Electro- and Photoproduction of Vector Mesons at Jefferson Lab

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Abstract. The total and differential cross section for exclusive electro- and photoproduction of vector mesons in the resonance region and above ($1.6 < W^* < 2.0$ GeV) was measured at Jefferson Laboratory in a wide kinematic range ($0 < Q^2 < 4$ GeV² and $0 < -t < 5$ GeV²). The measurement of the total and differential cross section down to 100 pb/GeV² with the full kinematic coverage, was possible for the first time thanks to the combination of the 100% duty cycle of CEBAF and the large acceptance of the CLAS detector. The main results from the CLAS Collaboration activity in this field will be presented and discussed.

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1. Introduction

Electro- and photoproduction of vector mesons are powerful tools to investigate baryon structure and strong interaction dynamics in the transition domain between perturbative QCD and hadronization scale. At CMS energy $W^* < 2$ GeV ρ [1] and ω meson production provides information about high mass nucleon excited states (*baryonic resonances*) difficult to see in $\pi^- N^+$ scattering. At higher energy the photon shows its hadronic structure fluctuating into a ($q\bar{q}$) state that can propagate and interact with the target nucleon. Being the formation time inversely proportional to the photon virtuality (Q^2), reactions with virtual and real photons allow to study complementary regimes: ρ and ϕ meson electroproduction [2] are sensitive to small propagation length and consequently to the quark structure of the interacting meson and nucleon; photoproduction at low momentum transfer shows the typical diffractive pattern of an elastic (hadron-hadron) scattering while large momentum

transfer selects small transverse size components of both photon and hadron. In this situation, hard processes (gluon and quark exchange) and other mechanisms like quark correlations may play a dominant role. It is expected that the combined measurement of ϕ [3] and ρ meson [4] over a wide range of t will allow the different contributions to be disentangled and better understood.

In this report I illustrate some general aspects of the electro- and photoproduction of vector mesons, as well as experimental issues and some selected results achieved by the CLAS Collaboration.

2. Electro- and Photoproduction of Vector Mesons at JLab -- Why?

Vector mesons (ρ , ω and ϕ) have the same quantum numbers as the photon ($J^{PC} = 1^{--}$) therefore, in certain conditions, a photon beam can be considered as a beam of quark-antiquark pairs. The hadronic structure of the photon arises from fluctuation of the virtual photon in a $(q\bar{q})$ state of mass M_V during a formation time τ given by the indetermination principle of Heisenberg:

$$\tau = \frac{2\nu}{(Q^2 + M_V^2)}, \quad (1)$$

where Q^2 is the squared mass and ν is the energy of the virtual photon. A given formation time corresponds to a formation distance (referred to as *coherence length*) $c\tau$ that has to be compared with the target (proton) diameter (~ 1.5 fm). In the kinematics of the CLAS experiments, electroproduction ($Q^2 \neq 0$) corresponds to a small propagation length (~ 0.5 fm) giving information about the nucleon and the vector meson structure while photoproduction ($Q^2 = 0$) at large energy is sensitive to the constituents of the exchanged quanta.

2.1. $W < 2$ GeV: the baryonic resonances

The low-mass region of the baryonic spectrum has been well reproduced by a variety of constituent quark models differing in confining potential, quark-quark spin/flavor interaction, etc. but the number of observed states is lower than predicted by theories originating the *missing states* issue. Although other models as the Quark Cluster Model [5] predict a smaller number of states based on reduced degrees of freedom. Taking in mind that the experimental information on baryon resonances has been obtained in reactions with a single pion present either in the initial or final state ($\pi N \rightarrow \pi N$ or $\gamma N \rightarrow \pi N$) and that many of the nucleons excited states in the mass region above 1.7 GeV decay predominantly in multipion channels, it is clear that ρ and ω production can be used for testing symmetry properties of the quark models.

2.2. $W > 2$ GeV: hadronic structure of the real/virtual photon

At higher photon energies we can distinguish two well-defined dynamical regimes depending on the momentum transfer $-t$.

