OVERVIEW OF PHYSICS WITH CLAS AT JEFFERSON LABORATORY

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Inclusive and exclusive electron-scattering at intermediate energies is a powerful tool to study the structure of the nucleon and understand the nature of strong interactions in terms of fundamental QCD constituents. The CLAS Collaboration in Hall B at Jefferson Lab (USA) has a broad scientific program ranging from excitation and decay of nucleon resonances to the investigation of hard processes involving perturbative QCD aspects. After a brief description of the CLAS detector, some selected results will be outlined with particular emphasis to the possibility to describe this kinematic regime in terms of microscopic degrees of freedom.

1 Introduction

The use of electromagnetic probes in hadron physics has a long history and led to important discoveries: the proton electric and magnetic form factors, the scaling law of deep inelastic scattering etc. Many other experiments were performed thereafter, aiming at the study of particular exclusive channels like pion photo- and electro-production, but mostly with limited statistics and accuracy, due to the low luminosity and duty factors of the machines previously available, as well as to the small detector solid angles. The availability of continuous and high intensity electron and photon beam together with a new large acceptance detector provides coverage over a wide kinematic range for many different final states, including multi-hadron channels.

The CLAS collaboration in Hall B at Jefferson Laboratory has a broad scientific program based on the use of both the primary CW electron beam and a tagged photon beam. In our kinematics (center of mass energy $W \sim$ 1-3 GeV, photon virtuality $Q^2 \sim$ 0-5 GeV^2, and momentum transfer in exclusive reactions $-t \sim$ 0-6 GeV^2) it is possible to study the transition between the so called *'Soft Physics'*, where models based on Constituent Quarks or phenomenology are widely applied, to the *'Hard Physics'* regime, where perturbative QCD or dimensional analysis are used to interpret the data. In this contribution some of the main topics of the CLAS physics will be discussed: baryon resonances, nucleon structure functions and their moments, dynamics of strong interactions.

2 CLAS at Jefferson Lab

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab delivers a low emittance, high resolution, 100% duty-cycle electron beam to three different experimental halls A, B and C, simultaneously. The maximum energy is 5.8 GeV (with 80% polarization available) with a maximum current of 180 μA. The Hall B is mainly devoted to experiments that require the detection of several particles in the final state. It hosts the CLAS detector [1](CEBAF Large Acceptance Spectrometer), built around six superconducting coils producing a toroidal magnetic field. The detector package consists of three layers of drift chambers for track reconstruction, one layer of scintillators for time-of-flight measurements and hadron identification, forward Cerenkov counters for electron-pion discrimination, and electromagnetic calorimeters to identify electrons and neutral particles. A longitudinally polarized target [2] has been designed to fit within the 1 m central bore of the CLAS. Protons ($^{15}NH_3$) and deuterons ($^{15}ND_3$) are continuously polarized by microwave-induced spin-flip transition at 1K and 5T via the Dynamical Nuclear Polarization technique. The maximum polarization obtained is 90% and 40% for proton and deuteron respectively. The combination of polarized beam and polarized target allows measurement of polarization observables both in inclusive and exclusive reaction channels.

3 Baryon Resonances: The N^* program

One of the features of real and virtual photon interactions with the proton is the appearance of bumps in the inelastic part of the cross section, corresponding to values of the invariant CM energy W between 1.1 and about 2 GeV. This is interpreted as manifestation of excited states of the nucleon (with definite angular momentum and parity), also observed in pion absorption and nucleon-nucleon scattering. A lot of progress has been made in the framework of quark models to provide a consistent picture of all resonant states in terms of three constituent massive quarks. Various recipes have been introduced to account for relativity and to reproduce form factors [3], while other models rely on different treatment of the basic degrees of freedom and the potential [4]. *It is a goal of the CLAS experimental program to provide accurate data to test these different quark-model approaches to nucleon structure.* An important aspect of resonance physics is the measurement of their decay angular distributions, as these are connected to basic properties such as angular momentum and parity of the states. To access this information it is necessary to measure the differential cross section for exclusive reactions. It can be shown that the cross section for a reaction of the type $ep \rightarrow e'MB$, where M is a meson and B is a baryon can be written as:

$$\frac{d\sigma}{dW dQ^2 d\Omega_M} = \sigma_0 + P_{el}\sigma_{el} + P_{tg}\sigma_{tg} + P_{el}P_{tg}\sigma_{el-tg} \tag{1}$$

where the σ_X correspond to the unpolarized, electron polarized, target polarized and electron-target polarized differential cross sections while P_X are the beam and target degree of polarization. Each part can be expressed in terms of kinematics variables and a response functions R, a bilinear combination of the production amplitudes that describes the specific reaction. The R's show different angular dependence according to the angular momentum and parity of the partial waves involved (in other words, according to the different electromagnetic multipoles involved), therefore allowing a separation of different resonance contributions.

