N^* program at CLAS

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Abstract

The N^* program is one of the major goals of CLAS experiments in Jefferson Lab and many outstanding results have been carried out. In this note, I will present some highlight recent measurements of nucleon resonance transition form factors from electro-production as the second resonances. The new pion electro-production data resolve a long-standing puzzle of the nature of the Roper resonance, and confirm the assertion of the symmetric constituent quark model of the Roper as the first radial excitation of the nucleon. The single pion electro-production data for high Q^2 confirms the slow fall off of the $S_{11}(1535)$ transition form factor with Q^2, and better constrain the branching ratios $\beta_{N\pi} : \beta_{N\eta} = 0.50 : 0.45$. For the first time, the longitudinal transition amplitude to the $S_{11}(1535)$ was extracted from the $n\pi^+$ data. Also, new results on the transition amplitudes for the $D_{13}(1520)$ resonance are presented showing a rapid transition from helicity $3/2$ dominance seen at the real photon point to helicity $1/2$ dominance at higher Q^2.

Keywords: N^*, nucleon resonance, transition form factors, Roper, $S_{11}(1535)$, $D_{13}(1520)$, helicity amplitudes

1. Introduction

Electro-excitation of nucleon resonances has long been recognized as a essential tool in the exploration of the complex nucleon structure at varying distances scales. Resonances play an important role in fully understanding the spin structure of the nucleon. Electro-excitation of resonances allows us to probe the internal structure of the excited state knowing the structure of the ground state. The most comprehensive predictions of the resonance excitation spectrum come from the various implementation of the symmetric constituent quark model based on broken $SU(6)$ symmetry [2]. Other models predict a different excitation spectrum, e.g. through a diquark-quark picture, or through dynamical baryon-meson interactions. The different resonance models not only predict different excitation spectra but also different Q^2 dependence of transition form factors. Mapping out the transition form factors will tell us a great deal about the underlying quark or hadronic structure. The CLAS is the large acceptance instrument with sufficient resolution to measure exclusive electro-production of mesons with the goal of studying the excitation of nucleon resonances in detail. The entire resonance mass region, a large range in the photon virtuality Q^2 can be studied, and many meson final states are measured simultaneously [1].

2. Exclusive single pion electro-production

The latest investigation of baryon resonances with new optimized detector systems, such as large angle and momentum covered CLAS and a high-intensity continuous electron beam, have been started and their data has recently become available. Isoscalar, isovector, and electric, magnetic or longitudinal multipoles of coupling to hadronic matter proves different aspects of the strong interaction. Here I briefly present some helicity amplitudes in the second resonances.

- The $P_{11}(1440)$ state

The $P_{11}(1440)$ resonance has been an attention for more than 40years, largely due to the inability of the standard constituent quark model to describe basic features such as the mass, photocouplings, and Q^2 evolution. This has led to alternate approaches where the state is treated as a gluonic excitation of the nucleon [3], or has a small quark core with a large meson cloud [4], or is a hadronic molecule of a nucleon and a σ meson [5]. Quenched lattice QCD calculations [10] indicate that the state has a significant 3-quark component, and calculate the mass to be close to the experimental

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value. Many different theoretical concept for the structure of the state predicted various way. So, essential question about nature of the Roper has been a focus of the N^* program with CLAS. The state couples to both $N\pi$ and $N\pi\pi$ final states. It is also a very wide resonance width about 350 MeV. Therefore single and double pion electro-production data covering a large range in the invariant mass W, with full center-of-mass angular coverage are crucial in extracting the transition form factors in a broad Q^2 range. As an isospin $I = 1/2$ state, the $P_{11}(1440)$ couples more sensitive to $n\pi^+$ and much reduced contributions of the high energy tail of the $\Delta(1232)$ in that channel due to different $I = 3/2$ of the $\Delta(1232)$.