The low $-t$ ($-t < 1$ GeV²) shows a diffractive behavior interpreted in the frame of the Vector Meson Dominance (VMD) model [6] as the elastic scattering of vector mesons off the proton target. In a more recent approach, this process is described by the t -channel exchange of the Pomeron and some other Regge trajectories (π , σ meson, $f_2(1270)$, etc.) [7]. Figure 1 shows the main reaction mechanisms and the good agreement in a wide W range for the total cross section dominated by the low $-t$ dynamics. Within a geometrical approach the coefficient of the exponential

Fig. 1. Total cross section of vector meson photoproduction. Dashed lines: Pomeron exchange. Dotted lines include also f_2 meson exchange. Full lines include in addition π and σ exchange.

diffractive term is related to the interaction radius and it is expected that the interaction region scales with the fluctuation time. While the existing good-quality photoproduction data show a good agreement for both the ρ and ϕ production, the available inaccurate ϕ electroproduction measurements do not show this trend. The same flat unexpected behavior is visible when the Q^2 dependence is considered. New precise data are necessary to really understand this dynamical region.

At high $-t$ ($-t > 1$ GeV²) the underlying physics can be described using parton degrees of freedom. In a QCD-inspired framework, the small impact parameter ($\approx 1/\sqrt{t}$) prevents the constituent gluons (quarks) of the exchange from interacting and forming a Pomeron (Reggeon). Within certain models [8,9] this means that the constituents can be resolved into two-gluon (two-quark) structures (Fig. 2a). Moreover, small transverse sizes select configurations where each gluon couples to different quarks both in the vector meson and the nucleon, giving access to the correlation function in the proton (Fig. 2b) [7]. Due to the dominant ss component of

the ϕ , and to the extent that the strangeness of the proton is small, the ϕ photoproduction at large $-t$ is a good tool to resolve the Pomeron into its simplest 2-gluon component. In the ρ case, its light quark composition also allows valence quarks to be exchanged between the baryon and the meson states (Fig. 2c) [7]. The comparison between the two channels puts stringent constraints on our understanding of reaction mechanisms. Vector meson experiments planned at Jefferson Laboratory

Fig. 2. The Feynman diagrams corresponding to a) two-gluon exchange from a single quark, b) two-gluon exchange taking into account quark correlations in the nucleon and c) quark exchange

in the resonance region and above ($1.6 < W < 2.9$ GeV), covering the whole momentum transfer (up to $-t = 5$ GeV²) and a wide range in Q^2 ($0 < Q^2 < 4$ GeV²) have been partially completed, giving useful information in this transition regime.

3. Experimental Setup

The data were obtained with the CEBAF Large Acceptance Spectrometer (CLAS) in Hall B of the Thomas Jefferson National Accelerator Facility. CLAS is a nearly 4π spectrometer based on a toroidal magnetic field generated by 6 superconducting coils. Three drift chamber regions allowed tracking of charged particles; time of flight scintillators were used for hadron identification. Scattered electrons were detected by a coincidence between Cherenkov counters and electromagnetic calorimeters (also used for neutral particles detection). Momentum resolution of the electron and hadron is of the order of 1% while detector efficiencies, referred to the full solid angle, range from 50% for electron to about 70% for protons and pions. To cover a wider Q^2 range, the electroproduction data were taken with different electron beam energies (2.6 and 4.2 GeV). The photoproduction experiments were performed using the CEBAF Hall B bremsstrahlung photon beam, tagged in the E_γ range 3–4 GeV high intensity flux (6×10^6 γ/s), which was measured with a pair spectrometer calibrated using a total absorption counter in dedicated low intensity runs. In electroproduction experiments, the trigger required a single scattered electron signal, identified as a coincidence of the calorimeter and the Cherenkov counters. Data were recorded at an instantaneous luminosity of 10^{34} cm⁻²s⁻¹. In photoproduction experiments the coincidences between the photon tagger and the CLAS detector (TOFs) triggered the recording of hadronic interactions. In both cases the acquisition rate was higher than 1 kHz.

4. Data Analysis

The reaction $\gamma_{e,p} \rightarrow p\phi$ has been measured via proton and k^+ detection and missing (k^-) mass technique. Due to the good CLAS resolution, a clear peak in the k^- mass region is visible and allows the identification of the two-kaon final state. In each t bin of the invariant (k^+k^-) mass, the non-resonant background under the ϕ peak was subtracted in different ways (fitting the shape of the data and using a simple model). In this approach an evaluation of the systematic error related to the ϕ separation was obtained. The CLAS efficiency and its geometrical acceptance was determined using a realistic event generator (improved using the measured distribution and iterating the procedure) and a GEANT-based description of the detector. The small width of the ϕ allowed to bin the efficiency as a function of the a quasi-two-body reaction variables without introducing any model dependence.