3.1 Quadrupole deformation of the Δ(1232)

An interesting aspect of nucleon structure at low energy is a possible quadrupole deformation in the transition between the ground and the first excited state of the nucleon. Within the SU(6) model, the $\gamma^* N \rightarrow \Delta(1232) \rightarrow N\pi$ transition is mediated by a single quark spin flip leading to M_{1+} magnetic dipole dominance and E_{1+}=S_{1+}=0. Non-zero values for E_{1+} would indicate a quadrupole deformation. Such deformation may arise dynamically through the interaction of the photon with the pion cloud [5] or through the one-gluon exchange mechanism [6]. On the other hand, helicity conservation in perturbative QCD requires E_{1+}=M_{1+} as $Q^2 \rightarrow \infty$. Precise determination of the ratio $\frac{E_{1+}}{M_{1+}}$ is therefore an important test about the underlying quark structure of the nucleon. Results of the multipole analysis of the CLAS data [7] for the reaction $ep \rightarrow e'p\pi^0$ are shown in figure 1. The new and accurate data prove that R_{EM} remains negative and small in the whole kinematic range of our measurement, indicating that pQCD behavior is not yet reached at these moderate Q^2. The ratio R_{SM} also remains negative but in magnitude it is strongly rising with Q^2. Comparison with microscopic models (relativized quark models, chiral quark soliton model and dynamical models) shows that the simultaneous description of both R_{EM} and R_{SM} is achieved when the pion cloud is add to the usual constituent quark degrees of freedom.

Model dependences in the analysis are largely related to the non-resonant processes contributing to the final state. Allowing to measure different combinations of production amplitudes, polarization degrees of freedom help to disentangle the signal from the background processes. For instance, comparison with dynamical models of the fifth structure function [8] and the double

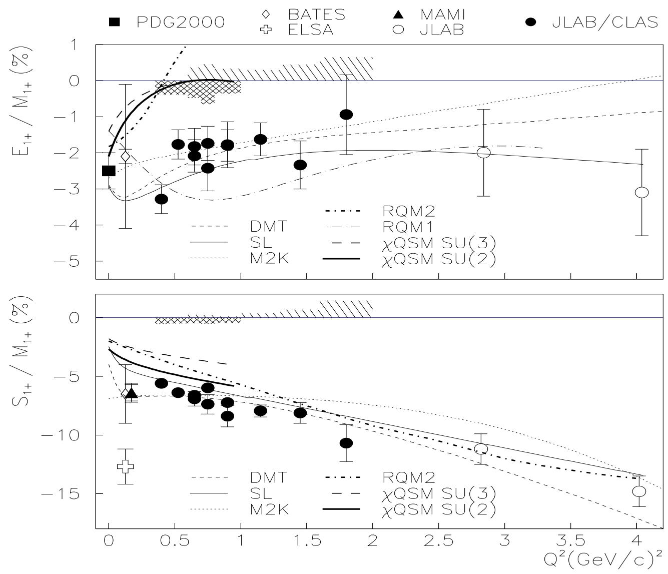

Figure 1. Results for Q^2 dependence of the electric (E_1) and scalar (S_1) quadrupole/dipole ratios in $\Delta(1232)$ resonance excitation. Data from other labs as well as various theoretical predictions are also reported.

spin asymmetry [9] for the reaction $ep \to e'n\pi^+$, both measured for the first time with CLAS, show the sensitivity to the non resonant contributions.

3.2 Missing resonances

Another important issue in baryon resonance physics is the number of states observed in the spectrum. SU(6) symmetric quark models predict more states than have been found in experiments. A possible explanation concerns the underlying symmetry: e.g. the Quark Cluster Model[10], where two of the three constituents stay together in a di-quark configuration, predicts a fewer number of states. Another possibility is related to the QCD mixing effects that could decouple many of these states from the pion-nucleon channel [6], with consequent lack of evidence in elastic πN scattering, while strongly coupling them to multipion channels ($N\pi\pi$) or higher masses mesons ($N\eta$, $N\omega$, kY) [11]. *Search for the states still missing in the experimental observation is therefore crucial in understanding the basic degrees of freedom in baryon structure.* As an example of possible evidences of missing resonances I will report about the η photoproduction [12] and $\pi\pi$ electroproduction [13].

