EXCITATION OF NUCLEON RESONANCES

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I discuss developments in the area of nucleon resonance excitation, both necessary and feasible, that would put our understanding of nucleon structure in the regime of strong QCD on a qualitatively new level. They involve the collection of high quality data in various channels, a more rigorous approach in the search for "missing" resonances, an effort to compute some critical quantities in nucleon resonance excitations from first principles, i.e. QCD , and a proposal focussed to obtain an understanding of a fundamental quantity in nucleon structure.

1 Introduction

It is not easy to give an "OUTLOOK" talk after we have heard so many interesting new results, and most speakers talked already about plans for the future. So, I will be just speaking about a few selected aspects of nucleon resonance physics where progress may be possible in the next few years. I will point out a few areas where there have been significant advances recently, and where we may expect important progress soon. Finally, I want to present to the community a proposal for a focussed effort to study the Q^2 evolution of the generalized Bjorken integral from small to large distances. If successful, this would be an *important milestone of nucleon structure studies.*

Electromagnetic production of mesons, which is what we are doing when studying resonances, may be crudely characterized by 3 regions representing different distance scales. At large distances, say 1 fm, we study nucleon properties near the surface. Nucleons and pions are the relevant degrees-of-freedom. Chiral perturbation theory describes many phenomena, and is linked to QCD via chiral symmetry and chiral symmetry breaking. At the other end, at very small distances, we probe the parton structure of the nucleon. Elementary quark and gluon fields are the relevant degrees of freedom used in perturbative QCD. This workshop has been mostly about the regime of intermediate distances, where the excitation of baryon resonances is prominent. Quarks and gluons are relevant; however, they interact more like constituent quarks and glue. This domain is currently addressed theoretically by quark models, flux tube models, QCD sum rules, instanton models, etc., with some success. The relationship of these approaches to QCD is often not fully developed, making it difficult to assess the accuracy of the model prediction.

The regions of different distance scales are likely not strictly separated

from each other. This should provide areas of overlap where different theoretical approaches can be used to compute the same observables, thus allowing important checks of the range of validity of a specific approach. What I see as an important task for the community is to anchor more firmly these descriptions to the fundamentals of QCD, and finally come to an understanding of resonance phenomena and nucleon structure from the largest to the smallest distances within fundamental theory.

Nucleon structure studies are often associated with deep inelastic scattering where the interpretation of data in terms of the underlying degrees-of-freedom is usually more straightforward. However, quark structure function measurements and the test of asymptotic sum rules are only one small area of the nucleon structure to be explored, and certainly not the one most strongly related to QCD. Strong interaction plays no role in asymptotic sum rules, and the determination of quark structure functions is related to QCD only via secondary effects such as gluonic corrections. It is understanding the measured parton distributions that is the real challenge for QCD.

Information on nucleon structure from formfactors or nucleon resonance excitations is much richer, albeit more difficult to interpret. Nevertheless these are quantities closer to the "real" world, and they need to be described and understood in terms of the underlying degrees-of-freedom if we want to make progress.

2 The $\gamma N \Delta(1232)$ transition - from precision experiments to precision calculations.

This is the region where we aim for precision. The $\Delta(1232)$ is the only resonance that is well separated from all the higher mass states. At low Q^2 the $\Delta(1232)$ has the largest cross section. There has been considerable progress in experiments and analyses over the past 5 years or so. The uncertainties in ratios of multipoles $R_{EM} = E_{1+}/M_{1+}$ and $R_{SM} = S1+/M_{1+}$ have been reduced by an order of magnitude since the early studies. This now allows sensible comparisons with model predictions. One of the most noteworthy results is the quantitative realization that a description of the $N\Delta(1232)$ transition requires the inclusion of pions as effective degrees of freedom. A simultaneous description of both ratios is achieved only by models that include pion d.o.f[1]. Also the total absorption cross sections for the $N\Delta(1232)$ transition is well described by models that include pion cloud effects.

A more precise description of quantities such as R_{EM} in lattice QCD (LQCD) is long overdue. The only LQCD "prediction" of R_{EM} is nearly a decade old[3] and "predicts" a value of $3 \pm 8\%$ at the photon point, while

the experimental value is $(-2.75 \pm 0.50)\%$, where the experimental error is estimated generously. An order of magnitude smaller LQCD error is needed to have any impact here. A simple extrapolation of the computer performance using Moore's law, gives precisely the factor ten needed for progress. The next step would be to evolve this quantity in Q^2, and compute the magnitude of the magnetic transition multipole vs Q^2. This would mark real progress on the lattice!

