

Appendix G

Summary of the PAC 25 mini- workshop on the physics on Nucleon Excited States at JLAB January 17, 2004

Kingsmill Resort

Introduction

This was the fifth workshop to provide an opportunity for the Program Advisory Committee to focus on one of the five broad scientific areas that comprise the Jefferson Lab physics program. The goals of these workshops are to review the approved program in the context of recent developments, to identify the key scientific questions in the area of concentration and to suggest opportunities for future experimental work. After hearing the presentations and summarizing the discussions the following questions should be addressed according to the charge of the PAC:

- are the relevant questions in this subfield addressed optimally by the presently approved experiments?
- would extensions to or modifications of presently approved experiments provide clearer answers to these questions?
- finally, are there important open questions not addressed by approved experiments that should be added to the program?

The recent discoveries of potential members of the pentaquark family gave this mini-workshop an unexpected relevance. However, the definitive proof of existence of this new species of bound states of quarks is still lacking. Nevertheless, a tremendous excitement in the community drives the discussions about the structure of these objects and about the best way to carry out the experimental investigations. In those discussions it became obvious that a common approach to the newly discovered exotic states as well as to the conventional three quark states has to be found. Both species, the exotic states as well as the conventional resonance states, occupy the same mass range and can mix with each other if they have the same quantum numbers.

Simon Capstick presented an overview of the theoretical status for the nucleon excited states and stressed that the identification of important effective degrees of freedom in low-energy QCD provides the key for a qualitative understanding of the structures under discussion. In order to achieve a description of the full excitation spectrum, models based on QCD are required. He explained the virtues and the shortcomings of four classes of models, the gluon exchange model, the one boson exchange model, an instanton-based model, and the formation of baryon resonances as implied by chiral coupled channel dynamics. Ralf Gothe demonstrated, on well chosen examples like the N - Δ transition, the considerable progress which has been achieved to extract relevant observables to test the predictions of model calculations. In his outlook, he presented the upcoming technical improvements to extend the resonance program at JLAB. Volker Burkert showed results of the JLAB experimental investigations to identify N^* resonances, via exclusive meson production reactions, and extract from the data transition form-factors. The recently found pentaquark signatures are results on top of a program comprising 33 experiments for which the analysis of the data, in many cases, is still going on. Rolf Ent explained the use of the concept of quark-hadron

duality in the resonance region and presented a large body of precise data, mainly from JLAB, which bridge the gap for descriptions where perturbative QCD is applicable and where models have to be used. Kees de Jager reported the recent results on sum rules and the spin structure of the nucleon, based on data from JLAB. The data allowed to extract Q^{*2} extensions of the Baldin and GDH sum rule. Those results provide for all theoretical calculations the long awaited bench mark data. Lively discussions started already during the presentations and continued into the dedicated discussion session.

The highlights of the N*-program at Jefferson Lab

The presentations of the results of the N* program at Jefferson Lab and the discussion of the status of the theory provided the basis for the following general discussion. The experimental studies of quark-hadron duality yielded a wealth of data and triggered theoretical investigations addressing the question why quark-hadron duality works at surprisingly low energies. The results of these duality studies open an extended access for experimental investigations of parton distributions in the large x regime and allow for direct comparison to QCD moments. The first accurate measurements of A^{n_1} at intermediate x-values are a major achievement for the spin structure studies of the nucleon. The data provide the first convincing indication that A^{n_1} deviates from 0 at large x. This experiment needed the availability of a polarized beam and a polarized target. Another mayor achievement by performing double polarization experiments has been the determination of the Q^2 -evolution of the GDH-integral for the neutron as well as for the proton.. These accurate results provide benchmark data for extended calculations on the partonic and hadronic scales fixed at $Q^2=0$ by the GDH-sum rule and in the limit as Q^2 goes to infinity by the Björken-sum rule. Altogether those investigations address, in a more integral way, the nucleon resonance region.

Photo- and electro-induced reactions have been measured on the nucleon in the resonance region. Final states such as $N\pi$, $N\eta$, $N\pi\pi$, $N\omega$, $N\rho$, ΛK^+ and ΣK^+ have been analyzed or are in the analysis phase, mainly with the CLAS detector. The goal has been, so far, the study of transition form-factors for known resonances and the search for “missing resonances.” For example, by finding a few resonances with special quantum numbers, models like the diquark model could be ruled out. As a beautiful example of what can be achieved by investigating with a well chosen reaction, recent results of the electropion production of the N-Delta(1232) transition on the proton have been extensively presented and discussed. The $p\pi^0$ and $n\pi^+$ final states have been measured in a wide Q^2 -range. The most spectacular feature of the presented preliminary results resides in the zero crossing of the E_{1+}/M_{1+} ratio at around $Q^2 \sim 2-3$ (GeV)² indicating the onset of the region where scattering off quarks occurs. Another very interesting result has been extracted by a global analysis of the $N\pi$ data for the Roper resonance: the slope of the transition form-factor, starting from the photon point, is positive. A zero crossing occurs at $Q^2 \sim .5$ (GeV)². This result rules out several theoretical approaches using different versions of constituent quark models. Interesting signals indicating structures, possibly missing resonances, have been seen in an analysis of electroproduction data analyzing the $p\pi^+\pi^-$ final state.