The reaction $\gamma p \to p\eta$ acts like an isospin filter allowing the excitation of T=1/2 resonances only. While $S_{11}(1535)$ is known to dominate near threshold, measurement of the differential cross sections with a broad coverage of scattering angle and center of mass energy W provides insight into which other resonances couple to ηN final state. When compared to CLAS data, models based on the present knowledge of resonances properties show a good agreement at threshold while they do not fit the data at large W: a better agreement is obtained when a missing state, the $S_{11}(1790)$, is add. Even more striking is the reaction $ep \to e'p\pi^+\pi^-$. The new CLAS data show for the first time a clear evidence of the presence of bumps in the total cross section at different Q^2 values, and a 'missing' strength around $W \sim 1.7$ GeV (see fig. 2). The comparison to a phenomenological model incorporating the available knowledge on N^* and Δ states shows an evident discrepancy. A better description of the data is obtained either by a sizeable change of the $P_{13}(1720)$ resonance or by introducing a new baryon state not reported in published analysis.

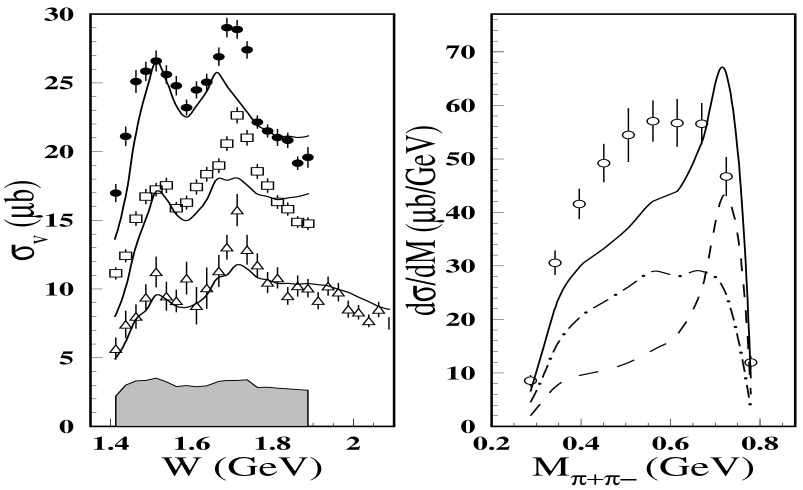

Figure 2. Left: Total cross section for $\gamma^* p \to p\pi^+\pi^-$ as a function of W at $< Q^2 >\sim 0.65\ GeV^2$ (full points), $< Q^2 >\sim 0.95\ GeV^2$ (open sqares) and $< Q^2 >\sim 1.3\ GeV^2$ (open trangles). Right: $d\sigma/dM_{\pi^+\pi^-}$ at $< Q^2 >\sim 0.95\ GeV^2$. The curves rapresent a phenomenological model. Dashed line includes all resonances, dot-dashed non resonant part while solid lines are the full calculation.

4 Nucleon Structure functions

Inelastic scattering off the nucleon and the related inclusive structure functions (F_1 and F_2 for unpolarized scattering and g_1, g_2 for polarized scattering) have been studied for three decades in many laboratories providing important results such as the quark-parton picture of the nucleon or the so-called "spin crisis". In short, inelastic scattering is important for its connection with low energy degrees of freedom, those manifested in resonance excitation, and high energy degrees of freedom, quarks and gluons (or partons) indirectly revealed in deep inelastic scattering and whose interactions are described by QCD.

4.1 The inclusive proton structure function F_2 and its moments

Data from the CLAS collaboration [14] covers the poorly known nucleon resonance region (W <2.5 GeV) at Q^2 below 4.5 GeV. The large acceptance of CLAS allowed the measurement of the cross section in a large kinematics domain making it possible to perform a weighted integration of the data at fixed Q^2 over the significant Bjorken-x_b interval (the weight is the power $x_b^{(n-2)}$ defining the n-moments of the structure functions). The small error (systematics and statistics) and the complete kinematic coverage allows the evaluation of the highest moments (up to order eight with the percentage of experimental points in the integral grater than 70%) where the contribution of the higher twist is more significant. Figure 3 show CLAS results. A recent analysis [15] of the experimental moments of the F_2 show a new type of scaling behavior and interpreted the resulting scaling function as the constituent quark form factor. This analysis clearly suggest that in the range of Q^2 between 0.1 and 2 GeV^2, the inclusive proton structure function F_2 originates mainly from the elastic coupling with *extended objects inside the proton.*