We also would like to know whether the apparent trend in the R_{em} data really indicates[2] that there will be a zero crossing at $Q^2 \approx 4\text{GeV}^2$. This may give us a clue where leading order pQCD contributions may have some relevance. Since the signal/background at high Q^2 will be a lot smaller we also need to refine our analysis techniques and collect more data that give us more direct information on background contributions. Beam spin asymmetries as well as other polarization observables are needed to reduce the model-dependenc of the analysis techniques at high Q^2.

3 The 2nd Resonance Region

The so called 2nd resonance region, comprising the mass range from 1.4 to 1.6 GeV, is of particular interest for nucleon structure studies. It contains 3 states, the $N(1440)P_{11}$ "Roper", the $N^*(1535)S_{11}$, and $N^*(1520)D_{13}$ states, all of which are highly interesting for the study of nucleon structure properties, and for the testing of basic symmetry properties.

3.1 Mysteries of the Roper resonance $N(1440)P_{11}$

A natural candidate for detailed studies beyond the $\Delta(1232)$ would be the Roper resonance $N(1440)P_{11}$. However, more than 35 years after its discovery its structure is basically still unknown. The non-relativistic constituent quark model (nrCQM) puts its mass above 1600MeV, the photocoupling amplitudes are not described well, and the transition formfactors, although poorly determined, are far off. Relativized variations of the nrCQM improved the situation only modestly. To obtain a better description of the data a number of alternative models have been proposed. Does the Roper have a large gluonic component[4]? Is it a small quark core with a large pion cloud[5]? Is it a nucleon-sigma molecule[6]? Or, is it not a single resonance but two appearing in different reactions differently[7]? These questions will be discussed at future workshops, however, it is crucial to get more precise electroproduction data, as it is the Q^2 dependence where the models differ strongly. From the model builders we must require that their models make predictions for the

electromagnetic couplings and formfactors.

There is also some good news: lattice QCD calculations are beginning to produce results for the mass of the Roper which may soon be accurate enough to have a real impact.

3.2 The $N^*(1535)S_{11}$ and $N^*(1520)D_{13}$, and the $[70, 1^-]$ supermultiplet

There is some good news from the constituent quark model. The slow fall-off of the transverse $N^*(1535)S_{11}$ transition formfactor, which has been a problem for model builders for a long time, is now quite well described by the CQM using a potential containing a Coulomb form and a linear term[8]. At the same time the $A_{1/2}$ amplitude of the D_{13} is described as well, while there remains a large discrepancy for the $A_{3/2}$ amplitude at small Q^2. Could this be explained by pionic contributions which then would have to contribute to the helicity nonconserving (nonleading) term but not to the helicity conserving (leading) amplitude? Calculations that include pionic contributions explicitly are needed to answer this question.

Another piece of good news comes from LQCD. As already discussed at the previous workshop[9], mass predictions for the lowest N^* state with negative parity agree well with the experimental values. The obvious next step would be to compute the $A_{1/2}$ amplitude for that state at the photon point in LQCD.

For a better understanding of the Roper as well as the $N^*(1520)D_{13}$, data in the $n\pi^+$ channel are crucial to obtain more complete isospin information. Also, beam spin asymmetry measurements will give information about the background amplitudes which are especially important in that mass region. Such data have been taken and are currently being analyzed[11].

The ordering of excited states according to the $SU(6) \otimes O(3)$ symmetry group and the assumption that excitations are due to a single quark transition (SQT) allows predictions for a large number of states belonging to the same supermultiplet based on only three known amplitudes. In the case of the $[70, 1^-]$ the $N^*(1535)S_{11}$ and the $N^*(1520)D_{13}$ may serve that purpose. These are the only states in this multiplet whose transition amplitudes have been measured with some accuracy. This allows tests of the SQT assumption, and how the symmetry will break down as a function of the distance scale. While the predicted photocoupling amplitudes are in quite good agreement with the data, there are not enough data at finite Q^2 to test this simple model at shorter distances. The lack of data for two of the prominent states, the $\Delta(1620)S_{31}$ and $\Delta(1700)D_{33}$, is largely due to the complete lack of data in the $N\pi\pi$ channel. Also, amplitudes for neutron resonances are absent for all

states. This situation will hopefully change soon with new data from CLAS[10].

