The Spectroscopy of Excited Baryon Resonances at CLAS: A Review of the 6-GeV Program

Volker Crede[1,*]
for the CLAS Collaboration

[1]Florida State University, Tallahassee, FL 32306 USA

Abstract. One of the most striking phenomenon of strong 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, nucleon excitations provide a unique opportunity to explore the many facets of non-perturbative QCD. The last few years have seen significant progress toward mapping out the nucleon spectrum. The rapidly growing database of high-quality experimental results on exclusive meson photo- and electroproduction off the nucleon from experimental facilities around the world allows us to determine the scattering amplitudes in the underlying reactions and to identify nucleon resonance contributions with minimal model dependence. The available precision data and improvements in multi-channel amplitude analysis procedures have resulted in the discovery of several new excited baryon states, which have been added to the particle listings in the Review of Particle Properties (RPP).

1 Introduction

The mass spectrum of hadrons is clearly organized according to the flavor content, spin, and parity of the states. For intermediate and long-distance phenomena such as hadron properties, the full complexity of QCD emerges (non-perturbative QCD), and is a strong obstacle to understanding hadronic phenomena at a fundamental level. The recent advances in lattice gauge theory and the availability of large-scale computing technology make it possible for the first time to complement 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. Even though the used pion masses are still large, with $m_\pi \gtrsim 400$ MeV, a rich spectrum of excited states has been observed, and the low-lying states of some lattice-QCD calculations, e. g. those of [1], 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 $SU(6) \otimes O(3)$. 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. The lattice-QCD

*e-mail: crede@fsu.edu

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 [2].

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. [3]. 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.

1.1 The Search for new Excited Baryons

Several new excited nucleon states have been proposed based on the recent high-statistics photoproduction data [4]. Table 1 shows the group of six additional nucleon resonances now listed by the Particle Data Group and their evidence in various decay modes. A summary of the progress toward understanding the baryon spectrum is given in Refs. [5, 6].

In the hyperon channels, $\gamma p \to K\,Y$ ($Y = \Lambda, \Sigma$), precise cross section and polarization data have been obtained at Jefferson Laboratory (JLab), e. g. Refs. [7–10]. 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 [11], and finally to a 4-star state by the Particle Data Group in the 2018 edition of the Review of Particle Physics (RPP) [4]. This resonance is required in particular by the CLAS measurements of the double-polarization observables, C_x and C_z [7], 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.

The hyperon channels have also played a crucial role in the discovery of the new N^* states (Table 1). 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.

Table 1. The new nucleon resonances listed by the Particle Data Group [4].

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

2 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 [4] clearly shows that the vector-meson decay modes have remained underexplored 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 to 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 $I = \frac{1}{2}$; no contributions from Δ^* resonances with $I = \frac{3}{2}$ are allowed. In the CLAS $\gamma p \to p\omega$ data presented here [14], significantly non-zero target asymmetries are observed (see Fig. 1), which indicate significant s-channel contributions, in agreement with the expectation from the BnGa PWA. At low energies, close to the reaction threshold, the leading partial waves have $J^P = 3/2^+$ and $5/2^+$ quantum numbers, which are identified with the $N(1720)\,3/2^+$ and the sub-threshold $N(1680)\,5/2^+$ nucleon resonances.

