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Light baryon spectroscopy

A. Thiel
Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn, Nussallee 14-16, 53115 Bonn, Germany

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One of the unresolved questions in Hadron Physics comes from the field of Baryon Spectroscopy. Here, the exact interaction between the quarks inside the nucleons is investigated via measurement of the excitation spectrum of the nucleons. Comparison to constituent quark models as well as lattice QCD calculations reveal substantial differences in the number of observed states and in the mass hierarchy of the first excitations. This proceeding will give a short recap about the current developments in the field of *Light Baryon Spectroscopy*.

Keywords: Light baryon spectroscopy; photoproduction.

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1. Introduction

One method of understanding the interaction of the quarks inside the nucleon is baryon spectroscopy. For this, the baryon is excited and the excitation spectrum extracted from measurement scattering data in order to compare it to theoretical models. The interaction between the quarks can be described by quantum chromodynamics (QCD). In the energy region of the stable hadrons, QCD is not solvable, therefore constituent quark models [1] or Lattice QCD calculations [2] are exploited to generate predictions for the excited states. Comparisons to measured data revealed differences not only in the amount of excited states, the so-called *missing resonances*, but also in the mass hierarchy of the excited states. A more detailed investigation is therefore necessary.

Due to the short lifetime of the excited states of the nucleons, the states are broad and strongly overlapping. Disentangling these states and identifying small resonance contributions poses a substantial challenge in the field of baryon spectroscopy. For this, polarization observables are an important tool. By using either polarized beam photons, polarized target nucleons or by the measurement of the polarization degree of the meson or the recoiling baryon, different observables become available. A complete overview of the observables for photoproduction of pseudoscalar mesons can for example be found in [3]. In order to determine all amplitudes without discrete ambiguities, a so-called *complete experiment*, i.e. a well-chosen set of polarization observables needs to be selected. An overview of different possible sets for various initial and final states can be found in [4, 5].

In recent years, a large amount of data sets were published by the different experiments [6, 7]. In the following, selected recent highlights of the field of *Light Baryon Spectroscopy* will be presented.

2. Experimental Facilities

In the last decade, three different experiments contributed dominantly to the field of baryon spectroscopy. First of all there is the CBELSA/TAPS experiment [37] at the ELSA accelerator facility in Bonn, Germany, which is able to excite polarized or unpolarized nucleons by circularly or linearly polarized photons with up to $E_\gamma = 3.2$ GeV. The detector setup is ideally suited to measure final states comprising photons, therefore it is focused on reactions containing neutral mesons. The second experiment is the A2 experiment [13], which is located at the MAMI accelerator in Mainz, Germany. Similarly to the CBELSA/TAPS experiment, it can perform experiments of polarized or unpolarized photons off polarized or unpolarized nucleons, although at lower beam energies. The third experiment is the former CLAS experiment [28], which was operated at Jefferson Lab. The CLAS collaboration also used polarized or unpolarized photons impinging on a polarized or unpolarized target, but in contrast to the two previously mentioned experiments, their detector setup allowed measurements of charged final states at higher photon beam energies.

3. Recent Developments

A well-measured observable for different final states is the cross section. Recently, the A2 experiment managed to extract the cross section for various final states in a previously unachieved precision. The differential cross section for $p\pi^0$ was determined with an energy resolution of a few MeV and full angular coverage [8]. With decreasing statistical uncertainty, careful investigation of systematic effects becomes necessary [9]. In addition to the final state containing a neutral pion, high statistics measurements were also published for final states with an η or η' meson [10] and even for final states containing multiple mesons [11, 12]. Additionally, cross section measurements off neutrons were published [13], which pose a substantial challenge in comparison to the proton data.