The detection of possible pentaquark states may revolutionize the whole field. The analysis of three charged particles in the final state has been necessary to see signals in various channels in photoproduction experiments on the deuteron and on the proton with the CLAS detector.

Several new tools complementing the experimental set-ups, planned or under construction, have been presented:

- a frozen spin target for the CLAS detector which allows double polarization experiments with a photon beam without limiting the angular acceptance,
- the insertion of a detector(BoNuS) into CLAS for the detection of low energy protons (e.g. spectator protons in the deuteron) in order to tag neutrons as is foreseen also for BigBite in HALL A,
- a forward PbWO₄ (436 crystals) array for CLAS to carry out DVCS experiments
- a new electron Cherenkov detector optimized to detect electrons in the CLAS inverted field configuration .

The research on N* physics in the wider national and international context

Studies of the excitation spectrum of the nucleon are carried out in several laboratories worldwide. The ELSA accelerator, in Bonn, Germany, delivers a low intensity electron beam of 3.5 GeV, well suited for tagged photon experiments. With the Crystal Barrel detector consisting of 1394 CsI crystals and dedicated forward detectors almost a 4π angular coverage for multi photon final states becomes possible. Polarized photon beams and polarized proton and deuteron targets are at hand. A wealth of data of photon induced reactions on the proton with multi charged particles in the final state have been obtained and analyzed. Recent highlights of this laboratory are: 4.8σ signals for the Θ^+ and measurements of the GDH sum rule on the proton and the neutron in double polarization experiments.

At the GRAAL set-up, in Grenoble, France, a backscattered laser beam provides a polarized photon beam up to a photon energy of 1.7 GeV. A BGO-detector with large angular acceptance and a dedicated forward detector enables the investigation of photon and charged particle final states. A recent highlight of this laboratory: η -production with linearly polarized photons with a precise determination of the small η -D₁₃ coupling.

At MAMI, in Mainz, Germany, a 800 MeV, high intensity electron accelerator provides several experimental set-ups with electron and photon beams. The N*-program has been driven by a high flux tagged (polarized) beam in combination with dedicated detector set-ups for neutral and charged particles. Highlights of this program were the precise determination of the threshold cross sections for π^0 and η production as well as the determination of the E_{1+}/M_{1+} ratio of the N-Delta(1232) transition on the proton. The doubling of energy and the installation of new detector systems like the Crystal Ball detector enable for the future a vigorous program with real and virtual photons up to $E_\gamma = 1.6$ GeV.

With a laser backscattered polarized photon beam at LEGS, in Brookhaven, USA, a photon energy range of up to $E_\gamma = 450$ MeV can be covered. The final state detection is optimized with dedicated detector systems, especially for the detection of π^0 's and γ s. A highlight has been the extraction of the E_{1+}/M_{1+} ratio of the N-Delta(1232) transition on the proton by using simultaneously the data of π^0 -production and Compton scattering.

Last but not least, the backscattered laser beam of SPRING8, in Hyogo, Japan, provides a polarized photon beam up to a photon energy of $E_\gamma = 2.4$ GeV. Its present speciality is the detection of charged particles in the final states, especially under forward direction. The recent highlight, certainly, has been the signature for a Θ^+ on carbon.

Questions and suggestions in the general discussion

The general discussion began with the impression created by the five presentations. Many questions and suggestions came up, especially, concerning the explicit studies of the nucleon excitation spectrum.

- What is the coherent message that can be found by comparing the inputs and results of the different models?
- A systematic study of conventional as well as hybrid and exotic states should be undertaken.
- Very quickly the discussion centered on the question: are we able to disentangle all relevant multipoles, model independently?
- Even the beautiful data for the N-Delta(1232) transition like the signature of a turnover of the E_{1+}/M_{1+} ratio at around $Q^2 \sim 2-3 \text{ (GeV)}^2$ is not considered convincing as long as in extracting this ratio from the data no contributions of the higher partial waves are included.
- How can one hope to isolate the different broad resonance excitations in an unambiguous way?
- A strong case has been made for a combined effort to create a kind of Excited Baryon Analysis Center which coordinates the activities and develops the tools for a fully coupled channel analysis including all final states, in all spin and isospin channels. The feeling has been that if the manpower can be provided such an ambitious program can be carried out.
- It was felt that high priority should be given for experimental investigations of reactions for which a complete set of amplitudes can be extracted, model independently, like in the photoproduction of kaons by measuring the reactions $\gamma + p \rightarrow \Lambda + K^+$ and $\gamma + n \rightarrow \Lambda + K^0$ with polarized beams and targets and using the weak decay of the Λ to determine the recoil polarization of the Λ .
- To achieve decisive progress in theory, a reliable data base has to be established. In addition, it can be expected that intensified activities in lattice gauge theory will come up with results which help to discriminate between the different theoretical models.