4 Missing baryon resonances

Understanding the fundamental structure of baryons remains the main focus of the N^* progam. There is now a significant effort underway to search for some of the states predicted by the symmetric quark model[12] that have not been seen in πN scattering. The importance of this effort lies in the fact that these states can tell us much about internal baryon structure. For example, models that do not have approximate SU(6) symmetry may not predict some or even many of these states to exist[15]. Some of these states are predicted to couple to $\Delta\pi$, $N\omega$, Y^*K, and other hadronic channels, as well as to photons[13]. Photo- or electroproduction may therefore be the only way to search for some of these states. Experiments at GRAAL, JLab, ELSA (Crystal Barrel), Spring-8, and BEPC have begun a vigorous search employing large acceptance detectors[16]. This effort is accompanied by a theoretical effort to understand how these resonances might show up in experimental observables[17,18].

There are indications for one or even two of such states which have been discussed at this workshop. Some of this evidence is, however, due to improvements that model curves show in comparison to data in case such states are included. Clearly, this is not sufficient. Other partial wave contributions need to be tested and excluded. For the evidence to be fully convincing, partial wave analyses must be done that seek to analyse such states in the energy-dependence of partial-wave amplitudes and their phase motion.

The strangeness sector offers excellent prospects in the search for missing states. Hyperon resonances are more narrow than states made of u and d quarks only, and they can be separated more easily from other overlapping resonances[19].

Another kind of "missing" baryons are the gluonic excitations or "hybrid" states where the "glue" or flux tubes are excited and produce a $|q^3G>$ state. They have been predicted in bag models and flux tube models. Lattice QCD predicts such states in the meson sector. They are likely expected in the baryon sector as well, although no LQCD calculations have been performed. In distinction to the meson sector no exotic quantum numbers are expected in the baryon sector. This will make it experimentally more difficult to identify gluonic excitations. QCD sum rules[20], flux tube[21], and bag models[22] predict the lowest gluonic states to be P_{11} or P_{13} with masses between 1.5 GeV for bag models and QCD sum rules, and 1.8 - 1.9 GeV for the flux tube model[21]. Possible signatures could be the overabundance of states, unusual

decay channels, form factors which are different from the 3-quark sector due to the larger sizes of $|q^3 G >$ states, and different threshold behavior due to different $SU(6) \otimes O(3)$ assignment. Another possibility is the production of hybrid states in the gluon rich environment of J/ψ decays[23].

None of these signatures alone will be convincing. It will take various pieces of evidence, and a good understanding of these states within models that treat 3-quark states and gluonic states on an equal footing, to have sufficient confidence in any discovery in this area.

5 The nucleon spin integral from small to large distances - A proposal for the next 5 years

Coming back to the goals outlined in the introduction one may ask what quantities are most directly accessible to a description within fundamental theory. As "fundamental" I would characterize exact sum rules, such as the GDH and Bjorken sum rules, QCD, pQCD, and chiral perturbation theory. I will argue that $\Delta \Gamma_1^{pn}(Q^2) = \int [g_1^p(x, Q^2) - g_1^n(x, Q^2)] dx$ is such a quantity.

What would be the significance of such a project? Why is it important, and why should the N^* community be involved in this? Clearly, from a physics perspective such a project, if successful, would be a milestone, as it would *mark the first time a fundamental quantity of nucleon structure is described by fundamental theory from small to large distances*, a worthwhile goal of nucleon structure physics, and worth a serious effort by the community. First, the expertise of the N^* community is important as nucleon resonances make significant contributions to the spin integral at medium and large distances[24,25]. Second, such a project provides a focus for the community to solve a fundamental problem. Third, the description of the resonance contributions to the first moment in LQCD may be the biggest effort, and there are proposals from within the community to have significant computing resources available for nucleon structure studies in the next five years, that can be brought to bear on such a project.

5.1 What is the experimental and theoretical situation?

The experiments to measure polarized structure function $g_1(x, Q^2)$ in a large Q^2 range are far along as has been reported at this conference[26,27]. The deep inelastic regime has been studied for decades, and good data are available for $Q^2 > 1.5 GeV^2$ mostly for the proton but also for the neutron. Experiments at JLab in CLAS and in Hall A are near to final results for the range in $Q^2 = 0.1 - 1.0 \, \text{GeV}^2$. These data currently require an extrapolation at small x
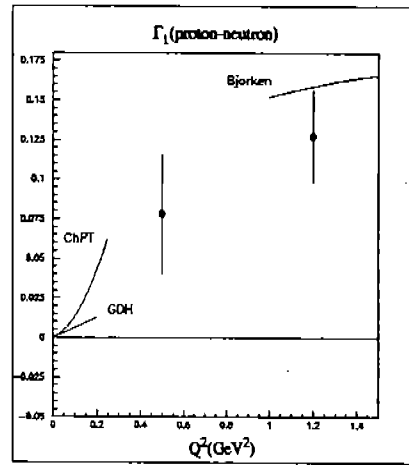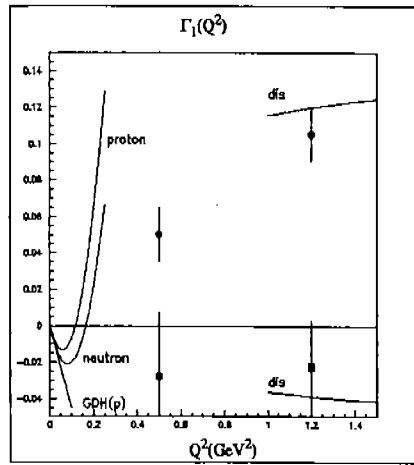
Figure 2

