1. Introduction

The $N^*$ series of workshop focuses on the part of the nucleon landscape where the excited states are prominent features in cross sections and polarization observables. Clearly, we can understand the complexity of the nucleon’s internal structure only if we also study the excitation spectrum and the underlying degrees of freedom. In this first talk I highlight some of the progress the community has made over the past five years or so, and touch on some of the very recent developments that we will discuss in course of this conference. The study of the $N^*$ structure (I use $N^*$ here generically for the non-strange spectrum of isospin $\frac{1}{2}$ nucleon and isospin $\frac{3}{2}$ $\Delta$) is not only an important subject of hadron physics, but it is fundamental to our understanding of the origin of the hadronic mass scale.

One of the experimental tools we employ is the study of the $N^*$ spectrum as a reflection of the underlying degrees of freedom. Excited states could be represented by a bag of 3 constituent quarks, possibly held together by glue strings, that themselves can be excited to generate gluonic or hybrid baryons. Quarks may also cluster dynamically into quark-diquark configurations with a different excitation spectrum, and resonances may be excited dynamically through meson-baryon interactions. These configurations can result in variations of the excitation spectrum which we study with hadronic and electromagnetic probes. The second line of research is to measure the strength of the resonance excitations at different distance scales. Beyond these experimental aspects there has been significant progress in the theory sector, e.g. predictions from Lattice QCD, Dyson Schwinger equations of QCD, holographic QCD, dynamical approaches and others. A number of reviews\textsuperscript{1,2,3,4,5,6} discuss many of these recent developments.
2. Search for new Baryon States

The strong hadronic couplings make most excited nucleon states very broad, often hundreds of MeV in width. Resonance parameters must be measured by measuring the coupling to the hadronic final states. This involves a separation of resonance and non-resonant processes that can both lead to the same final state. As a consequence resonances of different masses overlap and interfere. The search for new baryon states requires large amounts of data on cross section and polarization observables. Most of the states with significant coupling to single pion production may have been found already in elastic $\pi N \rightarrow \pi N$ scattering. For the past decade the focus has shifted to photoproduction. The search for new states is aimed at high statistics data sets with complete or nearly complete kinematic coverage of a number of two-body final states, such as $\gamma p \rightarrow \pi N$, $\eta p$, $KY$, both on proton and on neutron targets. Some of the higher mass states may couple to more complex final states such as $\gamma p \rightarrow p\omega$, $p\phi$, $K^*Y$ or multi-meson channels, e.g. $\gamma p \rightarrow \pi\pi N, \eta\pi N$.

Essential component for the success of the effort is the engagement of groups involved in single channel coupled-channel analyses. Figure 1 illustrates the interaction of experimental data, phenomenological models and theory predictions. QCD through lattice or DSE, or model approximations make predictions for the spectrum and e.m. couplings. The data are input to amplitude analysis supported by reaction theory to extract the spectrum and transition amplitudes.
2.1. Complete experiments

The experimental effort has shifted from the nearly exclusive use of hadronic probes to electromagnetic probes. In the search for new baryon states, complete or even over-complete experiments have become the holy grail of baryon resonance analysis. The photo-production of single pseudo-scalar mesons is described by 4 complex parity conserving amplitudes requiring 8 well-chosen measurements to determine the production amplitudes. The observables are shown in Fig. 2. In unpolarized, single and double polarization experiments, 16 observables can be measured directly. Of the 16 observables 3 double polarization observables measure also single polarization quantities (underlined in Fig. 2). Additionally, 13 triple polarization quantities are related to the cross section and 12 double polarization observables (bold face). While the 32 measurements are not independent, knowledge of as many polarization quantities as possible helps to tighten constraints and allows for systematic cross checks. Some double polarization observables have recently been published.

\[ \text{Table 2. Polarization observables in pseudoscalar meson photoproduction. Each observable appears twice in the table. The 16 entries in italics indicate the leading polarization dependence of each observable in the general cross section. The three underlined entries (\( \hat{P}, \hat{T}, \hat{\Sigma} \)) are nominal quantities that can be measured with double-polarization. Those single-polarization quantities that can be measured with triple-polarization. (See the text.)} \]

| Beam \((P^\gamma)\) | Target \((P^T)\) | Recoil \((P^R)\) | Target \((P^T) +\) Recoil \((P^R)\) |
|------------------|------------------|------------------|------------------|
| Unpolarized \(d\sigma_\gamma\) | \(\hat{t}\) | \(\hat{p}\) | \(\hat{t}\) \(\hat{p}\) |
| \(F^\gamma_{\text{un}(2\Delta)}\) | \(-\Sigma\) | \(-\hat{p}\) | \(-\hat{t}\) \(\hat{p}\) |
| \(F^\gamma_{\text{con}(2\Delta)}\) | Circular \(P^\gamma\) | \(-\hat{t}\) | \(-\hat{t}\) \(\hat{t}\) |

