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Baryon Resonances in Photoproduction

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The composite nature of baryons manifests itself in the existence of a rich spectrum of excited states, particularly in the important mass region 1-2 GeV for the light-flavored baryons. After decades of research, the fundamental degrees of freedom underlying the baryon excitation spectrum are still poorly understood. Highly-excited baryon resonances are also sensitive to the details of quark confinement which is well described in constituent quark models where all of the non-perturbative dynamics of the gluons being exchanged between pairs of quarks are assumed to be mimicked by a potential. A satisfying understanding of confinement within quantum chromodynamics (QCD) has not emerged, yet. The search for hitherto undiscovered but predicted baryon resonances continues at many laboratories around the world such as Jefferson Laboratory, ELSA, and MAMI. In these photo- and electroproduction experiments, a large amount of data has been accumulated in recent years including unpolarized cross section and polarization data for a large variety of meson-production reactions. These are important steps toward so-called complete experiments that will allow us to unambiguously determine the scattering amplitude in the underlying reactions and to identify the broad and overlapping baryon resonance contributions. Several new nucleon resonances have been proposed and changes to the baryon listings in the 2012 Review of Particle Physics reflect the progress in the field. However, the continuing study of available data sets with consideration of new observables and improved analysis tools have also called into question some of the earlier findings in baryon spectroscopy.

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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. 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 $\mathrm{SU(6)} \otimes \mathrm{O(3)}$. 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. The lattice 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.

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" quark 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. [2]. 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 [3]. 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. [4, 5, 6]. 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 (BoGa) PWA framework requires a $N(1900)\,\frac{3}{2}^+$ resonance. This state has been upgraded from a 2-star to a 3-star state by the Particle Data Group in the 2012 edition of the Review of Particle Physics (RPP) [3] and is required in particular by the recent CLAS measurements of the double-polarization observables, C_x and C_z [4], which describe the spin transfer from a circularly-polarized photon to the recoiling hyperon along and perpendicular to the beam axis in the c.m. system, respectively.

Using different experimental setups worldwide, high-statistics data on differential cross sections were also obtained for the reactions $\gamma p \to p\pi^0$ [7, 8, 9], $\gamma p \to n\pi^+$ [10], $\gamma p \to p\eta$ [11, 12, 13],

$\gamma p \to p\eta'$ [12, 13], and $\gamma p \to p\omega$ [14]. A new resonance was first proposed by the CB-ELSA collaboration [11] decaying to $p\eta$ and later confirmed by CBELSA/TAPS [12]; the state is now listed as $(**)\ N(2060)\,\frac{5}{2}^-$ in the RPP [3]. The high-spin resonance $(****)\ N(2190)\,\frac{7}{2}^-$, previously only observed in πN scattering experiments, was identified in ω photoproduction at CLAS [14] and confirmed more recently by CBELSA/TAPS in π^0 photoproduction [9]. Moreover, a higher-mass spin-$\frac{5}{2}$ resonance was proposed by CLAS in ω production [14]. It can be identified with the poorly-established $(**)\ N(2000)\,\frac{5}{2}^+$ resonance, which was also observed in the latest analysis by the SAID PWA group [15]. In the photoproduction of two pseudoscalar mesons, evidence was found for the poorly-established $\Delta(1940)\,\frac{3}{2}^-$ resonance in $\gamma p \to p\pi^0\eta$ [16, 17]. This resonance has now been upgraded from a 1-star to a 2-star state [3].

