PROBING THE STRUCTURE OF NUCLEONS IN THE RESONANCE REGION

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Status, open questions, and future prospects of the physics of excited nucleons, and what they tell us about the internal nucleon structure are discussed.

1 Introduction

Electromagnetic production of hadrons may be characterized according to distance and time scales (or momentum and energy transfer) probed in the interaction. This is illustrated with the three regions in Figure 1. For simplicity I have omitted the time scale. At large distances mesons and nucleons are the relevant degrees of freedom. Due to the limited spatial resolution of the probe we study peripheral properties of nucleons near threshold for pion production. Chiral perturbation theory describes many of these processes and has a direct link to QCD via (broken) chiral symmetry. At short distances (and short time scales), the coupling involves elementary quark and gluon fields, governed by perturbative QCD, and we map out parton distributions in the nucleon. At intermediate distances, quarks and gluons are relevant, however, confinement is important, and they appear as constituent quarks and glue. We study interactions between these constituents via their excitation spectra and wave functions. This is the region where the connection to the fundamentals of QCD remains poorly established, and where JLab experiments currently have their biggest impact. These regions are not strictly separated from each other but overlap, and the hope is that due to this overlap the nucleon structure may eventually be described in a more unified approach, based on fundamental theory, from small to large distances. Because the electromagnetic probe is well understood, it is well suited to provide the data for such an endeavor.

1.1 Structure of the Nucleon at Intermediate Distances - Open Problems

QCD has not been solved for processes at intermediate distance scales. A direct consequence is that the internal structure of nucleons is poorly known. On the other hand, theorists are often not challenged due to the lack of high quality data in many areas. The following are areas where the lack of high quality data is most noticeable, and where data from CLAS are expected to