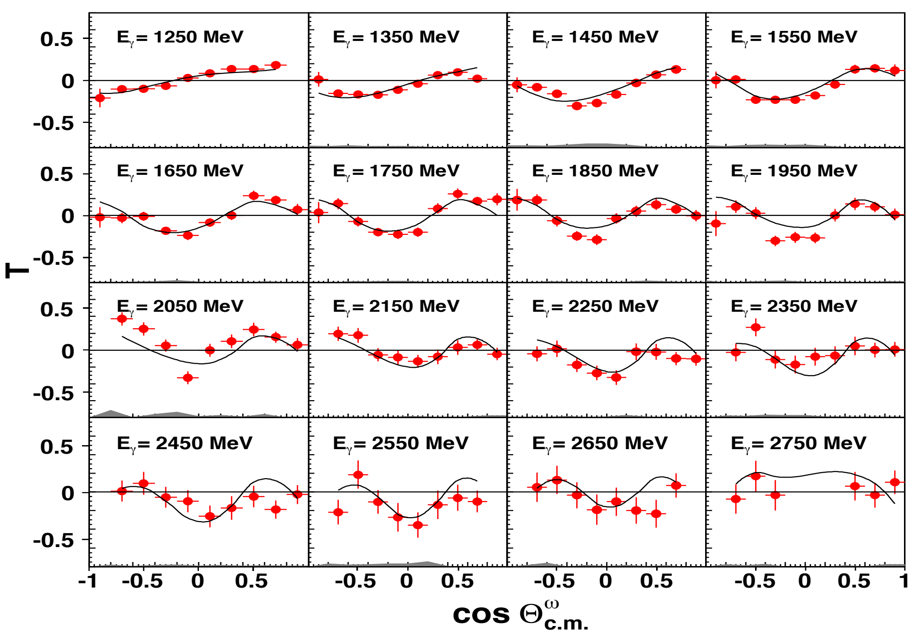

Figure 1. Results for the target asymmetry, T, using a transversely-polarized target in the reaction $\gamma p \to p\,\omega$. The data are shown for the energy range $E_\gamma \in [1.2, 2.8]$ GeV in 100-MeV-wide bins. The gray band at the bottom of each panel represents the absolute systematic uncertainties of our results due to the background subtraction. The horizontal bars of the FROST data points indicate the angular range they cover. The black solid line denotes the BnGa-PWA solution [12]. Picture from Ref. [14].

Recent calculations that used an effective chiral Lagrangian approach [17] 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 [16]. The BnGa PWA finds indications for at least one more $3/2^+$ resonance around $W = 1.9$ GeV.

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 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 [4] and considered a missing baryon resonance.

3 Open Strangeness Photoproduction

The production of open 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 [20] or a collective string-like 3-quark model [21] 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. Additional $N^*(3/2^+)$ and $N^*(5/2^+)$ resonances were needed in a BnGa re-fit of the data.

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 [22]. This was observed as a rapid fall 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 data from CLAS in comparison with the published data from CBELSa/TAPS. A smooth behavior of the cross section is observed across the 1700 - 1900 MeV energy range and the cusp-like structure is not confirmed.

4 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

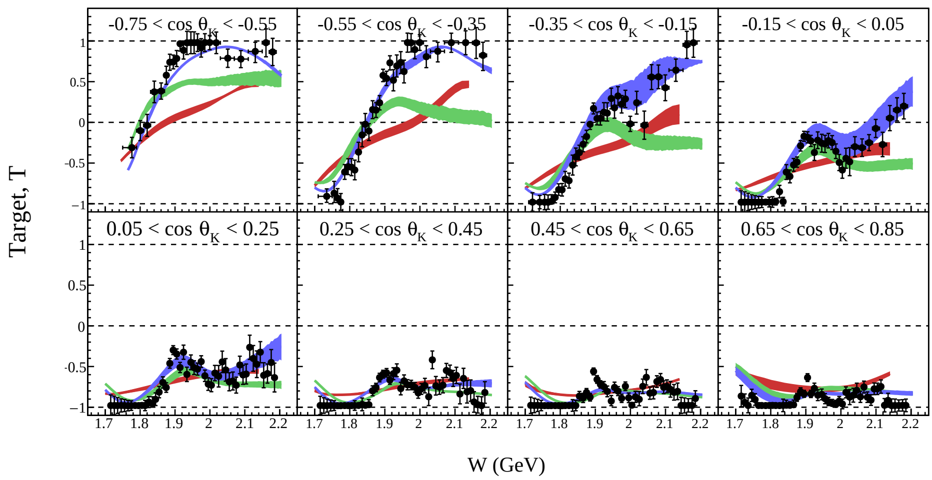

Figure 2. The energy dependence of the target asymmetry, T, for the reaction $\vec{\gamma} p \to K \vec{\Lambda}$. Red curves - ANL-Osaka predictions from coupled-channels calculations [18]; Green curves - predictions from the 2014 solution of the BnGa partial wave analysis [19]; Blue curves - BnGa calculations after a re-fit including the present data, which include additional $N^*(3/2^+)$ and $N^*(5/2^+)$ resonances. Picture from Ref. [10].

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. 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 questions remain in the study of excited baryons.

The author thanks the technical staff at Jefferson Lab and at all the participating institutions for their invaluable contributions to the success of the experiment. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Contract No. DE-AC05-06OR23177. The group at Florida State University acknowledges additional support from the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Contract No. DE-FG02-92ER40735.