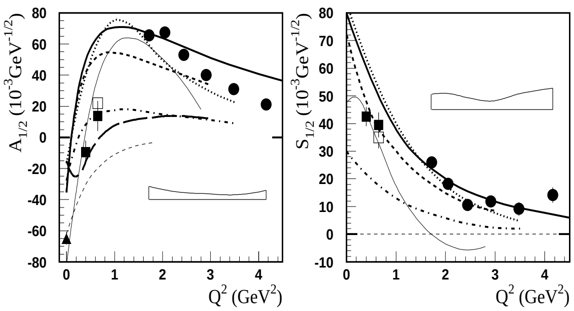

Figure 1: Transverse electrocoupling amplitude for the Roper $P_{11}(1440)$ (left panel). The full circles are the new CLAS results. The squares are previously published results of fits to CLAS data at low Q^2. The bold curves are all relativistic light front quark model calculations [11]. The thin solid line is a non-relativistic quark model with a vector meson cloud [4], and the thin dashed line is for a gluonic excitation [3]. The right panel shows the longitudinal amplitude.

The recent single charged pion electro-production data from CLAS [7] have been analyzed using a fixed-t dispersion relations approach and a unitary isobar model (UIM) [6]. Some of the features of the data may best be seen in the Legendre moments. Response functions can be expressed in terms of Legendre polynomials, e.g. the azimuthal angle independent part of the differential cross section can be written as: $\sigma_T + \epsilon\sigma_L = \sum_{\ell=0}^{\infty} D_\ell^{T+L} P_\ell(cos\Theta_\pi^*)$. The transverse and longitudinal electro-coupling amplitudes $A_{1/2}$ and $S_{1/2}$ of the transition to the $P_{11}(1440)$ resonance are extracted from fits to the data [8]. They are shown in Fig. 1. At the real photon point $A_{1/2}$ is negative. The CLAS results show a fast rise of the amplitude with Q^2 and a sign change near $Q^2 = 0.5$ GeV^2. At $Q^2 = 2$ GeV^2 the amplitude has about the same magnitude but opposite sign as at $Q^2 = 0$. It slowly falls off at high Q^2. This remarkable behavior of a sign change with Q^2 has not been seen before for any nucleon transition form factor or elastic form factor. The longitudinal amplitude $S_{1/2}$ is large at low Q^2 and drops off smoothly with increasing Q^2. These measurements allows us to rule out the hybrid baryon model for both amplitudes. At high Q^2 both amplitudes are qualitatively described by the light front (LF) quark models, which strongly suggests that the Roper is indeed a radial excitation of the nucleon. The low Q^2 behavior is not well described by the LF models and they fall short of describing the amplitude at the photon point. This indicates that important contributions, e.g. meson-baryon interactions at large distances are missing.

- The $S_{11}(1535)$ state

The $S_{11}(1535)$ state was found to have an unusually hard transition form factor, i.e. the Q^2 evolution shows a slow fall-off. This state has mostly been studied in the $p\eta$ channel where the $S_{11}(1535)$ appears as a rather isolated resonance near the $N\eta$ threshold and with very little non-resonant background. Data from JLab using CLAS [12, 13] and Hall C [14] instrumentation, have provided a consistent picture of the Q^2 evolution obtained from η electro-production data alone, confirming the hard form factor behavior with precision. There are two remaining significant uncertainty in the electromagnetic couplings of the $S_{11}(1535)$ that need to be examined. The first one is due to the branching ratio of the $S_{11}(1535) \to p\eta$, the second one is due to the lack of precise information on the longitudinal coupling, which in the $p\eta$ channel is usually neglected. The $p\eta$ data have been normalized using a branching ratio $\beta_{N\eta} = 0.52$, while the PDG gives a range of $\beta_{N\eta}^{PDG} = 0.45 - 0.60$. Since this state practically does not couple to other channels than $N\eta$ and $N\pi$, a measurement of the reaction $ep \to e\pi^+ n$ will reduce this uncertainty. Also, the $N\pi$ final state is much more sensitive to the longitudinal amplitude due to a strong $S_{11} - P_{11}$ interference term present in the $N\pi$ channel. With these goals in mind the CLAS $n\pi^+$ data have been used to determine the electrocoupling amplitudes for the $S_{11}(1535)$. Using the average values $\bar{\beta}_{N\pi}^{PDG} = 0.45$ and $\bar{\beta}_{N\eta}^{PDG} = 0.52$, the $n\pi^+$ data fall systematically above the $p\eta$ data set. Adjusting $\beta_{N\pi} = 0.50$ and $\beta_{N\eta} = 0.45$ brings the two data sets into excellent agreement for the higher Q^2 data, as shown in Fig. 2. There could be a 10-20% difference for the $Q^2 = 0.4,\ 0.6$GeV^2 points, which indicates that meson-cloud effects may play some role at low Q^2, possibly affecting the results differently in the two channels. Analysis that take coupled channel effects into account are needed to fully clarify the low Q^2 behavior.