Exclusive Hadron Production

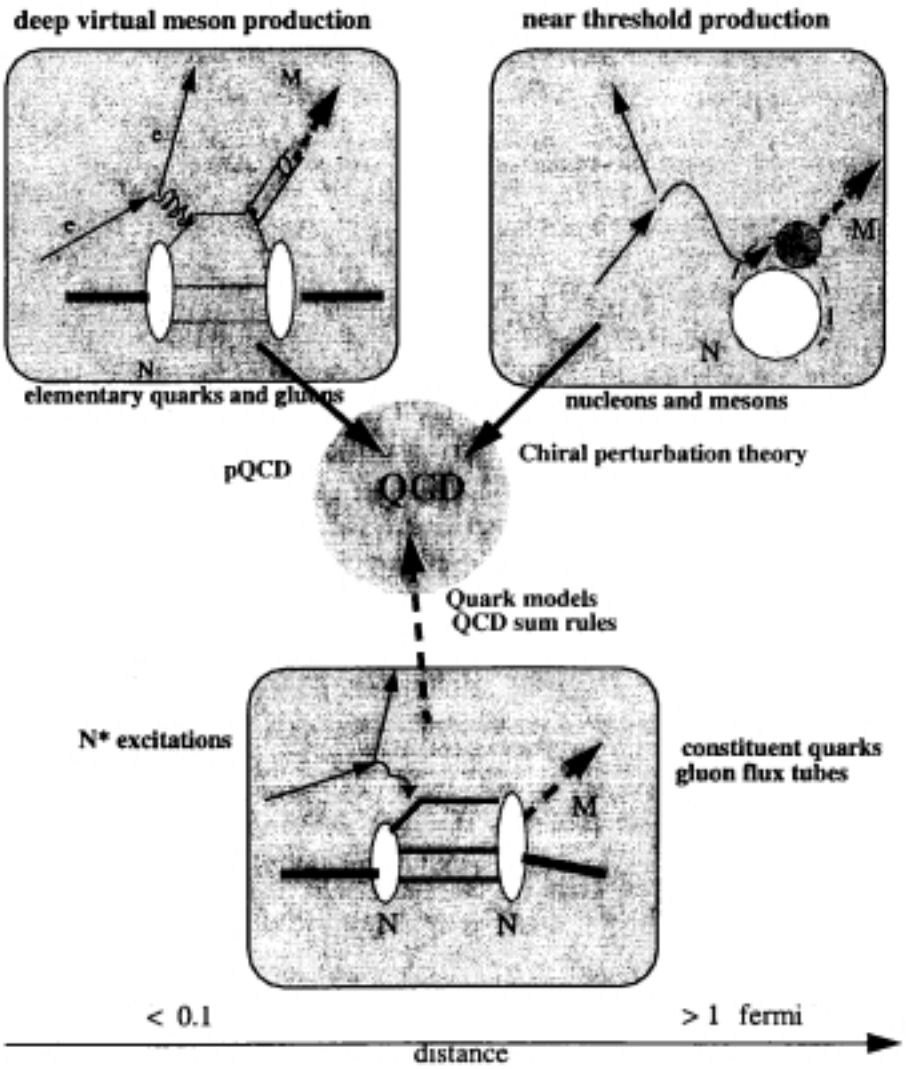

Figure 1: Exclusive meson electroproduction. A subdivision in distance scales is used to illustrate three kinematic regions and their respective (effective) degrees of freedom.

contribute significantly in the future. Some of the first results will be presented at this conference.

- The form factors of the neutron G_{En}, G_{Mn} are poorly known. This means that the charge and magnetization distribution of the basic building blocks of matter in the visible universe is virtually unknown.

- To understand the internal nucleon structure, it is not sufficient to measure the charge and current distribution in the ground state, we need to study the full excitation spectrum as well as the continuum. Few transitions to excited states have been studied well, and many states are missing from the spectrum as predicted by our most accepted models.

- The role of the glue in the baryon excitation spectrum is completely unknown, although gluonic excitations of the nucleon are expected to be produced copiously [1], and predictions of hybrid baryon masses and quantum numbers are available.

- The nucleon spin structure has been explored for more than two decades at high energies in laboratories such as CERN, SLAC, and DESY. The confinement regime and the transition between these regimes have not been explored at all.

- The long-known connection between the deep inelastic regime and the regime of confinement (parton-hadron duality) [2] remained virtually unexplored in its potential implications for theoretical developments.

Carrying out an experimental program that will address these questions has become feasible due to the availability of CW electron accelerators, modern detector instrumentation with high speed data transfer techniques, the routine availability of spin polarization in beam and targets, and recoil polarimetry.

2 Excitation of Baryon Resonances

A large effort is being extended to the study of excited states of the nucleon. The transition form factors contain information on the spin structure of the transition and the wave function of the excited state. We test predictions of baryon structure models and of strong interaction QCD. Another aspect is the search for, so far, unobserved states which are missing from the spectrum but are predicted by QCD inspired quark models [3]. Also, are there other than $|Q^3>$ states? Gluonic excitations of the nucleon, i.e. $|Q^3G>$ states may be be copious [1], and some resonances may be "molecules" of baryons and

mesons $|Q^3Q\bar{Q}>$. Searching for at least some of these states is important to clarify the intrinsic quark-gluon structure of baryons and the role played by the glue and mesons in hadron spectroscopy and structure. Photo- and electroproduction of mesons are important tools in these studies as they probe the internal structure of hadronic systems. The scope of the N^* program [4] at JLAB includes measurement of many of the possible decay channels of resonances in a large kinematical range.

2.1 The $\gamma N\Delta$ transition.

The lowest excitation of the nucleon is the $\Delta(1232)$ ground state. The electromagnetic excitation is due dominantly to a quark spin flip corresponding to a magnetic dipole transition. This contribution is fairly well known up to quite large Q^2. The current interest is in probing the electric and scalar quadrupole transitions which are predicted to be sensitive to a possible deformation of the nucleon or the $\Delta(1232)$. Contributions at the few percent level may result from interactions with the pion cloud [5] at large and intermediate distances, and from one-gluon-exchange at small distances. An intriguing prediction is that in the hard scattering limit the electric quadrupole contribution should be equal in strength to the magnetic dipole contribution [6]. An analysis [7] of earlier DESY data found small nonzero values for the ratio E_{1+}/M_{1+} at $Q^2 = 3.2GeV^2$, showing that the asymptotic QCD prediction is far away from the data.

An experiment at JLAB Hall C [8,9] measured $p\pi^o$ production in the $\Delta(1232)$ region at high momentum transfer, and found values for $E_{1+}/M_{1+} \approx -0.02$ at $Q^2 = 4\ GeV^2$.