Another interesting observation was made for the final state containing an η meson. In the cross section measurement of η meson photoproduction by the A2 experiment [12], a clear cusp structure at the opening of the η' channel could be observed. This structure was expected to occur and was indeed measured in detail for the first time. Recently, a new publication by the CBELSA/TAPS experiment demonstrated

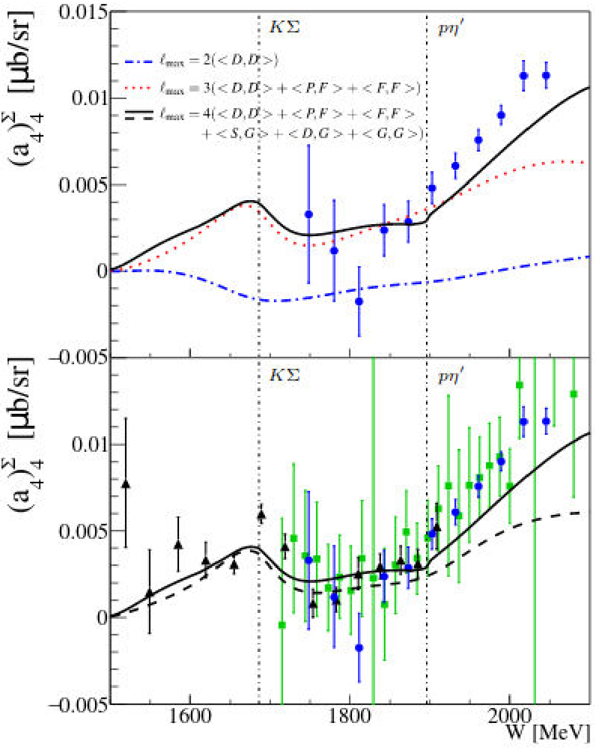

FIGURE 1. Legendre coefficient extracted from the measurement of the beam asymmetry for $\gamma p \to p\eta$ by the CBELSA/TAPS experiment [14] (blue dots), compared to previous data from the CLAS collaboration [15] (green squares) and the GRAAL experiment [16] (black triangles).

a high precision measurement of the beam asymmetry Σ for η photoproduction [14]. A Legendre analysis of this observable showed also influence of the opening of the η' phase space, as can be seen in Fig. 1. This is the first time that a cusp structure could be observed in the measurement of a polarization observable and demonstrates the necessity of high statistics measurements as well as measurements with wide angular coverage.

The η channel is especially interesting for its reactions off neutrons. Several years ago, an unidentified structure could be observed for measurements off neutrons in comparison to proton data [17]. Several experiments were able to confirm this structure [18, 19] and different suggestions for the interpretation were made. These suggestions reached from an intrinsic resonance with unusual properties [20] to coupled channel [21] or interference effects [22]. In order to shed further light on the origin of this structure, polarization measurements can provide an important tool. High statistics measurements for the double polarization observable E have been performed by the A2 [23, 24] and the CBELSA/TAPS [25] experiment. The observable E is determined from the asymmetry of the two different helicity states of the photon: $E = (\sigma_{1/2} - \sigma_{3/2})/(\sigma_{1/2} + \sigma_{3/2})$ and therefore allows for the extraction of the helicity-dependent cross sections $\sigma_{1/2}$ and $\sigma_{3/2}$, see [26]. This method was utilized and could show that the unidentified structure is only visible in the $\sigma_{1/2}$ cross section [23, 24], see Fig. 2. Additional analyses of the Legendre coefficients of the angular distributions were in good agreement with reaction model predictions assuming a narrow resonance in the P_{11} wave as the origin of this structure. Discussions also started about the possibility of a second, smaller peak in the same energy region [27].