1.2 Polarization Observables

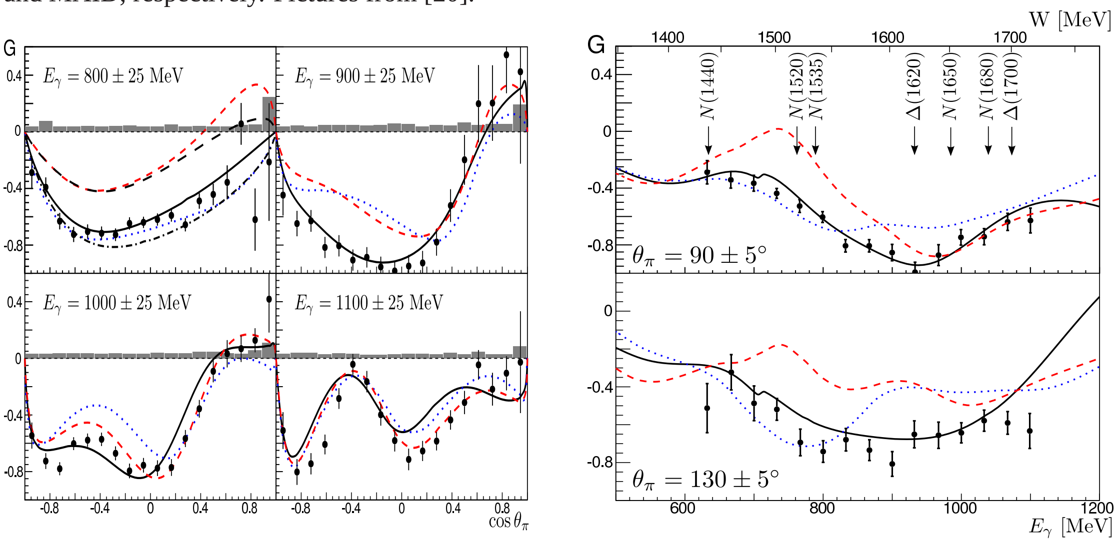
Differential cross sections alone usually result in ambiguous sets of resonances contributing to a particular photoproduction channel since almost all information on interference effects is lost. Thus, double-polarization experiments at several laboratories now aim at performing complete or nearly-complete experiments for reactions like $\gamma p \to N\pi$, $p\eta$, $p\omega$, K^+Y, and $p\pi^+\pi^-$, which will significantly reduce and eventually eliminate the ambiguities in the extraction of the scattering amplitude. Photoproduction of any pseudoscalar meson off the nucleon can be described by four complex reaction amplitudes. Bilinear combinations of these amplitudes lead to 16 observables. The measurement of these observables requires some combination of the polarization of the incident photon, nucleon target, and recoiling baryon [18]. The differential cross section is unique in that it depends only on the sum of the squared magnitudes of the amplitudes, whereas other observables involve various algebraic combinations of the amplitudes and of interference terms among them. It was shown in [19] that only eight observables must be measured: the unpolarized cross section, three single-spin, and four double-spin observables.

2. Excited Baryon Resonances in the Reaction $\gamma p \to p\pi^0$

The single-meson reactions $\gamma p \to p\pi^0$ and $\gamma p \to n\pi^+$ are among the best studied photoproduction channels, but a comprehensive study of polarization observables has only begun recently. Considered well understood about a decade ago, it has come somewhat to a surprise that many of the new polarization observables cannot be described well by current model solutions, not even at lower energies below 1 GeV incoming photon energy.

In 2012, CBELSA/TAPS reported on the first ever measurement of the double-polarization observable, G, for the photon energy range from 620 to 1120 MeV and the full solid angle [20]. The G observable describes the correlation between the photon polarization plane and the scattering plane for protons polarized along the direction of the incoming photon. Figure 1 shows the observable for fixed energies (left) and fixed angles (right). The deviations of the current model predictions from the data are clearly observed even for photon energies below 1 GeV. In particular, SAID shows large deviations for the two angles shown. It has been discussed in [20] that the discrepancies among the models arise from the two multipoles, E_{0+} and E_{2-}, which receive significant contributions from the $\frac{1}{2}^-$ resonances, $N(1535)$, $\Delta(1620)$, $N(1650)$, and the $\frac{3}{2}^-$ resonances, $N(1520)$, $\Delta(1700)$, respectively.

Figure 1: (Color online) Recent results for the double-polarization observable, G, from CBELSA/TAPS [20] for the reaction $\gamma p \to p\pi^0$ as a function of $\cos\theta_\pi$ (left) and as a function of energy for two selected $\cos\theta_\pi$ bins (right). Systematic errors are shown as gray bars. The curves represent predictions from the SAID (red, dashed) [21], MAID (blue, dotted) [22], and Bonn-Gatchina (black, solid) [23] PWAs. The black, long-dashed and dashed-dotted lines denote Bonn-Gatchina with the E_{0+} and E_{2-} amplitudes from SAID and MAID, respectively. Pictures from [20].