Preliminary data from CLAS [10] indicate negative values at small Q^2 with a trend towards more positive values at higher Q^2. Much more data are expected in the near future from CLAS.

2.2 What is so special about the Roper Resonance ?

The lowest positive parity N^* resonance is the $P_{11}(1440)$. Its internal structure has been subject of intensive debate in recent years. It is clearly visible in πN scattering, as well as in pion photoproduction. However, its transition strength drops rapidly with Q^2 in electroproduction [11], and its longitudinal coupling is weak. Neither of these properties is well described in quark models, which assigns the state to a radial excitation of the nucleon. It has been proposed that the observed "electro-quenching" behavior is well described if the state is assigned a large gluonic component [12]. While recent flux tube model calculations [13] give higher masses to hybrid baryons than previous estimates in the bag model [14] and QCD sum rules [15], the Roper could still have a substantial

gluonic component due to mixing with higher mass states [16]. Other models have been put forward recently that include meson degrees of freedom [17], or describe the state as a molecule of the nucleon and the σ pseudo-particle [18]. The soft formfactor suggests an extended or loosely bound system. Studying these transitions in electroexcitation allows us to probe the internal structure and help reveal the nature of this state. CLAS π^o and π^+ electroproduction data are currently being analyzed to measure the transition amplitudes in a large range of Q^2.

2.3 Higher mass resonances

The inclusive spectrum shows only 3 or 4 enhancements; however, more than 20 states are known in the mass region up to 2 GeV. By measuring the electromagnetic transition of many of these states we obtain a more complete picture of the nucleon structure.

The approximate SU(6) symmetry of the non-relativistic symmetric quark model predicts relationships between various states. For example, in the single-quark-transition model (SQTM) only one quark participates in the interaction. It predicts transition amplitudes for a large number of states based on a few measured amplitudes [19]. The current situation is shown in Figure 5, where the SQTM amplitudes for the transition to the $L_{3q} = 1$ $SU(6)\otimes O(3)$ multiplet have been extracted from the measured amplitudes for $S_{11}(1535)$ and $D_{13}(1520)$. Predictions for other states belonging to the same multiplet are shown in the other panels. The lack of accurate data for most other resonances prevents a sensitive test of even the simple SQTM.

The goal of the experimental N* program at JLAB with the CLAS detector is to provide data in the entire resonance region, by measuring many channels in a large kinematic range, including various polarization observables. The yields of several channels recorded simultaneously are shown in Figure 3 and Figure 4. Resonance excitations seem to be present in all channels. The figures also illustrate how the various channels have sensitivity to different resonance excitations. For example, the $\Delta^{++}\pi^-$ channel clearly shows resonance excitation near 1720 MeV while single pion production is more sensitive to a resonance near 1680 MeV [20]. The $p\omega$ channel seems to show resonance excitation near threshold, similar to the $p\eta$ channel. No resonance has been observed in this channel so far. For the first time, $n\pi^+$ electroproduction has been measured throughout the resonance region, and in a large angle and Q^2 range.

Figure 4 illustrates the vast improvement in data volume for the $\Delta^{++}\pi^-$ channel. The top panel shows DESY data taken more than 20 years ago. The