The reaction $\gamma_{e,p} \rightarrow pp^0$ with $p^0 \rightarrow \pi^+\pi^-$ has been measured detecting all possible final configurations containing at least two hadrons and using the missing mass technique when necessary. The large width of the rho meson (~ 150 MeV) required a careful evaluation of the detector efficiency as a function of the six kinematical variables (corresponding to the three hadrons in the final state) to avoid any model dependency. For each (E_γ , Q^2 , $-t$) bin, a simultaneous fit of both the invariant mass ($p\pi^+$) and ($\pi^+\pi^-$) was performed using an extension of the model of Ref. [10] in order to separate the ρ production from the other channels ($\Delta^0\pi^+$, $\Delta^+\pi^-$, phase space, $f_2(1270)$) contributing to the $p\pi^+\pi^-$ final state.

5. Results

5.1. The baryonic resonances

While the data analysis to separate the ρ channel is still in progress, Fig. 3 shows the two-pion total virtual photon cross section for two Q^2 bins in the full accessible W range; CLAS is providing very high statistics and moreover the data points exhibit a structure not visible in previous data. We can notice that the relative weights of the bumps changes in the two plots corresponding to a different Q^2 evolution of different resonance states. The lines correspond to the phenomenological model reported in Ref. [10] where the double charge pion production is described as superposition of three-body phase space and quasi-two-body channels ($\gamma p \rightarrow pp^0$, $\gamma p \rightarrow \Delta^+\pi^-$, $\gamma p \rightarrow \Delta^0\pi^+$) with subsequent decays. The non-resonant terms were introduced via Regge theory and diffractive production; resonance electromagnetic excitation was described through a Single Quark Transition Model fit [11], while partial decay widths were taken from a previous phenomenological analysis of hadronic data [12]. The structure observed at W around 1.5 GeV is strongly resonant, as expected in particular from the $D_{13}(1520)$, and well described by the model; there is instead a discrepancy around 1.4 GeV that may be an indication of a strong longitudinal resonance coupling (the 'Roper'). Also the structure observed at W around 1.7 con-

Fig. 3. Total virtual photon cross section as function of the CMS energy W for $\gamma p \rightarrow p\pi^+\pi^-$ at Q^2 between 0.5 and 0.8 GeV^2 (top) and Q^2 between 0.8 and 1.1 GeV^2 (bottom). Solid line represent the model described in the text.

tains sizable resonance excitations but the calculation underestimates the strength. This discrepancy is currently being investigated in terms of missing states.

The diffractive production and the meson-exchange can only reproduce the angular distribution at forward angles while the sizable cross section at backward angles could be explained in terms of known and missing resonance contribution.

Fig. 4. The reaction $\gamma p \rightarrow p\phi$. Left: differential virtual photon cross section as function of momentum transfer. Right: the Q^2 dependence of the total cross section.

5.2. The hadronic structure of the photon: small and large momentum transfer

In the low momentum transfer regime the measurements of exclusive ϕ electroproduction for $2 < W < 2.6$ GeV and $0.7 < Q^2 < 2.2$ GeV^2 [2] will be presented. Figure 4 (left) shows the measured differential cross section. While the diffractive pattern (exponential) is clearly visible at low momentum transfer, the data seem to indicate a change of slope around $-t \sim 1$ GeV^2 suggesting that additional mechanisms may be present. The good χ^2 obtained fitting to an exponential a limited (solid) and the whole $-t$ range (dashed) indicates that higher statistics is necessary for any conclusions. Figure 4 (right) shows the Q^2 dependence of the total cross section well reproduced by the Pomeron exchange model of Ref. [9]. The dependence of

Fig. 5. The reaction $\gamma p \rightarrow p\phi$. Left: the dependence of t -slope, b on cr . Right: the dependence of t -slope, b on Q^2 .

the t -slope, b , on formation distance, cr , is shown in Fig. 5 (left). We expect that b should decrease at low r as the interaction becomes more point-like. The previous electroproduction measurements do not show the expected behavior. However, a consistent picture emerges when we include photoproduction data as well. Both our data points (stars) lie in the region cr below 1 fm, and show a decrease of b with decreasing formation time, when combined with other data. From the fit of the ϕ world data (solid line in Fig. 5 (left)) and comparing the same fit for the p data, the ratio b_ϕ/b_p was extracted:

$$\frac{b_\phi}{b_p} = \left(\frac{R_\phi^{\text{int}}}{R_p^{\text{int}}} \right)^2 = 0.87 \pm 0.08, \quad (2)$$

indicating that the ϕ interaction size is smaller than that for the p meson.

