Probing the Structure of Nucleons in Electromagnetic Interactions

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I discuss open problems in nucleon structure studies using electromagnetic probes. The focus is on the regime of strong interaction QCD. Significant progress in our understanding of the nucleon structure in the region of strong QCD may be expected in the first decade of the new millenium due to major experimental and theoretical efforts currently underway in this field.

1. INTRODUCTION

Electron scattering may be characterized according to distance and time scales (or momentum and energy transfer). At large distances mesons and nucleons are the relevant degrees of freedom. We can study peripheral properties of the nucleon near threshold, or meson exchange processes at high energies. At short distances and short time scales, the coupling involves elementary quarks and gluon fields, governed by pQCD, and we can 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 can study interactions between these constituents via their excitation spectra and wave functions. This is the region I will be focussing on. These regions obviously overlap, and the hope is that hadron structures may eventually be described in a unified approach based on fundamental theory. Because the electro-magnetic and -weak probes are well understood, they are best suited to provide the data for such an endeavor.

1.1. Open problems in nucleon structure at intermediate distances

QCD has not been solved for processes at intermediate distance scales and, therefore, the internal structure of nucleons is generally poorly known in this regime. On the other hand, theorists are 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:

- The electric form factors of the nucleon are poorly known, especially for the neutron, but also for the proton. This means that the charge distribution of the most common form of matter in the universe is virtually unknown.

- What role do strange quarks play in the wave function of ordinary matter?
- The nucleon spin structure has been explored for more than two decades at high energies. The transition from the deep inelastic regime to the confinement regime has not been explored at all.
- To understand the ground state nucleon we need to understand 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 likely produced copiously.[1]
- The long-known connection between the deep inelastic regime and the regime of confinement (quark-hadron duality)[2] remained virtually unexplored for decades.

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

The main contributor to this field is now the CEBAF accelerator at Jefferson Lab in Newport News, Virginia, USA. A maximum energy of 5.6 GeV is currently available, and the three experimental halls can receive polarized beam simultaneously, with different or the same beam energies.

2. ELASTIC SCATTERING

2.1. Electromagnetic form factors

This process probes the charge and current distribution in the nucleon in terms of the electric (G_E^γ)and magnetic (G_M^γ) form factors. Early experiments from Bonn, DESY, and CEA showed a violation of the so-called "scaling law", which may be interpreted that the spatial distribution of charge and magnetization are not the same, and the corresponding form factors have different Q^2 dependencies. The data showed a downward trend for the ratio $R_{EM}^\gamma = G_E^\gamma/G_M^\gamma$ as a function of Q^2. Adding the older and newer SLAC data sets confuses the picture greatly (Figure 1). Part of the data are incompatible with the other data sets. They also do not show the same general trend as the other data sets. Reliable data were urgently needed to clarify the experimental situation and to constrain theoretical developments.

The best way to get reliable data at high Q^2 is via double polarization experiments, and the first experiments of this type have now produced results. Since the ratio R_{EM}^γ is accessed directly in the double polarization asymmetry

$$A_{\vec{e}\vec{p}} = \frac{k_1 R_{EM}^\gamma}{k_2 (R_{EM}^\gamma)^2 + k_3}$$

this experiment has much lower systematic uncertainties than previous experiments at high Q^2 (Figure 1). They confirm the trend of the early data, improve the accuracy at high Q^2 significantly, and extend the Q^2 range. The data illustrate the power of utilizing polarization in electromagnetic interactions.

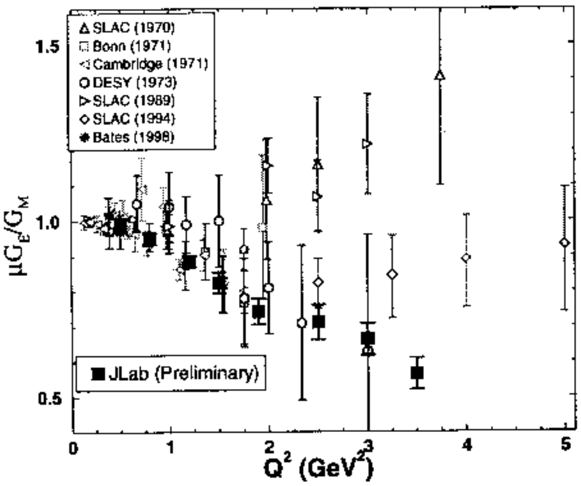

Fig. 1. Results for the ratio R^{γ}_{EM} of electric and magnetic form factors of the proton. The full squares are preliminary results from JLAB obtained with the double polarization techniques[3]