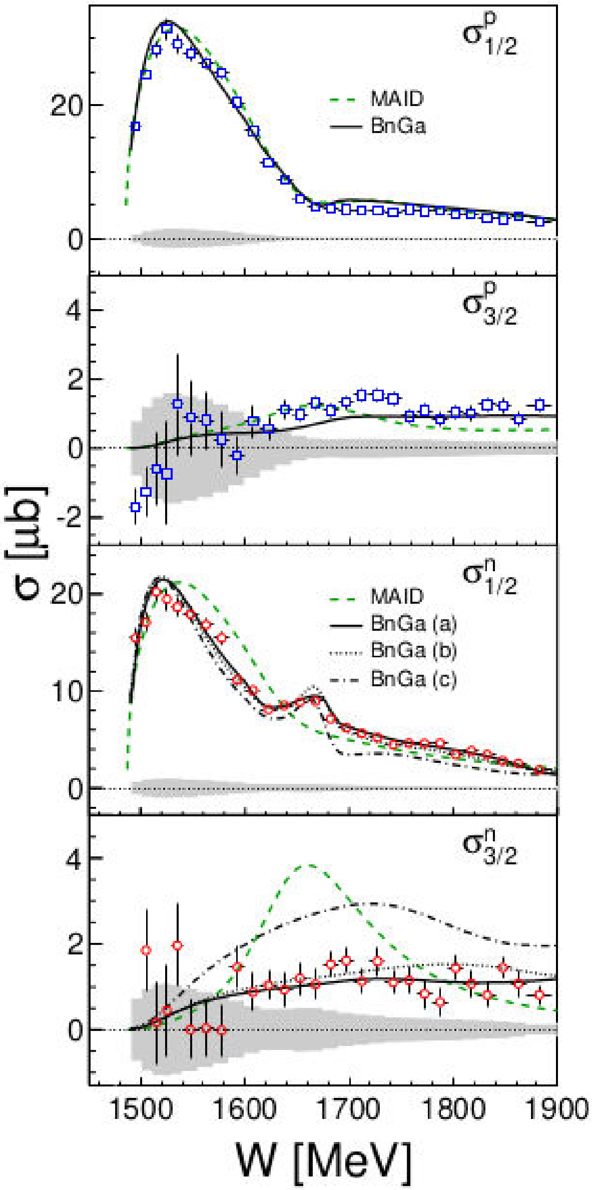

FIGURE 2. Helicity dependent cross sections for the reactions $\gamma N \to \eta N$ [23] for the proton (blue) and the neutron (red).

A significant improvement in the data base for strangeness photoproduction has been provided by the CLAS experiment. Several different measurements were analyzed and large data sets of observables for final states like $K\Lambda$ or $K\Sigma$ were published [28]. Final states containing strangeness are self-analyzing, which allow a direct extraction of observables comprising recoil polarization. This permits simultaneous extraction of multiple different polarization observables, as can be seen in [28]. These final states are the first ones in which *complete experiments* are within reach. Quadratic relationships between different polarization observables are given by the Fierz relations, see for example [29]. A large data set of extracted observables allows for the first time to exploit these relations. This gained interest due to the new measurement of the Λ decay parameter by the BESIII collaboration, which extracted a value of $\alpha_- = 0.750(9)(4)$ [30]. Their result is significantly larger than the previous value and triggered a lot of discussion, since this value is used in the extraction of observables for final states containing a Λ. An alternative method to evaluate the value of α_- was performed by [31], where they used the measured polarization observables for strangeness photoproduction by the CLAS collaboration and exploited the Fierz relations between them. In this way, an additional value of α_- could be extracted, which is in fact much closer to the new result from BESIII than the previous value [31].

In order to probe the high mass region of the excitation spectrum, the investigation of final states comprising multiple mesons can be advantageous. Excited states can de-excite into the ground states via cascading decays, which means decays via intermediate states. These intermediate states can become visible in Dalitz plots of multi-meson final states, were they can be observed as vertical or horizontal lines, see for example [32, 33]. An example of such a Dalitz plot is shown in Fig. 3. For final states comprising multiple mesons, an increased amount of polarization observables becomes accessible. Measurements of double polarization observables, which will also shed light on the excitation modes of the intermediate states, have been measured for the first time with high statistics and nearly complete angular coverage by the CBELSA/TAPS experiment [34] and will be published soon.