References

[1] R. G. Edwards *et al.*, Phys. Rev. D **84**, 074508 (2011)
[2] A. Bazavov *et al.*, Phys. Rev. Lett. **113**, 072001 (2014); Phys. Lett. B **737**, 210 (2014)
[3] O. Aharony *et al.*, Phys. Rept. **323**, 183 (2000)

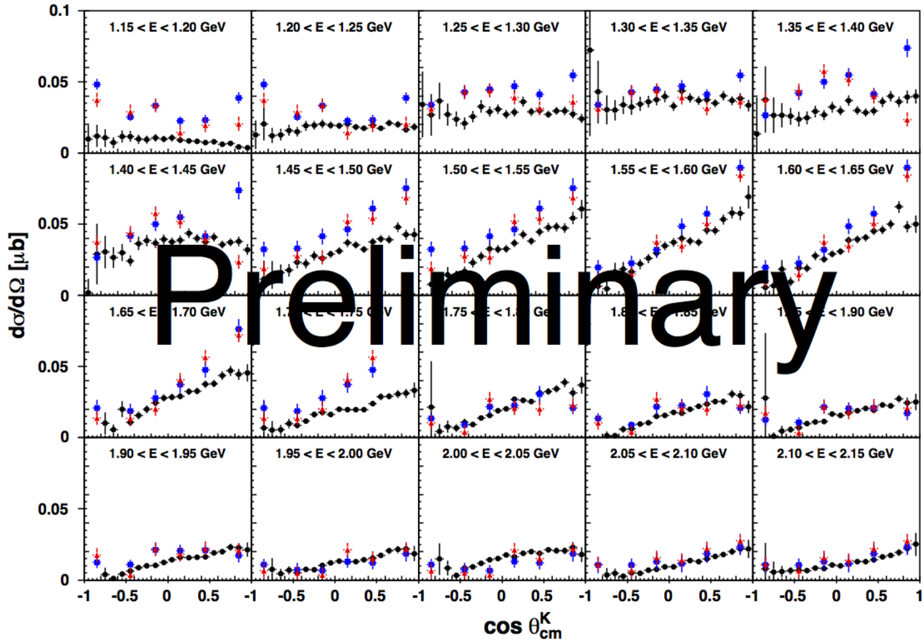

Figure 3. The angular distributions for the reaction $\gamma p \to K^0\,\Sigma^+$. Shown in black are the recent CLAS data in comparison with earlier results from CB-ELSA and CBELSA/TAPS.

[4] M. Tanabashi *et al.* [Particle Data Group], Phys. Rev. D **98**, 030001 (2018)
[5] E. Klempt and J. M. Richard, Rev. Mod. Phys. **82**, 1095 (2010)
[6] V. Crede and W. Roberts, Rept. Prog. Phys. **76**, 076301 (2013)
[7] R. K. Bradford *et al.* [CLAS Collaboration], Phys. Rev. C **75**, 035205 (2007)
[8] M. E. McCracken *et al.* [CLAS Collaboration], Phys. Rev. C **81**, 025201 (2010)
[9] B. Dey *et al.* [CLAS Collaboration], Phys. Rev. C **82**, 025202 (2010)
[10] C. A. Paterson *et al.* [CLAS Collaboration], Phys. Rev. C **93**, no. 6, 065201 (2016)
[11] J. Beringer *et al.* [Particle Data Group], Phys. Rev. D **86**, 010001 (2012)
[12] A. V. Anisovich *et al.*, in preparation
[13] A. Donnachie and P. V. Landshoff, Phys. Lett. B **348**, 213 (1995)
[14] P. Roy *et al.* [CLAS Collaboration], Phys. Rev. C **97**, no. 5, 055202 (2018)
[15] I. Denisenko *et al.*, Phys. Lett. B **755**, 97 (2016)
[16] M. Williams *et al.* [CLAS Collaboration], Phys. Rev. C **80**, 065209 (2009)
[17] Q. Zhao, Phys. Rev. C **63**, 025203 (2001)
[18] H. Kamano *et al.*, Phys. Rev. C **88**, no. 3, 035209 (2013)
[19] E. Gutz *et al.* [CBELSA/TAPS Collaboration], Eur. Phys. J. A **50**, 74 (2014)
[20] S. Capstick and W. Roberts, Phys. Rev. D **58**, 074011 (1998)
[21] R. Bijker, F. Iachello and A. Leviatan, Phys. Rev. D **55**, 2862 (1997)
[22] R. Ewald *et al.* [CBELSA/TAPS Collaboration], Phys. Lett. B **713**, 180 (2012)