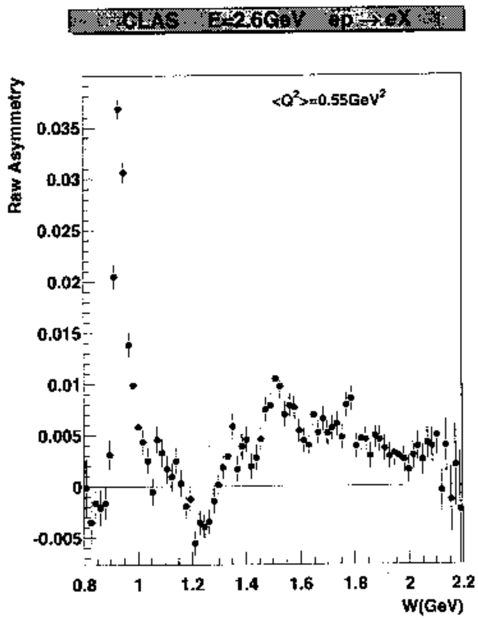

Fig. 2. Raw asymmetry measured in inclusive $\vec{e}N\vec{H}_3 \rightarrow eX$ scattering at JLAB.

2.2. Strangeness form factors

From the analysis of deep inelastic polarized structure function experiments we know that the strange quark sea is polarized, and contributes at the 5 - 10% level to the nucleon spin. Then one may ask what are the strange quark contributions to the nucleon wave function and their corresponding form factors? The flavor-neutral photon coupling does not distinguish s-quarks from u- or d-quarks. However, the tiny contribution of the Z^o is parity violating, and allows measurement of the strangeness contribution. The effect is measurable due to the interference with the single photon graph. The asymmetry

$$A_{\vec{e}p} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha} \frac{\epsilon G^{\gamma}_E G^Z_E + \tau G^{\gamma}_M G^Z_M}{\epsilon (G^{\gamma}_E)^2 + \tau (G^{\gamma}_M)^2}$$

in polarized electron scattering contains combinations of electromagnetic and weak form factors which can be expressed in terms of the electromagnetic and the strangeness form factors (G^s). For example, the weak electric form factor can be written:

$$G^Z_E = (\frac{1}{4} - sin^2\theta_W) G^{\gamma}_{Ep} - \frac{1}{4}(G^{\gamma}_{En} + G^s_E)$$

A similar relation holds for the magnetic form factors. The G^s form factors can be measured since the G^γ form factors are known. The elastic $\vec{e}p$ results of the JLAB HAPPEX experiment measured at $Q^2 = 0.47GeV^2$ show that strangeness contributions are small, consistent with zero, when measured in a combination of G_E^s and G_M^s[4]:

$$G_E^s + 0.4G_M^s = 0.023 \pm 0.034(stat) \pm 0.022(syst) \pm 0.026(G_E^n)$$

At least a factor 2 smaller statistical error will be obtained in the 1999 run, so that the systematic error is limited by our knowledge of the neutron electric form factor! New measurements of G_E^n should remedy this situation.[5,6]

3. NUCLEON SPIN STRUCTURE - FROM SHORT TO LARGE DISTANCES

The nucleon spin 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 shorter to larger distances the quarks are 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 for the proton-neutron difference in the asymptotic limit, and the Gerasimov Drell-Hearn sum rule (GDH-SR)at $Q^2 = 0$:

$$I_{GDH} = \frac{M^2}{8\pi^2\alpha} \int \frac{\sigma_{1/2}(\nu, Q^2 = 0) - \sigma_{3/2}(\nu, Q^2 = 0)}{\nu} d\nu = -\frac{1}{4}\kappa^2 \quad .$$

