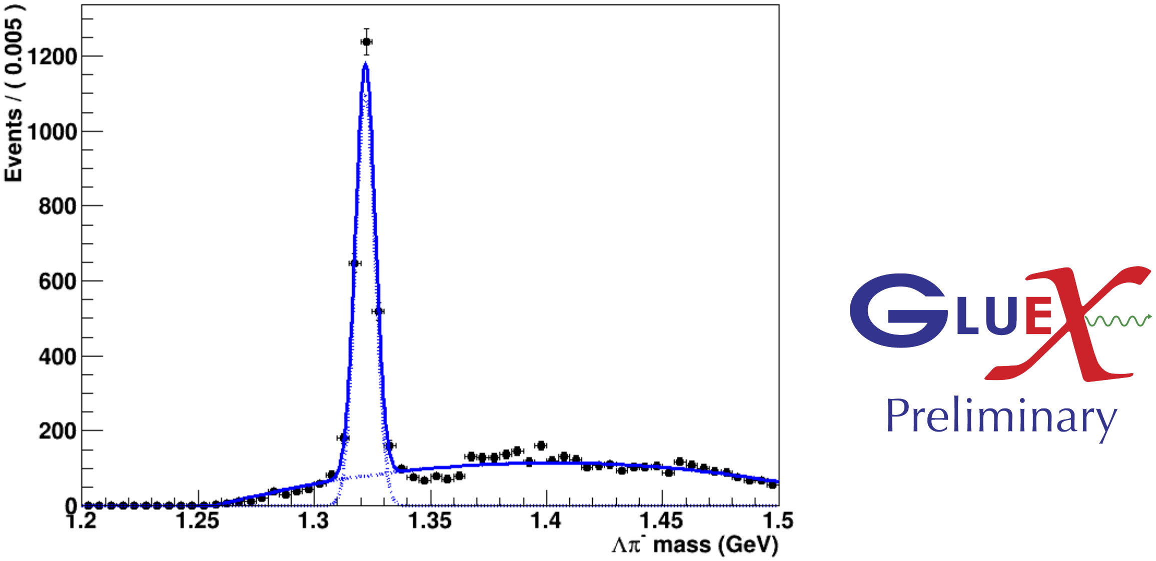

FIGURE 4. Invariant $\Lambda\pi^-$ mass distribution showing the $\Xi(1320)^-$ octet ground state. Courtesy of A. Ernst [28].

measure the isospin-symmetry violating mass splittings in a spatially-excited baryon for the first time. Copious data for excited strangeness $S = -1$ baryons will be collected along with the data for Cascade baryons in such an experimental program. First hints of excited Ξ resonances in GlueX data beyond the two ground states have been observed and a report was given at this conference [28]. However, the limited statistics currently does not render possible any statistically-significant claims. This will change with the planned high-intensity GlueX running in the Fall 2019 and later in 2020.

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 (see also Table I). For every N^* state, there should thus be a corresponding Ξ^* state *with similar properties*. Additionally, since the decuplets consist of Δ^*, Σ^*, Ξ^*, and Ω^* states, for every Δ^* state a decuplet Ξ^* with similar properties can be expected. 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. Are there 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 the understanding of them, which motivates the collection of a significant database on multi-strange baryons.

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

$$\gamma p \to K Y^* \to K^+ (\Xi^- K^+),\; K^+ (\Xi^0 K^0),\; K^0 (\Xi^0 K^+)\,. \tag{6}$$

An example invariant mass spectrum based on recent GlueX data is shown in Fig. 4 for the exclusive reaction $\gamma p \to K^+ K^+ \Xi^-$ [28]. The Ξ^- octet ground-state peak in the invariant $\Lambda\pi^-$ mass is nicely observed.

OUTLOOK

In a brief summary, baryon spectroscopy has made great leaps forward in recent years. Based on the available very precise photoproduction data from various facilities, including crucial polarization observables, six additional light-quark nucleon resonances were added to the summary table by the Particle Data Group with all but one listed as 3-star resonances. This indicates that evidence for their existence is almost certain. The focus of many experimental (nuclear) programs has now shifted to the strangeness sector with the goal to study the poorly-understood spectrum of doubly-strange Ξ resonances. Some of the open issues in light-baryon spectroscopy include the questions if unconventional states, e.g. states similar to the $\Lambda(1405)$ or the Roper resonance, $N(1440)$, can be observed among those multi-strange states.

On the structure side, high-quality measurements of the Q^2 dependencies of various helicity amplitudes has shed some light on the effective degrees of freedom in the underlying transition strength. However, what is the nature of non-quark contributions, e. g. of the meson-baryon cloud or dynamically-generated states? Other open questions remain in the study of excited baryons.

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