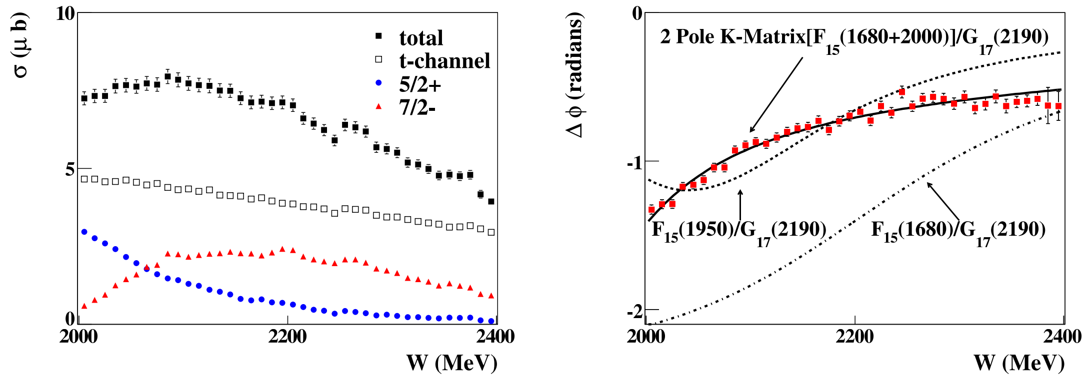


3. Excited Baryon Resonances in the Reaction $\gamma p \to p\omega$

Baryon resonances are generally broad and widely overlap, especially at higher energies, imposing challenges on the interpretation of the experimental data in terms of resonance contributions. Of particular importance are therefore well-chosen reactions which can help isolate contributions from individual excited states and clarify their importance. The photoproduction of η and ω mesons, for example, has the distinct advantage of serving as an isospin filter. Since both mesons have isospin $I = 0$, isospin conservation guarantees that the $N\eta$ or $N\omega$ final state can only be reached via formation of N^* resonances.

A PWA of the $p\omega$ channel was performed on a high-statistics data set obtained using the CLAS spectrometer at JLab for c.m. energies from threshold up to 2.4 GeV [14]. The CLAS data confirm the dominance of the t-channel π^0 exchange in the forward direction. In contrast to the production of a pseudoscalar meson, the ω decay provides additional polarization information, which further constrains the PWA for this reaction. The full determination of the spin-density matrix elements (SDMEs) has now become feasible and consequently, the SDMEs have received new interest in recent years. The PWA results from CLAS at higher energies are shown in Figure 2. The dominant resonance contributions are consistent with the previously identified and well-established $N(1680)\,\frac{5}{2}^+$ state and, near threshold, the $(***)\ N(1700)\,\frac{3}{2}^-$, as well as the $(****)\ N(2190)\,\frac{7}{2}^-$ at higher energies. Suggestive evidence for the presence of a second $J^P = \frac{5}{2}^+$ state around 2 GeV was also found. Evidence for other states is inconclusive. It is worth noting that questions have been raised about the existence of the $N(1700)\,\frac{3}{2}^-$ state which was not observed in several recent coupled-channel analyses based on or including π-induced reactions, e.g. [15, 24, 25].

Figure 2: (Color online) PWA results of the reaction $\gamma p \to p\omega$ at higher energies [14]. Left: Total cross section from all waves in the fit (filled squares), only t-channel waves (open squares), only $J^P = \frac{5}{2}^+$ waves (circles), and only $J^P = \frac{7}{2}^-$ waves (triangles). The cross section extracted for $J^P = \frac{5}{2}^+$ is consistent with the tail of a lower mass state and the $J^P = \frac{7}{2}^-$ cross section is indicative of a state near 2.2 GeV/c^2. The errors are statistical only. Right: Fit results of $\Delta\phi = \phi_{\frac{7}{2}^-} - \phi_{\frac{5}{2}^+}$ versus the $p\omega$ mass. The solid line used a constant width Breit-Wigner distribution for the $N(2190)\,\frac{7}{2}^-$, but a 2-pole single channel K-matrix for the $J^P = \frac{5}{2}^+$ wave. Pictures from [14].



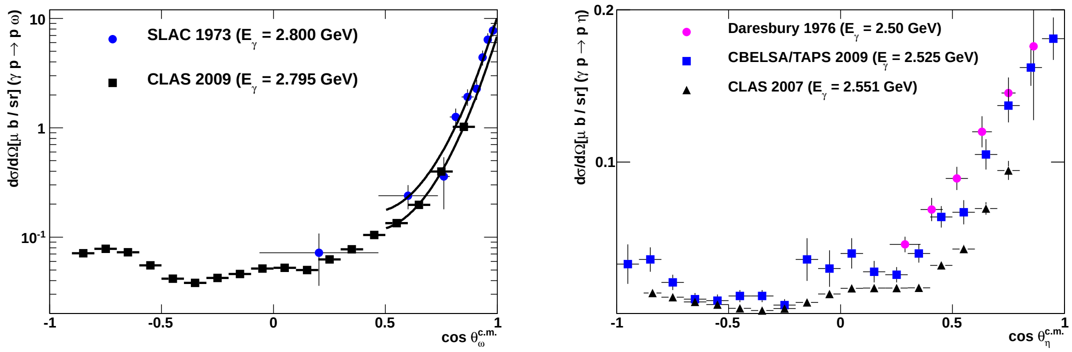
3.1 Normalization Discrepancies in Cross Section Results