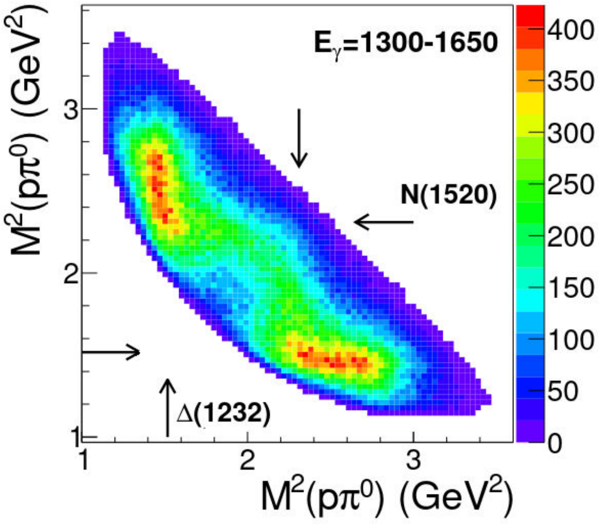

FIGURE 3. Example of a Dalitz plot for the final state $p\pi^0\pi^0$ [32]. Intermediate states can be observed as vertical or horizontal lines (see arrows).

These results are of special interest since they can shed light on the spatial wave function of the excited baryon. If the latter is expanded in a oscillator basis with two oscillators λ and ρ, see for example [32, 33], one can distinguish between states with wave functions where one or both oscillators are excited. Depending on this, the branching ratios for direct decay into the ground state and decay via an intermediate state differ, see [34].

New findings by the COMPASS experiment in the field of meson spectroscopy suggest that triangle singularities can generate structures similar to resonances in the cross sections [35, 36]. This triggered a lot of investigations and discussions also in the field of baryon spectroscopy about the origin of observed structures. Recently, the CBELSA/TAPS collaboration reported indeed an unidentified peak in the $p\eta$ invariant mass for the final state $p\pi^0\eta$ [37]. Calculations indicate that this structure could be generated by a triangle singularity where the pion of the decay of a $a_0(980)$ re-scatters with the proton of the reaction and forms a Δ resonance. Further details about this calculation can be found in [37]. More details about structures arising from triangle singularities, as also observed by the BGOOD experiment [38], can be expected in the future.

Another active topic is the discussion about the chirality restoration at high masses. This hypothesis would be confirmed by the occurrence of parity doublets, which are states of opposite parity but with identical quantum numbers and similar masses. Recent discussions were triggered by a set of Δ resonances with masses around 2 GeV [41]: $\Delta(1910)\frac{1}{2}^+$ and $\Delta(1900)\frac{1}{2}^-$, $\Delta(1920)\frac{3}{2}^+$ and $\Delta(1940)\frac{3}{2}^-$, $\Delta(1905)\frac{5}{2}^+$ and $\Delta(1930)\frac{5}{2}^-$ as well as the $\Delta(1950)\frac{7}{2}^+$. In order to complete these four sets of parity doublets, an additional state with quantum numbers $J^P = \frac{7}{2}^-$ and a mass around 1950 MeV would be expected. For this, a systematic search across different observables of multiple final states was performed, however, the next state with the desired quantum numbers was found at a substantially higher mass of $m = 2200$ MeV [42]. Therefore the expected pattern of parity doublets cannot be confirmed at this energy.

In order to extract the complete amplitudes from the measured observables, a full partial-wave analysis needs to be performed first. The amplitudes are defined by a sum over the angular momenta up to infinity. A first insight into the amplitudes and the sensitivities of the observables can be provided by a truncated partial-wave analysis (TPWA) [39]. Here, the sum up to infinity is truncated at a certain angular momentum and the resulting equations are used to describe the measured observables. Depending on the quality of this description for different cut-off values, conclusions about the sensitivity to partial-wave contributions up to certain angular momenta can be drawn. This method has been in detailed studied for the final state of $p\pi^0$ [9] and further investigations for other final states like $p\eta$ are ongoing. However, in order to fully extract all amplitudes from the observables, a complete partial wave analysis is necessary. The impact of the intensive measurement of polarization observables for the final state $p\pi^0$ can be found in Ref. [40].

4. Conclusion

As shown in this proceeding, *Light Baryon Spectroscopy* is a highly active field. Recent discoveries like cusp effects visible in polarization observables and the possible indication of triangle singularities stem from high statistics measurements, which are feasible due to the new and improved experimental setups. More precise data on even more complicated final states can be expected to be published within the next years.

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