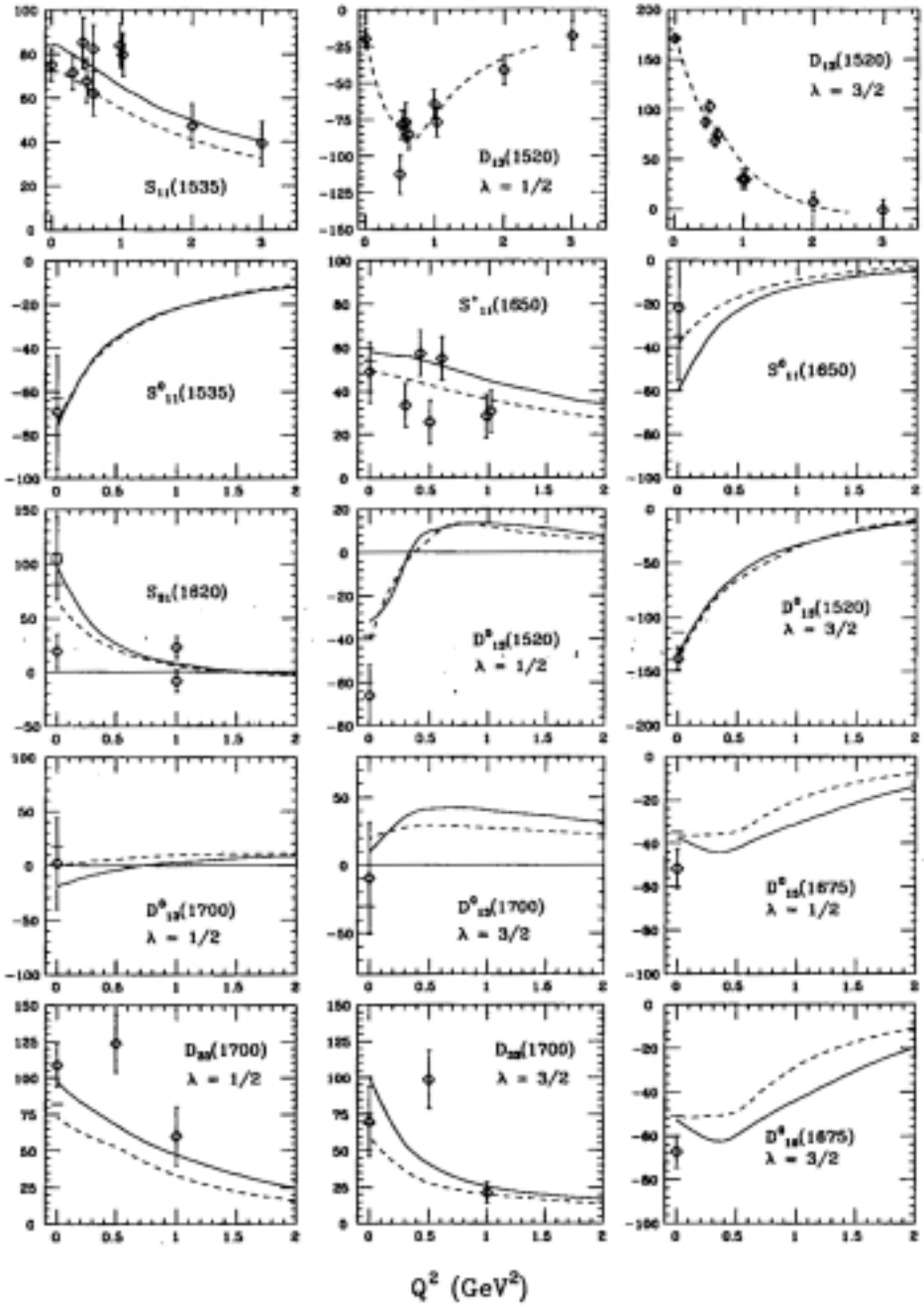

Figure 2: Single Quark Transition Model predictions for states belonging to the $SU(6) \otimes O(3)$ multiplet, discussed in the text.

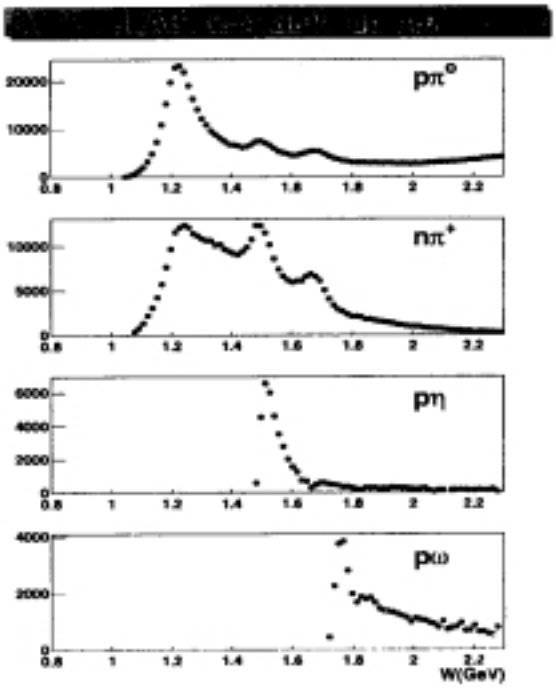

Figure 3: Yields for various channels measured with CLAS at JLAB. The statistical error bars are smaller than the data points.

other two panels show samples of the data taken so far with CLAS. At higher Q^2, resonance structures, not seen before in this channel, are revealed.