The integral 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 ($\Gamma_1^{pn}(Q^2) = \int g_1^{pn}(x, Q^2)dx$) 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-SR integral for the proton and neutron to finite Q^2 and connect it to the deep inelastic regime.[7] An interesting question is whether the transition from the Bj-SR to the GDH-SR for the proton-neutron difference can be described in terms of fundamental theory. While for the proton and neutron alone, the GDH-SR is nearly saturated by low-lying resonances[8,9] with the largest contributions coming from the excitation of the $\Delta(1232)$, this contribution is absent in the pn difference. Other resonance contributions are reduced as well and the Q^2 evolution may take on a smooth transition to the Bj-SR regime. A crucial question in this connection is how low in Q^2 the Bj-SR can be evolved using the modern techniques of higher order QCD expansion? Recent estimates[10] suggest as low as $Q^2 = 0.5$ GeV^2. At the other end, at $Q^2 = 0$, where hadrons are the relevant degrees of freedom, chiral perturbation theory is applicable at very small Q^2, and may allow evolution of the GDH-SR to finite Q^2. Theoretical effort is needed to bridge the remaining gap.

The importance of such efforts cannot be overemphasized as it would mark the first time that hadronic structure is described by fundamental theory in the entire kinematics regime, from short to large distances.

Experiments have been carried out at JLAB on NH_3, ND_3, and ^3He targets to extract the Q^2 evolution of the GDH integral for protons and neutrons in a range of $Q^2 = 0.1 - 2.0\ GeV^2$ and from the elastic to the deep inelastic regime. Results are expected in the year 2000. Figure 2 shows a raw asymmetry from an experiment on polarized NH_3. The positive elastic asymmetry, the negative asymmetry in the Δ region, and the switch back to positive asymmetry for higher mass resonances and the high energy continuum are evident.

4. EXCITATION OF NUCLEON 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 strong interaction QCD. Another aspect is the search for, so far, unobserved states which are missing from the spectrum but are predicted by the QCD inspired quark model.[11] Also, are there other than $|Q^3>$ states? Gluonic excitations of the nucleon, i.e. $|Q^3G>$ states should be copious, and some resonances may be "molecules" of baryons and mesons $|Q^3Q\bar{Q}>$. Finding 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. Electroproduction is an important tool in these studies as it probes the internal structure of hadronic systems.

The scope of the N^* program[13,14] at JLAB is to measure many of the possible decay channels of resonances in a large kinematics range.

4.1. 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. The interest today is in measuring the small electric and scalar quadrupole transitions which are pedicted to be sensitive to possible deformation of the nucleon or the $\Delta(1232)$.[12] Contributions at the few % level may come from the pion cloud at large distances, and 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.

An experiment at JLAB Hall C measured $p\pi^o$ production in the $\Delta(1232)$ region at high momentum transfer, and found values for $|E_{1+}/M_{1+}| < 5\%$ at $Q^2 = 4GeV^2$. There are no indications that the asymptotic value of $+1$ may be reached soon.

4.2. 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 can study symmetry properties between excited states and obtain a more complete picture of the nucleon structure. For example, in the single-quark-transition model only one quark participates in the interaction. It predicts transition amplitudes for a large number of states based on a few measured amplitudes.

The goal of the N* program at JLAB with the CLAS detector is to provide data in the entire resonance region, by measuring most channels, with large statistics, including many polarization observables. The yields of several channels recorded simultaneously are shown in Figures 3 and 4. Resonance excitations seem to be present in all channels.

These yields illustrate how the various channels have different sensitivity to various 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.[14]

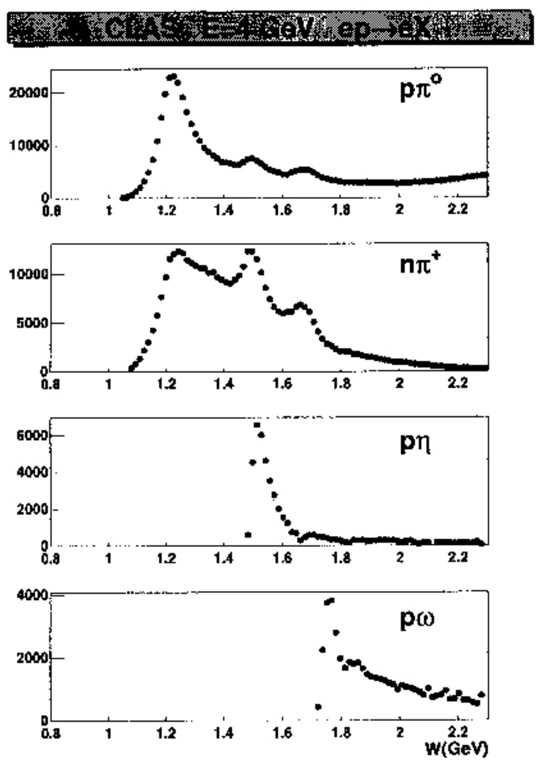

Fig. 3. Yields for various channels measured with CLAS at JLAB. The error bars are smaller than the data points.