2.2. Open strangeness photoproduction

For the first time strangeness photoproduction has played a major role in the search for new baryon states. The very precise cross section and polarization data from CLAS in the channels \(\gamma p \rightarrow K^+\Lambda, K^+\Sigma^0\), and \(\gamma p \rightarrow K^+\bar{\Lambda}\), were critical in providing evidence for new states and for improving evidence for poorly known states especially in the positive parity nucleon sector in the most recent coupled-channel analysis of the Bonn-Gatchina group. Figure 3 shows the changes in the excited nucleon and \(\Delta\) spectrum that were included largely due to the inclusion of the strangeness photoproduction data in the analysis. In this regard some comments on the \(N(1900)^{3+}\) may be appropriate. The state is clearly seen as a peak in the fully integrated \(\gamma p \rightarrow K^+\Lambda\) cross section. It has been first identified as a \(J^P = \frac{3}{2}^+\) state in a \(K\Lambda\) coupled-channel analysis. Since then it has been more firmly established in the coupled-channel analysis with high reliability and upgraded to a *** state in the 2012 RPP edition. Subsequently the state was confirmed in two single channel analyses using an effective Lagrangian approach. Moreover,
the multi-channel partial-wave analysis of Shrestha and Manley\textsuperscript{17} finds also strong coupling of the state to the $K\Lambda$ channel. Given that the state is clearly seen in the total $K\Lambda$ photoproduction cross section, and has during the last year consistently been identified as a $J^P = \frac{3}{2}^+$ state in four independent analyses with a Breit-Wigner mass of $\approx 1900\text{MeV}$, the state may have passed the criteria of a four star state.

2.3. \textit{New nucleon candidates from charmonium decays}

A different approach in the search for N* states comes from BESIII with studies of the decay $\psi' \rightarrow p\bar{p}\pi^0$. The $p\pi^0$ mass is analyzed\textsuperscript{18} and shows some of the well-known isospin $\frac{1}{2}$ states. Above 2 GeV a large, isolated enhancement was found to represent two new N* candidates at 2300 and 2570 MeV. An interesting aspect of this reaction is that it not only selects isospin $\frac{1}{2}$ states but suppresses high spin states due to the short range interaction involved in the $c\bar{c}$ annihilation that generates the $N^*\bar{p}$ system. The suppression of higher spin states greatly simplifies partial wave analysis.

2.4. \textit{Vector meson photoproduction}

Vector meson production, e.g. $\gamma p \rightarrow p\omega$ and $p\phi$ has generally not been incorporated in multi-channel analyses. Single channel analyses of high precision data on $p\omega$ have revealed sensitivity to several excited nucleon states\textsuperscript{19,20} and show evidence for "missing" states, such as the 2-star $N(2000)^{5/2}$. The role of the $N(1535)^{1/2}^-$ has been studied in $\pi N \rightarrow N\phi$\textsuperscript{21} and new high precision data on $\gamma p \rightarrow p\phi$ have become available\textsuperscript{22}, showing features that may indicate the presence of excited states. To explore these possibilities, these data must be included in coupled-channel analyses.
Electron scattering off nucleons probes the internal structure and the effective degrees of freedom at distance scales given by the inverse of the momentum transfer \(1/|Q|\) to the \(NN^*\) system. Precise electroproduction data in channels such as \(ep \rightarrow e(p\pi^0, \pi^+ n, p\eta, p\pi^+ \pi^-)\) have been collected over the past decade and have enabled extraction of the resonance electrocoupling\(^{23,24}\) amplitudes in a wide range of \(Q^2\). Precise amplitudes for the transition from the proton ground state to the \(\Delta(1232)_{1/2}^+, N(1440)_{1/2}^+, N(1520)_{3/2}^- \) and \(N(1535)_{1/2}^-\) excited states, have been determined using Unitary Isobar Model and Dispersion Relations\(^{3,4,25}\), and reveal strong meson-baryon contributions at low \(Q^2\) for several of the states, and 3-quark dominance at higher \(Q^2\). Further transition towards elementary quark-gluon degrees of freedom is expected to occur at \(Q^2 \geq 6\text{GeV}^2\), which is reachable only at the Jefferson Lab upgrade to 12GeV beam energy.

Probing the nucleon excitation with electron beams may be the only way of identifying hybrid baryons as they are not distinct by quantum numbers from ordinary baryons, and thus can mix with the quark states. In a simple quark model with gluon degrees of freedom\(^{26}\), the lowest hybrid state corresponds to the transition in the quark ground state without orbital excitation leading to \(J^P = \frac{1}{2}^+\). The form of the \(\gamma q \rightarrow \gamma G\) vertex makes the transition form factor drop rapidly with \(Q^2\). In the leading term the longitudinal component is exactly zero. Figure 4\(^{27}\) shows data of the lowest \(\frac{1}{2}^+\) state. Clearly, the data have a completely different behavior, both for the transverse and the longitudinal amplitude, allowing us to conclude that the lowest \(\frac{1}{2}^+\) state is not a hybrid baryon. The latest LQCD projections confirm the conclusion that this state is not the lowest hybrid baryon\(^{28}\), which supports the conclusion from the transition form factor measurements as a probe of the nature of the states and the underlying degrees of freedom.

![Fig. 4. Helicity amplitudes for the Roper \(N(1440)\frac{1}{2}^+\) state\(^27\). The lines close to the data are light cone quark models predictions. The solid green lines below are are predictions of a hybrid quark model. The \(A_{1/2}\) amplitude drops quickly to 0, and the longitudinal amplitude \(S_{1/2} = 0\) in leading order.](image)
4. Outlook

During the past few years a major milestone was reached with experiments collecting data that represent complete or nearly complete measurements, especially in open strangeness production. In the phenomenological sector extensive efforts are underway to cope with the quantity and high quality of the new data in a theoretically satisfying way. At this conference, some of the fruits resulting from this effort will be discussed. The coming years promise to be a period of discoveries of new excited states and the confirmation or dismissal of poorly known states, that will lead us to a much better understanding of the systematics and the nature of the nucleon excitations. It is an exciting time to be part of this effort.

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