Recent photoproduction data are of unprecedented statistical quality and exhibit excellent kinematical coverage. However, discrepancies among the cross section results render a combined analysis of all experimental results very challenging, see e.g. the discussion in [26, 27] for the case of η production. A rather similar normalization discrepancy of about 40 % and more at incoming photon energies at and above 2 GeV has been observed between results from CBELSA/TAPS and the CLAS g11a experiment for the reactions $\gamma p \to p\eta$ and $\gamma p \to p\omega$. Further comparisons (shown in Figure 3) of these CLAS results with older data from SLAC for the ω channel [28] and from Daresbury for the η channel [29] indicate that the CLAS g11a cross sections may be too low. Assuming an exponential behavior in the forward direction ($\cos\theta_{\text{c.m.}} > 0.5$), the ω distributions have been fitted to $a + bx + cx^2$ using a logarithmic scale for the y-axis; the coefficients b and c are identical for both data sets (Figure 3). The data are well described and the ratio of the offsets gives $a_{\text{SLAC}}/a_{\text{CLAS}} = 1.47 \pm 0.09$. This level of discrepancy is comparable with the one observed between CLAS g11a and CBELSA/TAPS. The effect could be related to an unkown trigger inefficiency in the CLAS experiment, but information is missing to further investigate the issue. Of course, normalization issues are also not excluded for the other experiments.

4. The Double-Polarization (FROST) Program at JLab

The g9-FROST program at JLab has successfully finished data-taking for all four combinations of beam and target polarization, thus providing near-complete sets of measurements for π^0, π^+, η, η', and $\pi^+\pi^-$ photoproduction. The additional determination of the recoil polarization in hyperon production, completes polarization measurements for the reactions $\gamma p \to K\Sigma$ and $K\Lambda$. More details on the experimental setup are given in [30].

Figure 3: (Color online) Left: Comparison between data for the reaction $\gamma p \to p\omega$ from CLAS g11a [14] and older data from SLAC [28] at a center-of-mass energy of $\sqrt{s} = 2.475$ GeV. Right: Comparison for the reaction $\gamma p \to p\eta$ between CBELSA/TAPS [12], CLAS g11a [13], and Daresbury data [29] for a center-of-mass energy of $\sqrt{s} \approx 2.35$ GeV. The error bars comprise statistical and systematic errors added in quadrature.



4.1 The Helicity Asymmetry E for the Reaction $\vec{\gamma}\vec{p} \to n\pi^+$

Although many of the *unobserved* baryon resonances may have small couplings to πN, it is still important to study pion photoproduction. Polarization observables will help sift the several competing descriptions of the spectrum by more conclusively indicating which resonances are involved in elastic pion-nucleon scattering, as well as providing evidence for previously unidentified resonances. New resonances found in reactions like $\gamma N \to \pi N$ are expected to have masses larger than about 1.8 GeV/c^2, although the higher-mass contributions are expected to be more important in double-meson photoproduction. The newly proposed resonances in the RPP have been observed in π production and have masses in the 1800-1900 MeV range [3].

The current database for π photoproduction is mainly populated by unpolarized cross section data and single-spin observables. Figure 4 shows preliminary results for the observable E in $\vec{\gamma}\vec{p} \to n\pi^+$ [31]. The predictions shown in the figure agree nicely with the new data at low energies (left side), but discrepancies emerge at higher energies (right side) for $W \geq 1.7$ GeV/c^2. Single-π photoproduction appears less well understood than previously expected. The present data will greatly reduce model-dependent uncertainties.

4.2 Double-Pion Photoproduction

One of the key experiments in the search for yet unobserved states is the investigation of double-pion photoproduction. Quark models predict large couplings of those states to $\Delta\pi$, for instance. The five-dimensional cross section for the photoproduction of two pseudoscalar mesons using longitudinal target polarization and circularly-polarized (or unpolarized) beam can be written in the form [32]:

$$I = I_0 \{ (1 + \Lambda_z \cdot P_z) + \delta_\odot (I^\odot + \Lambda_z \cdot P_z^\odot) \},$$

where I_0 denotes the unpolarized cross section and $\delta_\odot$ and Λ_z are the degree of beam and target polarization, respectively. The polarization observables, P_z and $I^\odot$, for the two-meson final state arise since the reaction is no longer restricted to a single plane. Figure 5 shows an example for the observable P_z in $\gamma\vec{p} \to p\pi^+\pi^-$ [33]. The variables ϕ_{π^+} and θ_{π^+} denote the angles of the π^+ in the

Figure 4: Preliminary results of the observable E (helicity difference) for $\vec{\gamma}\vec{p} \to n\pi^+$ [31]. The inner error bars indicate the statistical uncertainty; the outer error bars include a 10 % systematic uncertainty. The curves show solutions of the SAID SP09 [10], MAID [22] and SAID SM95 PWA.