4.2 The polarized structure function g_1 and its moments

When both the incident and the target nucleon are polarized the inclusive scattering cross section depends on two additional structure functions: g_1 and g_2 (actually if the target is longitudinally polarized only g_1 can be accessed). In the limit $Q^2 \to \infty$ g_1 has a simple interpretation as the sum over the x_b dependent polarizations of the various quark flavors. For finite Q^2 the pQCD corrections (higher twists) result in a good agreement with data down to $Q^2 \sim 2\ GeV^2$. The double polarization asymmetry measured in CLAS [16] extended the kinematic range at lower Q^2 (0.15-1.6 GeV^2) providing information on the transition between the pQCD behavior to the non perturbative regime. The disagreement of g_1 and its first moment Γ_1 with perturbative calculations indicate dominant contributions from the resonance regions. A better agreement is obtained with models that include s-channel baryon resonances excitation explicitly. The transition between the two regimes should take place at Q^2 between 1.2 and 2.0 GeV^2.

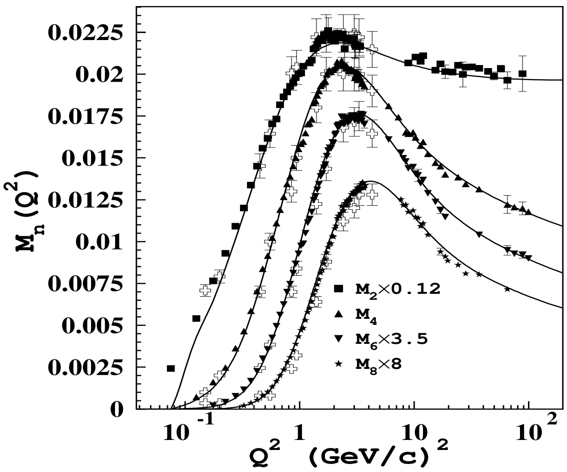

Figure 3. The inelastic moments of F_2 structure function extracted from the world data, including the new CLAS results.

5 Dynamics of strong interactions

One of the key issues in hadronic physics is the study of the interplay between the hadronic (mesons and baryons) and partonic (quarks and gluons) degrees of freedom. Exclusive reactions at large momentum transfer can be used to reduce the hadron complexity in term of elementary parton scattering. In fact, large momentum transfer (both Q^2 and $-t$) means short distance and taking advantage of the fundamental QCD property of the asymptotic freedom it should be possible to decouple the non perturbative long distance effects from the perturbative short distance interactions. In particular there are some theoretical arguments [17] supporting the idea that exclusive processes involving one or more photons are, at leading twist, insensitive to long distance physics. Photoreactions at large momentum transfer and deeply virtual Compton scattering are ideal tools to unravel the microscopic nuclear dynamics.

5.1 Deeply Virtual Compton Scattering

The DVCS is the reaction $\gamma^* p \to \gamma p$ with the electron kinematics of Deep Inelastic Scattering and the proton kinematics of elastic scattering. The theoretical framework for the interpretation of this process is given by the formalism of Generalized Parton Distributions (GPD's) [18] which give information on quark-quark correlations, transverse quark momentum distribution and contributions of correlated pairs (mesons) to the nucleon wave function. The basis for this approach is provided by the 'handbag" diagrams where the scattering amplitude can be factorized into a hard part exactly calculable in QCD and a nucleon structure part containing the *soft* physics parametrized via GPD's. For the DVCS, this framework should work already at Q^2 as low as 1 GeV^2. CLAS [19] gave one of the first experimental observation of this reaction using a 4.2 GeV polarized electron beam at $Q^2 = 1.5\ GeV^2$ and x_b=0.2. The experiment accessed the DVCS via the interference with the Bethe-Heitler (BH) process: for beam energies accessible at JLab, the BH contribution in the cross section is several times larger than DVCS contribution but it can be turned into an advantage by measuring the difference of beam-polarized cross sections. The measured beam spin asymmetry is reported in fig. 4. The clear asymmetry strongly supports expectations that DVCS will allow access to GPDs at relatively low energy and momentum transfer. Moreover, the results agree in sign and are not far in magnitude from predictions based on available models of GPD parameterization.