As far as the Q^2 dependence is concerned, the same coherent picture is obtained when our points are added to the existing photo- and electroproduction data. Figure 5 (right) shows the dependence of the t -slope b on Q^2 simply explained (solid lines) by the implicit dependence of α on Q^2 (Eq. (1)).

In the large momentum transfer regime both ϕ [3] and ρ [4] photoproduction data will be discussed. The measured $d\sigma/dt$ for elastic ϕ photoproduction on the proton, up to $-t = 4 \text{ GeV}^2$ is shown in Fig. 6. At low momentum transfer the two-

Fig. 6. The differential cross section of the reaction $\gamma p \rightarrow p\phi$. See text for explanation.

gluon exchange model of Laget and Mendez-Galain [7,9] (solid line) coincides with the well known diffractive behavior (dotted line). For $-t > 2 \text{ GeV}^2$ the data rule out the diffractive Pomeron exchange and strongly favor its two-gluon realization. In the calculation the gluons can couple to any quarks in the baryon (see Fig. 2a,b) and quark correlations in the proton are taken into account assuming the simplest form of its wave function with three valence quarks equally sharing the proton longitudinal momentum. Close to the kinematic limit t_{max} , the good agreement with data is obtained adding the baryon exchange in the u -channel. In the same plot two perturbative QCD calculations are also shown (dashed lines). Both of them are not able to describe the data demonstrating that the asymptotic regime is not

yet reached. The obtained $d\sigma/dt$ for elastic ρ photoproduction on the proton, up to $-t = 5 \text{ GeV}^2$ has been plotted in Fig. 7. The comparison with a model similar to Ref. [7] is also shown (dot-dashed line). The parameters of the two-gluon exchange mechanism are fixed from the analysis of the ϕ channel. The low momentum transfer region is well reproduced when the two Regge trajectories (f_2 and σ) are included while the model underestimates the large $-t$ region, indicating that other reaction mechanisms are needed. The good agreement with data is obtained (solid line) when quark-exchange processes (see Fig. 2c) are added. These hard scattering mechanisms can be incorporated in an effective way by replacing the linear Regge trajectories with a saturating trajectory [13]. Quark exchange increases the cross section at large $-t$ by a factor two.

Fig. 7. The differential cross section of the reaction $\gamma p \rightarrow p\rho^0$. See text for explanation.

The power law s^{-C} fit to $d\sigma/dt$ at 90° in the center of mass is performed using the old SLAC data and the new CLAS points. The fit yields $C = 7.9 \pm 0.3$ ($\chi^2 = 0.6$) showing a good agreement with s^{-8} behavior. The quark exchange diagrams of Fig. 2c (left: point-like interaction) and 2c (right: hadronic component of the photon) have a s^{-7} and s^{-8} power-law behavior respectively, both by dimensional counting [14] and by recent models [15]. Note that also the saturated σ Regge trajectory behaves like s^{-8} . Like the differential cross section at fixed energy, the s dependence suggests the presence of quark interchange hard mechanisms in addition to the two-gluon exchange process.

6. Conclusion

The electro- and photoproduction of vector mesons are unique tools to study and understand the quark-gluon structure of hadronic matter. Precise measurements and full kinematic coverage are necessary in order to disentangle the different mechanisms competing at intermediate energies. The Hall B of Jefferson Lab completed a set of experiments with photons and electrons covering a wide kinematic range: $1.6 < W < 2.9$ GeV, $0 < -t < 5$ GeV² and $0 < Q^2 < 4$ GeV². Billions of events were collected during the 1998–2001 data taking and first physics outputs are coming up. At low energy ρ and ω electroproduction show a significant resonance contribution and some evidence for ‘missing’ states. At high energy and low $-t$, the ϕ electroproduction shows that the interaction region scales with the formation time while at large momentum transfer a consistent picture is emerging from ϕ and ρ photoproduction showing that this kinematical region can be described as a *non perturbative partonic regime* where microscopic degrees of freedom (gluons and quarks) mix together with lower energy hadrons picture (constituent quarks, dressed gluons).

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