The investigation of the nucleon excitation spectrum

Before responding to the questions posed by the Lab explicitly, it might be helpful to lean back a little bit and put the whole subject matter in perspective with the mission of the Lab. The investigation of the structure of the nucleon constitutes one of the main missions of the Lab. There are two methods in physics to address experimentally questions concerning the structure of composed entities in the micro-cosmos: scattering and spectroscopy. It is the combined use of these methods which may lead to a solution to the complex task before us. Expertise in reaction physics is needed as well as in structure physics. The task is very complex and difficult to solve. Thus it is important at this point to remind ourselves of what is at stake.

What is the goal?

In his introductory talk at Baryons 98 Nathan Isgur set the stage to motivate an intense experimental as well as theoretical effort to study baryons. He wanted to see the answers to these questions:

- What are the important degrees of freedom?
- What is the physical origin of color confinement?
- Why is the low energy spectrum dominated by what appear to be $qq\bar{q}$ and qqq systems?
- Where, as a corollary, are the excitations of the gluonic degrees of freedom?
- Where are the excitations of the sea quark degrees of freedom?
- Why is a nucleus made of nucleons, instead of a “quark soup”?
- What is the origin of the well-established empirical nucleon-nucleon force?

Other questions, like issues of chiral symmetry and its breaking and the vacuum structure of QCD are implicitly contained in the questions.

What is necessary to do on the experimental side?

It has been recognized, long ago, that several key questions concerning the forming of structures in low energy QCD can be addressed by studying the complete spectrum of excited states. This includes the determination of position and width of the excited states as well as their quantum numbers, decay branching fractions and the extraction of the photocouplings and transition form-factors up to the highest momentum transfers. In uncovering the different layers of structures in nature, the problems and the solutions are very often similar. The main experimental tool behind all the theoretical speculations of the early 20th century was spectroscopy. Sommerfeld wrote in 1919 that the problem of the atom would undoubtedly be solved once physicists had learned to understand the language of spectra. What was true at that time for the structure of atoms, is probably true today for the structure of baryons and mesons.

General observations concerning the nucleon

In this situation the challenge resides in establishing the data base from which the spectra can be extracted; then, the language of spectra can hopefully be understood. What are the problems, experimentally, to identify all excited states of the nucleon? A first glance on the total gamma absorption cross section provides a clue to the problem: three broad peaks, on the low energy part of the excitation spectrum, stand up on a large, almost constant background. The measurements of the total partial cross sections of the reactions $\gamma + p \rightarrow p + \pi^- + \pi^+$ and $\gamma + p \rightarrow p + \pi^- + \pi^+ + \pi^0$ provide a large part of the strength of the total absorption cross section up to 3 GeV but show no structure either. Broader resonance structures can be identified in t-distributions of the ρ and ω channels, reconstructed from the $\gamma + p \rightarrow p + \pi^- + \pi^+$ and $\gamma + p \rightarrow p + \pi^- + \pi^+ + \pi^0$ -data. The large, almost constant background as the dominant part of the total cross section, for $E_\gamma \geq 1\text{GeV}$, can be successfully parametrized by a Regge-fit describing the cross section to the highest available photon energies with the same parameters. The general message becomes clear: rather broad resonances stand up on a scale which is 1-2 orders of magnitude smaller than the total absorption cross section.

Performing double polarization experiments opens up a way to suppress the non resonance background almost completely, as the results of the recently finished measurements of the polarized total cross section difference, $\sigma_{3/2} - \sigma_{1/2}$, have shown. The investigations of $\gamma + p \rightarrow p + \eta$ and $\gamma + p \rightarrow p + \eta'$ reactions open another way to search efficiently for certain classes of resonances without large background contributions. At γ -energies larger than ≈ 2 GeV, resonances seem to prefer to decay via sequential decays like $\pi^+ + \pi^0$, $\eta + \pi^0$, $\pi^- + \pi^+$ In any case, in order to extract in a coherent way from the data a complete set of observables which can be confronted with theory, a partial wave analysis has to be performed including each channel. The degree of ambiguity can be reduced considerably by measuring differential cross sections, single and double polarization asymmetries.