Figure 1. First moment of the spin structure function $g_1(x, Q^2)$ for the proton and neutron (left), and for the proton-neutron difference (right). The curves above $Q^2 = 1\text{GeV}^2$ are pQCD evolutions of the measured Γ_1 for proton and neutron, and the pQCD evolution for the Bjorken sum rule, respectively. The straight lines near $Q^2 = 0$ are the slope given by the GDH sum rule. The curves at small Q^2 represent the NLO HBChPT results.

which adds a small systematic error in the low Q^2 range, however, a significant uncertainty at $Q^2 > 1$ GeV^2. This situation is changing with the new data taken with CLAS in the energy range from 1.6 - 5.75 GeV, and in Hall A with an upcoming experiment at very small Q^2. Also, uncertainties in the extraction of the neutron contribution from measurements on ^3He require an improved treatment of the nuclear effects at small Q^2 where uncertainties are significant.

Within this year the first complete information on $\Gamma_1^p(Q^2) - \Gamma_1^n(Q^2)$ should be available in a Q^2 range from 0.1 - 1 GeV^2 from JLab experiments. At the same time, information on the proton and the neutron separately will be available as well. The current theoretical situation is illustrated in Figure 1. The left hand panel is for the proton and for the neutron separately. The high Q^2 behavior has been measured, and is known to approach a constant value. The asymptotic behavior has been evolved to lower Q^2 in perturbative QCD to order α_s^3. This is shown by the lines labelled "dis". At the low Q^2

end we have the GDH sum rule believed to be valid at the photon point. It also defines the slope of $\Gamma_1(Q^2 \to 0)$. The slope is negative for both proton and neutron. Heavy Baryon Chiral Perturbation Theory (HBChPT) has been used[28] to evolve the GDH integral to finite Q^2. The curves are from NLO calculations. Unfortunately, for the proton and neutron this expansion appears to break down already at very small Q^2. A potential problem in these calculations is the treatment of the $\Delta(1232)$. To avoid this problem we take the proton-neutron difference, where this contribution is not present. The result is a dramatic improvement in the low Q^2 description of the apparent trend of the data[29]. Q^2 values up to 0.25 GeV^2 or higher might be reachable in this quantity. Taking the proton-neutron difference $\Delta\Gamma_1^{pn}$ is also suggested from the behavior in the deep inelastic regime where the Bjorken sum rule[30] establishes an important constraint for the absolute normalization of the first moment, which has been verified experimentally within 5-10%

The combination of two fundamental sum rules at the opposite sides of the distance scale, with the pQCD evolution at small distances and the ChPT evolution at large distances provide powerful constraints for the Q^2 evolution of that quantity throughout the entire distance scale. This provides a unique opportunity to describe $\Delta\Gamma_1^{pn}$ within fundamental theory. This may require going to higher order in ChPT, and to lower Q^2 in the Operator Product Expansion of pQCD. In addition, it may be nessecary to employ lattice QCD to cover the intermediate distance scale and provide an overlap with both the higher and the lower Q^2 domains. These calculations must be confronted with precise measurement of resonance contributions to the spin integral.

Closing remarks

As the last speaker of this workshop I have the honor, and the pleasant obligation and opportunity, to express the gratitude of the participants at this workshop to the organizing committee and its chairman, Dieter Drechsel, for an excellent scientific program, organized in a most friendly atmosphere, for the superb food, and for providing the opportunity for in-depths discussions with collegues and friends. For this we say

D a n k e !

In memoriam

One of our best, who is no longer is with us, Nimai Mukhopadhyay, a friend to many of us, and a champion of nucleon structure studies and of baryon resonances, was sorely missed at this workshop. Nimai made many important

contributions to this field, and organized workshops like this one. We can honor his name by making baryon resonances an even more visible part of nucleon structure studies in the years to come.

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