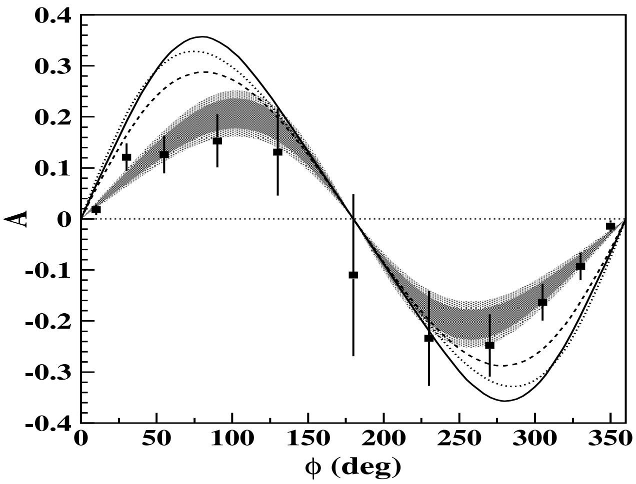

Figure 4. Φ dependence of the beam spin asimmetry A in the DVCS. Curves are modelcal culations at leading-Twist (dsahed and dotted) and with Twist-3 added (solid).

5.2 Vector meson photoproduction at large momentum transfer

At moderate energy and momentum transfer, this reaction can be described using hadronic (meson-baryon) degrees of freedom. As higher energies and momenta are reached this picture fails and the partonic degrees of freedom emerges.

The known forward-peaked cross section, traditionally interpreted in terms of diffractive production, can be parametrized by a hard mechanism at high momentum transfer, where exchange of gluon pairs can take place [20,21]. Beside the 'QCD-inspired' two-gluon exchange, other microscopic mechanisms such as quark exchange or quark correlations can also be investigated. CLAS experiments have measured the t dependence of the photoproduction of ϕ [22], ρ [23], and ω [24] on the proton up to values around 5 GeV^2 where, previously, only scarce data were available for the ρ and the ω and no data existed for ϕ production at $-t > 1\ GeV^2$. Figure 5 show the experimental results compared with a QCD-inspired model that successfully reproduces the three reactions. In the ϕ channel, due to the dominant $s\bar{s}$ component, the exchange of quarks is strongly suppressed. In fact, for $-t > 2$ GeV^2 the data rule out the diffractive Pomeron exchange, and its two-gluon realization alone is able to reproduce the data. In the calculation the gluons can couple to any quarks in the baryon, and quark correlations in the proton are taken into account. The two-gluon exchange mechanism alone badly misses the cross section at large $-t$ for the ρ and the ω photoproduction indicating that other reaction mechanisms are needed. Good agreement with data is obtained when quark-exchange processes are added to the calculation.

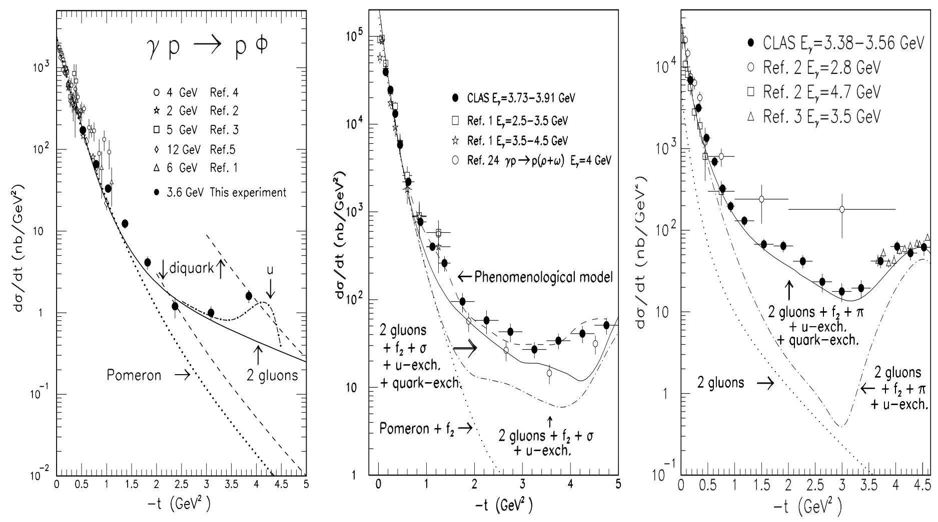

Figure 5. Differential cross sections for vector meson photoproduction at CLAS: ϕ (left) ρ (middle) and the ω (right).

6 Conclusions

Electromagnetic reactions provide insight into the world of hadronic structure, ranging from different aspects in the excitation of nucleon resonances to the partonic picture of hard processes. The large and broad experimental effort of the CLAS collaboration at Jefferson Laboratory is providing a wealth of new data that will help to clarify our understanding of nucleon structure and nuclear dynamics in the intermediate energy region, which is the domain of non-perturbative QCD. The new data put stronger constraints on QCD-inspired calculations showing that this kinematical region can be described as a *non perturbative partonic regime*, where microscopic degrees of freedom (gluons and quarks) are combined with a low-energy picture of hadrons (constituent quarks, dressed gluons).

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