The necessary experimental equipment

To carry out a program of systematic studies of the excitation spectrum of the nucleon, photo- and electro-production experiments have to be performed with detectors which have large acceptance for charged and neutral particles. Polarized beams and targets with sufficient luminosities are as important to study the spin-structure of the nucleon as proton and neutron targets to explore the isospin-structure. For well selected cases, in special kinematics, spectrometer set-ups are best suited to carry out the measurements.

Are the relevant questions in this subfield addressed optimally by the presently approved experiments?

All investigations studying in a more integral way the nucleon resonance region like questions of the duality and sum rules are addressed optimally by the presently approved program. The program, more specific to the resonance region, conveys another impression. Looking at the program on the books, in total 33 experiments, more than half of the experiments deal with single pion production, almost all on the proton. In addition, the final channels $\omega+p$, $\eta+p$, $K+\Lambda/\Sigma$ and $\pi^+ + \pi^- + p$ make up for the rest of the program of the investigations of the conventional resonance research. Vector meson and the kaon channels hold the promise of the discovery of resonant states which are missing thus far. Recently, the pentaquark research on the proton and the neutron has been added. With those spectacular discoveries the potential of the CLAS set-up for investigations of the hadron spectroscopy has been demonstrated. However, it is clear from what has been said in the general discussion and the following chapters that in order to address optimally the salient features of the excitation spectrum of the nucleon, systematic studies of the nucleon spectrum have to be carried out. In this respect, the program on the books has to be considered as the opening phase of a more systematic program. With data analyses in progress, many new results can be expected in the near future. However, any such results will need verification by means of a concerted multi-channel analysis effort from both inside and outside the lab.

Would extensions to or modifications of presently approved experiments provide clearer answers to these questions?

The necessary studies in the framework of a systematic program of the nucleon spectrum comprise the investigations of the spin and isospin responses as well as the extension of the observation of the meson multiplicities in the final state which opens the route to the measurement of sequential decays.

The already visible extensions due to the implementation of experimental equipment leading to such a systematic program are:

- systematic measurements on the neutron and proton, Bonus, and Big Bite which will lead to: *isospin decomposition of the amplitudes*.
- frozen spin target for CLAS, which allows one to perform double polarization experiments with large acceptances for tagged photons and will lead to: *measurements of the spin structure and a suppression of non resonance contributions*.
- luminosity increase for CLAS-experiments, using higher computer power and a more specific trigger by means of higher segmentation of the start detector will lead to: *an extension to higher multiplicities in the final state and thus to observation of sequential decays of resonances*
- strengthening of the manpower at JLab by adding manpower for data analysis at the interface experiment-theory will lead to: *the step from beautiful data towards results and answers to the physics questions asked in the chapter “What is the goal”*

These steps extend the specificity of the observables, increase the body of data and help to establish powerful analysis tools. Small amplitudes can be extracted via interference effects. Further necessary extensions on the way to a systematic investigation of the excitation spectrum of the nucleon are:

- a dynamically polarized spin target for large acceptances, opens the door for double polarization experiments with an electron beam and *adds the knowledge of the Q^2 -response of the resonances*.
- an extended capability to measure neutral, (e.g. γ), channels in the final state which enables the *observation of sequential γ -decay of resonances*.

The final point will be achieved, at latest, with the Hall D detector which opens up a new round of experiments for meson and baryon spectroscopy.

The described effort on the experimental side should lead to dramatic progress on the theory side also. So one can hope for clearer, and perhaps even definitive, answers to the difficult questions being asked in this challenging field of hadron physics.

Finally, are there important open questions not addressed by approved experiments that should be added to the program?

The dramatic developments in recent months answer this question. Yes, one can expect that there will be plenty of new proposals for measurements dedicated to this new area. After the series of photoproduction experiments, more specific proposals addressing the structure of the pentaquark family by using electroproduction experiments can be expected. The use of a spin and isospin decomposition of the response function will be as important as the various decay channels of resonances. And again, new insights will come from careful multichannel analyses of the data. Future investigations will be unable to answer an important open question by one or two experiments. It will become more and more important to formulate a program in order to solve a complex of questions. The electromagnetic interaction provides, besides energy and momentum transfer, a wealth of quantum numbers in the initial state. By performing e.g. a complete experiment, as for kaon production, a complete set of isospin amplitudes could be extracted over the whole excitation spectrum. The isovector, isoscalar even and odd pieces reflect the hadronic composition of the photon and the response of the hadronic system to it. Unfortunately, the most interesting information about structure very

often resides in the smaller pieces of the amplitudes. The nucleon σ -term provides a good example in this respect for the case of pion nucleon scattering. An intimate interaction between theorists and experimentalists is necessary, to identify such complexes of most relevant questions.