2.4 Missing quark model states

These are states predicted in the $|Q^3>$ model to populate the mass region around 2 GeV. However, they have not been seen in πN elastic scattering, our main source of information on the nucleon excitation spectrum.

It is important to search for at least some of these states since their absence from the spectrum would be evidence that either SU(6) symmetry is strongly broken in baryon spectroscopy, or quark model calculations of electromagnetic or hadronic couplings are unreliable. How do we search for these states?

Channels which are predicted to couple strongly to these states are $N(\rho, \omega)$ or $\Delta\pi$ [20]. Some may also couple to KY or $p\eta'$ [21].

Figure 5 shows preliminary data from CLAS in ω production on protons. The process is expected to be dominated by π^o exchange with strong peaking

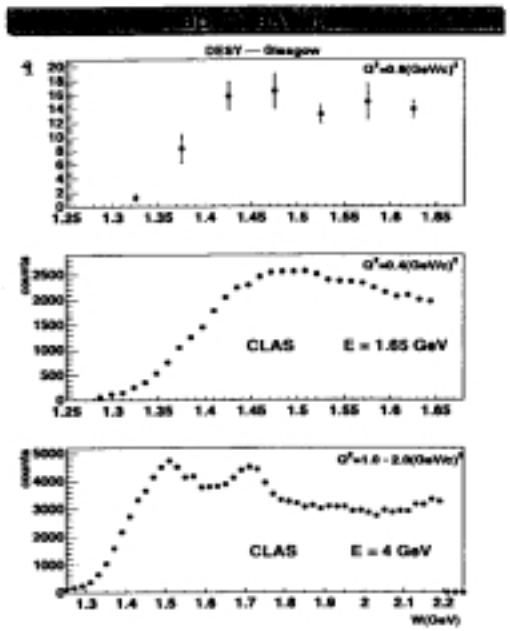

Figure 4: Yields for the channel $\Delta^{++}\pi^-$ measured with CLAS at different Q^2 compared to previous data from DESY.

at forward ω angles, or low t, and a monotonic fall-off at large t. The data show clear deviations from the smooth fall-off for the W range near 1.9 GeV, where some of the "missing" resonances are predicted, in comparison with the high W region.

Although indications for resonance production are strong[22], analysis of more data and a full partial wave study are needed before definite conclusions may be drawn.

CLAS has collected $3 \cdot 10^5$ $p\eta'$ events in photoproduction. Production of η' has also been observed in electron scattering for the first time with CLAS. This channel may provide a new tool in the search for missing states as well[23]. The quark model predicts two resonances in this mass range with significant coupling to the $N\eta'$ channel[21].

$K\Lambda$ or $K\Sigma$ production may yet be another source of information on resonant states. Previous data show some evidence for resonance production in these channels. New data with much higher statistics are being accumulated with the CLAS detector, both in photo- and electroproduction[24]. Analysis of the Λ polarisation possible in CLAS provides additional information sensitive

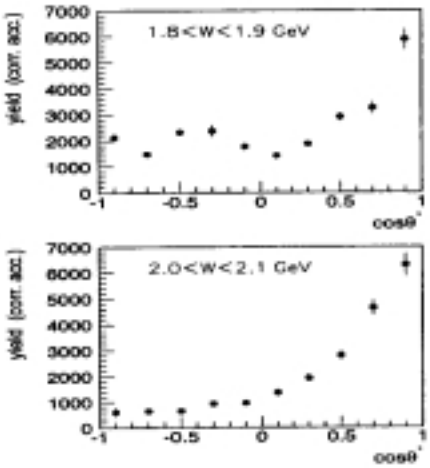

Figure 5: Electroproduction of ω mesons for different W bins. The deviation of the $\cos\theta$ -distribution from a smooth fall-off for the low W bin suggests significant s-channel resonance production.