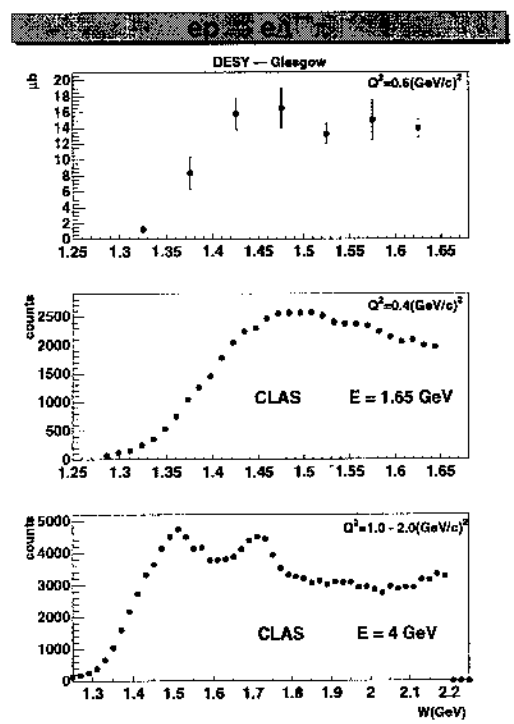

Fig. 4. Yields for the channel $\Delta^{++}\pi^-$ measured with CLAS at different Q^2 compared to previous data from DESY

The $p\omega$ channel shows 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.

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

4.3. 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.

How do we search for these states? Channels which are predicted to couple strongly to these states are $N(\rho,\omega)$ or $\Delta\pi$. Some may also couple to KY or $p\eta'$.[15]

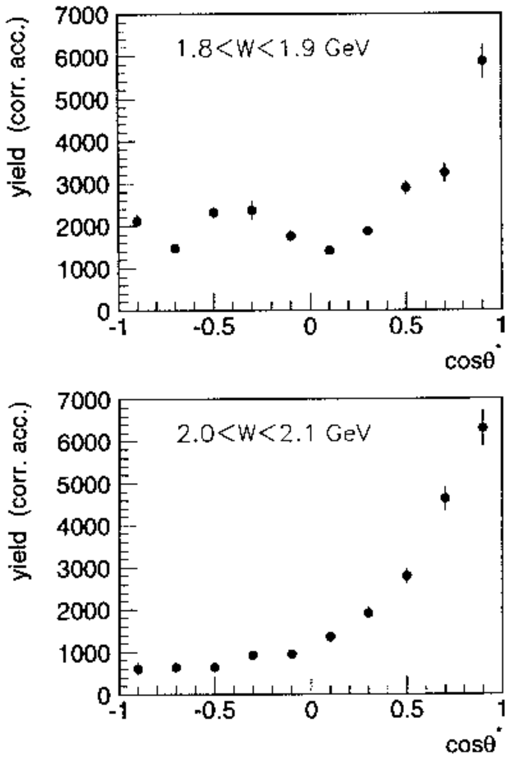

Fig. 5. Electroproduction of ω mesons for different W bins. The deviation of the $\cos\theta$ -distribution from a smooth fall-off for the low W bin suggests significant s-channel resonance production.