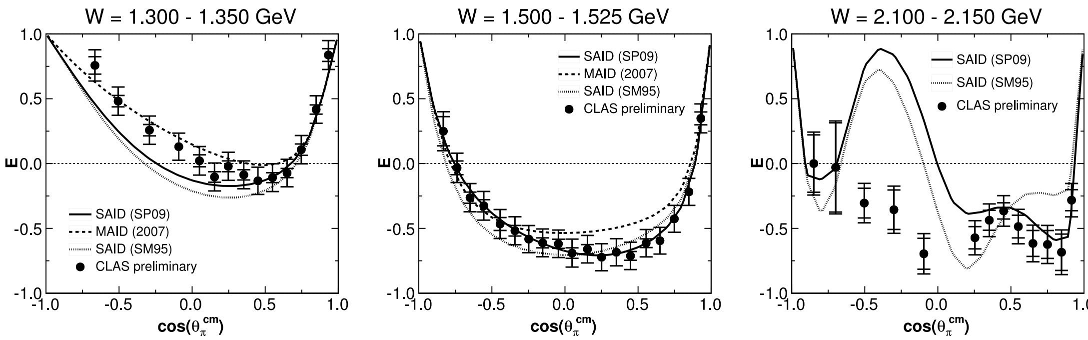
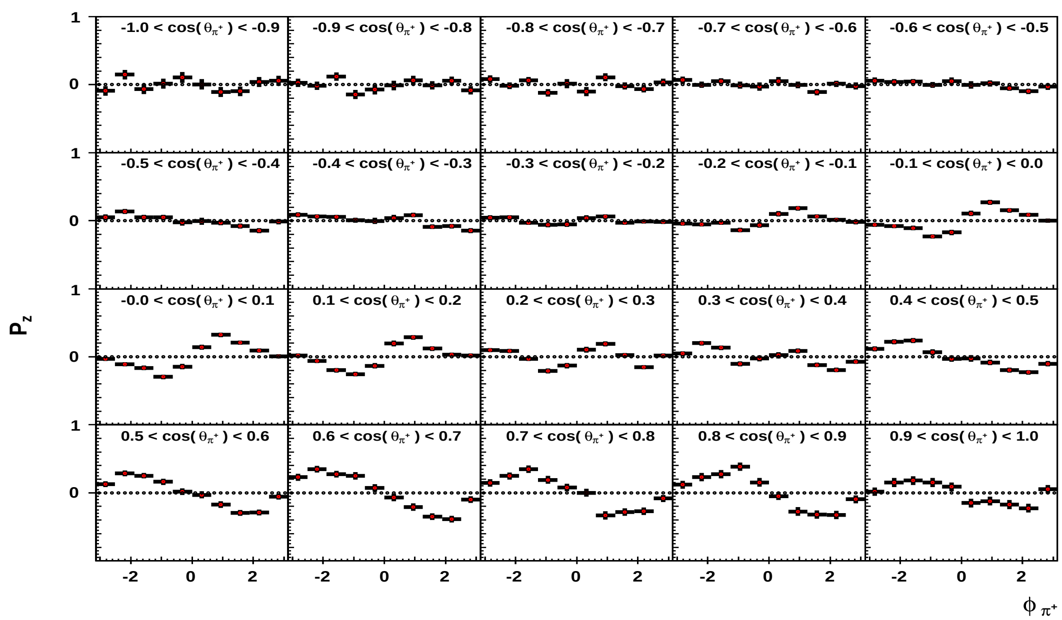


Figure 5: Preliminary target asymmetry from FROST in $\gamma\vec{p} \to p\pi^+\pi^-$ for $E_\gamma \in [0.7, 0.8]$ GeV [33]. The variables θ and ϕ are the two angles of the π^+ in the two-meson rest frame. Errors are statistical only.



rest frame of the two mesons. The observable acquires surprisingly large values for $\cos\theta_{\pi^+} > 0$ with the statistical errors in some cases smaller than the symbol size. The expected odd behavior is clearly visible.

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