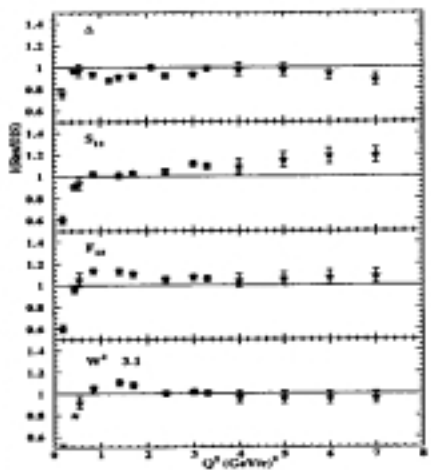

Figure 6: Ratio of resonance excitations as observed and predicted from deep inelastic processes using quark-hadron duality[41].

to resonance excitations.

3 The Nucleon Spin Structure - from Small to Large Distances

The internal spin structure of the nucleon has been of central interest ever since the EMC experiment found that at small distances the quarks carry only a fraction of the nucleon spin. Going from small to large distances the quarks get dressed with gluons and $q\bar{q}$ pairs and acquire more and more of the nucleon spin. How is this process evolving with the distance scale? At the two extreme kinematic regions we have two fundamental sum rules. The Bjorken sum rule (Bj-SR) which holds in the asymptotic limit is usually written for the proton-neutron difference as

$$\Gamma_1^{pn} = \int g_1(x)dx = \frac{g_A}{6} \quad .$$

At the finite Q^2 where experiments are performed, QCD corrections have been calculated, and there is good agreement between theory and experiment at $Q^2 > 2\ GeV^2$. At the other end, at $Q^2 = 0$, the Gerasimov Drell-Hearn sum

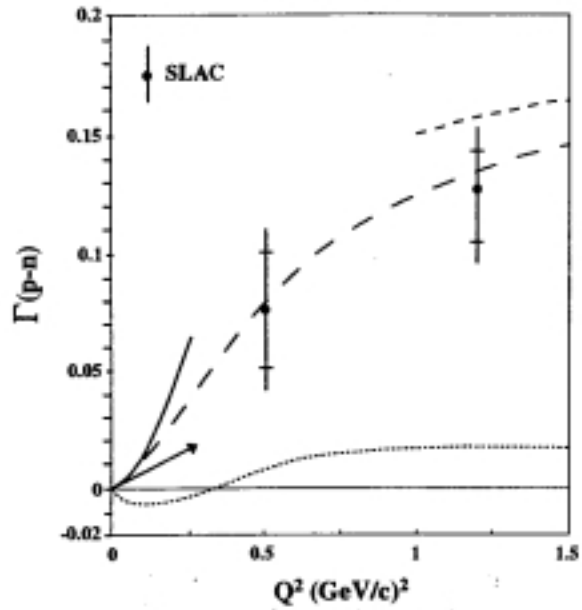

Figure 7: The Bjorken integral $\Gamma_1^{p-n}(Q^2)$ of the polarized structure function $\int(g_1^p(x,Q^2) - g_1^n(x,Q^2))dx$. The solid line is the χPT prediction in NLO[36,35]. Short dashed line is Bjorken sum rule with pQCD corrections to $O(\alpha_s^3)$. The long dashed line is a model predictions from [27]. The dotted line shows s-channel resonance contributions [31]. The solid arrow indicates the slope given by the GDH sum rule constraint. Data are from SLAC [25]

rule (GDH-SR) is expected to hold:

$$I_{GDH} = \frac{M^2}{8\pi^2\alpha}\int \frac{\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu)}{\nu} d\nu = -\frac{1}{4}\kappa^2 \quad .$$

The integral for the difference in helicity 1/2 and helicity 3/2 total absorption cross sections is taken over the entire inelastic energy regime. The quantity κ is the anomalous magnetic moment of the target.

One connection between these regions is given by the constraint due to the GDH-SR - it defines the slope of the Bjorken integral ($\Gamma_1(Q^2) = \int g_1(x,Q^2)dx$) at $Q^2 = 0$:

$$I_{GDH}^{pn}(Q^2 \to 0) = 2\frac{M^2}{Q^2}\Gamma_1^{pn}(Q^2 \to 0)$$

Phenomenological models have been proposed to extend the GDH integral for the proton and neutron to finite Q^2 and connect it to the deep inelastic regime [26,27,33]. The data[25] at low Q^2 are in good agreement with the predictions if nucleon resonances are taken into account explicitly [27] (Figure 4).