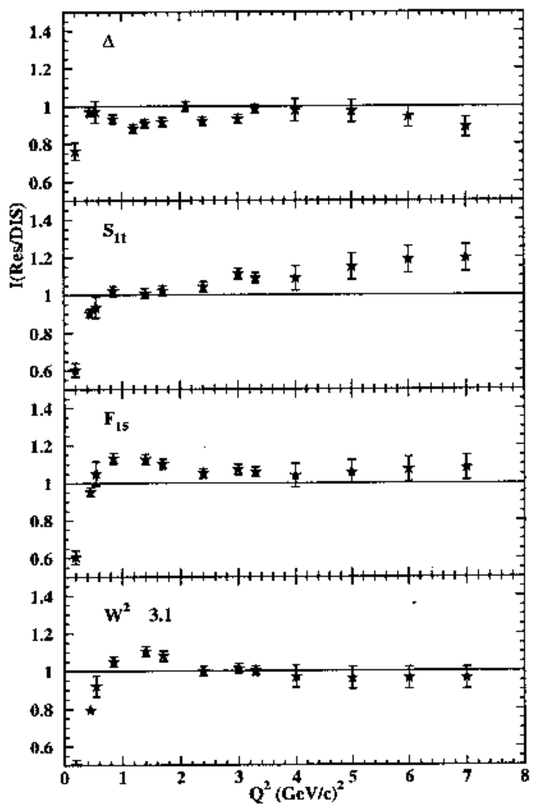

Fig. 6. Ratio of resonance excitations as observed and predicted from deep inelastic processes using quark-hadron duality.[17]

Figure 5 shows preliminary data from CLAS in ω production on protons. The process is expected to be dominated by diffraction-like π^o exchange with strong peaking 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, were some of the "missing" resonances are predicted, in comparison with the high W region.[16] Although indications for resonance production are strong, analysis of more data and a full partial wave study are needed before definite conclusions may be drawn.

The SAPHIR experiment with an analysis of just 250 $p\eta'$ events at ELSA found evidence for two states with masses of 1.9 and 2.0 GeV.[18] The quark model predicts indeed two resonances in this mass range with coupling to the $N\eta'$ channel.

CLAS has already collected 50,000 η' events in photo production, and a lot more are forthcoming later this year. Production of η' has also been observed in electron scattering for the first time with CLAS. This channel may also provide a new tool in the search for missing states.

$K\Lambda$ or $K\Sigma$ production may yet be another source of information on resonant states. The KΛ data from SAPHIR[19] show a bump near W = 1.72 GeV, which could be due to resonance decay of the $P_{11}(1710)$ and $S_{11}(1650)$, both of which couple to the KΛ channel. Possible resonance excitation is also seen in $K\Lambda(1520)$ production at SAPHIR, compatible with a predicted state with a mass near 2 GeV. New data with much higher statistics are being accumulated with the CLAS detector, both in photo - and electro production.[20,21] Strangeness production could open up a new window for light quark baryon spectroscopy, not available in the past.

5. QUARK-HADRON DUALITY

I began my talk by expressing the expectation that we may eventually arrive at a unified description of hadronic structure from short to large distances. Then there should be obvious connections visible in the data between these regimes. Strong connections have indeed been observed by Bloom and Gilman,[2] in the observation that the scaling curves from the deep inelastic cross sections also describe the average inclusive cross sections in the resonance region.

This observation has recently been filled with more empirical evidence using inclusive ep scattering data from JLAB.[17] Remarkably, elastic form factors or resonance excitations of the nucleon can be predicted approximately just using data from inclusive deep inelastic scattering at completely different momentum transfers. 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, indicating that the concept of duality likely is a non-trivial consequence of the underlying dynamics.

6. QUTLOOK

The ongoing experimental effort will provide us with a wealth of data in the first decade of the next millennium to address many open problems in hadronic structure 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.* New instrumentation will become available, e.g. the G^o experiment at JLAB ,allowing a broad program in parity violation to study strangeness form factors in electron scattering in a large kinmatics range.

Moreover, there are new physics opportunities on the horizon. Recently, it was shown[22,23] that in exclusive processes the soft part and the hard part factorize for longitudinal photons at sufficiently high Q^2. A new set of "skewed parton distributions" can then be measured which are generalizations of the inclusive structure functions measured in deep inelastic scattering. For example, low-t ρ production probes the unpolarized parton distributions, while pion production probes the polarized structure functions. Experiments to study these new parton distributions need to have sufficient energy transfer and momentum transfer to reach the pQCD regime, high luminosity to measure the small exclusive cross sections, and good resolution to isolate exclusive reactions.

This new area of research may become a new frontier of electromagnetic physics well into the next century.

To accommodate new physics requirements, an energy upgrade in the 10-12 GeV range has been proposed for the CEBAF machine at JLAB. This upgrade will be accompanied by the construction of a new experimental hall for tagged photon experiments with a 4π solenoid detector to study exotic meson spectroscopy, and production of other heavy mesons. Existing spectrometers in Hall C will be upgraded to reach higher momenta and improvements of CLAS will allow it to cope with higher multiplicities.

This will give us access to kinematics where copious hybrid meson production is expected, higher momentum transfer can be reached for form factor measurements, and we may begin to map out the new generalized parton distributions.

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