An important question is whether we can go beyond models and describe the transition from the Bj-SR to the GDH-SR within fundamental theory, i.e. QCD. Ji and collaborators [30] have recently generalized the sum rule integral to include finite Q^2. The question is if the right-hand side of the integral can be predicted by theory. Chiral perturbation theory has been proposed [30,28] to provide an extension of the sum rule for proton and neutron to finite Q^2. If we look at this problem for the proton or neutron separately, we find that the sum rule is nearly saturated by low-lying resonances [31,32] with the largest contributions coming from the excitation of the $\Delta(1232)$. This is still correct if the GDH-SR is generalized to finite, but not too large Q^2 [31,34]. This will make it very difficult to describe the sum rule within chiral perturbation theory[35] at any, but the smallest Q^2. The situation looks more promising if we take the proton-neutron difference [36]. The dominant contribution from the $\Delta(1232)$ is absent, and other resonance contributions are reduced as well indicating that the GDH-SR may be evolved to $Q^2 \approx 0.2$ GeV^2 if higher orders are taken into account. An important question in this connection is: how low in Q^2 may the Bjorken-SR be evolved using higher twist expansion? Recent estimates [35] suggest these techniques may be valid as low as $Q^2 = 0.5$ GeV^2, leaving a gap from $Q^2 = 0.2 - 0.5$ that need to be bridged, perhaps utilizing lattice QCD.

The connection of deep inelastic regime, higher twist, and resonance contributions for the proton spin structure function $g_1(x, Q^2)$ has recently been studied by Weise and collaborators [37]. They estimate large resonance contributions even at high Q^2.

These efforts are of utmost importance since, if successful, *it would mark the first time that hadronic structure is described by fundamental theory in the entire kinematic regime, from small to large distances, a goal worth a significant effort!*

Experiments have been carried out at JLAB [38,39,40] on NH_3, ND_3, and ^3He targets to extract the Q^2 evolution of the generalized GDH integral for protons and neutrons in the low Q^2 range, $Q^2 = 0.1 - 2.0\ GeV^2$, and from the elastic to the deep inelastic regime. Currently, only two data points with large errors exist for $Q^2 < 2\ GeV^2$. Because of the current limitations in machine energy to 6 GeV, some extrapolation will be needed to determine the full integral, especially at the larger Q^2 values. First results from the JLAB experiments are expected in the year 2000 [38].

4 Connecting Constituent Quarks and Valence Quarks

I began my talk by expressing the expectation that we may eventually arrive at a unified description of hadronic structure from small to large distances.

If such description is possible then there should be obvious connections in the data between these regimes. I have already mentioned the evolution of the Gerasimov-Drell-Hearn and Bjorken sum rules as one area where such connections are visible in the data, and where significant progress seems likely in the near future.

Inclusive electron scattering is another area where strong connections have been observed by Bloom and Gilman [2]. They noted that the scaling curves from the deep inelastic cross section also describe the average inclusive cross sections in the resonance region if a scaling variable is chosen that takes into account target mass effects. Until recently, this intriguing observation was little utilized. A new inclusive ep scattering experiment [41] at JLAB helped rekindle the interest in this aspect of hadron physics. Remarkably, resonance excitations of the nucleon can be predicted approximately from inclusive deep inelastic scattering data. Figure 6 shows the ratio of measured integrals over resonance regions, and predictions using deep inelastic data only. The agreement is surprisingly good, though not perfect. It remains to be seen if this intriguing observation can be translated into the development of new theory approaches to resonance physics. Studies of exclusive channels, as well as of polarized structure functions in the resonance region may contribute towards a deeper theoretical understanding of this observation.

5 Outlook

The ongoing experimental effort at Jefferson Lab will provide the community with a wealth of data in the first decade of this millennium to address many open problems in hadronic structure in the resonance region and at intermediate distances.

The experimental effort must be accompanied by a significant theoretical effort to translate this into real progress in our understanding of the complex regime of strong interaction physics.

The nucleon resonance region is of special interest as it represents a region where different degrees of freedom, from hadronic, to constituent quarks, to valence quarks overlap. On the one hand this provides a challenge to theory, but on the other hand an opportunity, as only under such circumstances is there a realistic chance for a unified description of hadron structure from short to large distances.

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