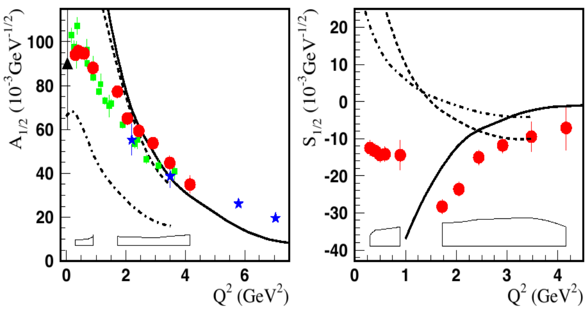

Figure 2: (color online) The transition amplitude $A_{1/2}$, $S_{1/2}$ for the $S_{11}(1535)$. The bullets are from the CLAS $n\pi^+$ and $p\pi^0$ analysis data [8] [9]. The other data are from the $p\eta$ channel [12–14]. Curves are various constituent predictions: thin solid: [15], thick-solid: [16], dashed: [17], dashed-dotted: [18] and dotted: [19].

As mentioned above an advantage of the $N\pi$ channel in studying the $S_{11}(1535)$ is that it is also sensitive to the longitudinal transition amplitude, while the $N\eta$ channel has little sensitivity and requires a Rosenbluth separation to separate the transverse and longitudinal terms. In the $N\pi$ case, the sensitivity is due to a significant $s-p$ wave interference with the nearby p-wave amplitude of the $P_{11}(1440)$. This can be seen in the multipole expansion of the lowest Legendre moment for the σ_{LT} response function: $K/|\vec{q}|\ D_0^{LT} = Re(E_{0+}S^*_{1-} + S_{0+}M^*_{1-})$. The second term is very sensitive to the S_{0+} multipole of the $S_{11}(1535)$ due to the strong transverse Roper multipole (M_{1-}), especially at high Q^2. The results show significant negative values for the $S_{1/2}$ amplitude of $S_{11}(1535)$.

- The $D_{13}(1520)$ state

A calculation of the dynamical constituent quark model predicts the rapid helicity switch from the dominance of the $A_{3/2}$ at the $Q^2 = 0$ GeV^2 to the dominance of the $A_{1/2}$ amplitude at $Q^2 > 1$ GeV^2. In the simple non-relativistic harmonic oscillator model with spin and orbit flip amplitudes only, the ratio of the two amplitudes is given by: $\frac{A^{D13}_{1/2}}{A^{D13}_{3/2}} = \frac{-1}{\sqrt{3}}(\frac{\vec{Q}^2}{\alpha} - 1)$, where α is a constant adjusted to reproduce the ratio at the photon point where $A_{1/2}$ is very small. It is clear that the model predicts a rapid rise of the ratio with Q^2. Figure 3 shows the results for the two transverse amplitudes. We observe the decreasing $A_{3/2}$ amplitude rapidly as increasing Q^2. The $A_{1/2}$ amplitude increases rapidly in magnitude with increasing Q^2, before falling off slowly at $Q^2 > 1$ GeV^2 and $A_{1/2}$ completely dominates at $Q^2 > 2$ GeV^2.

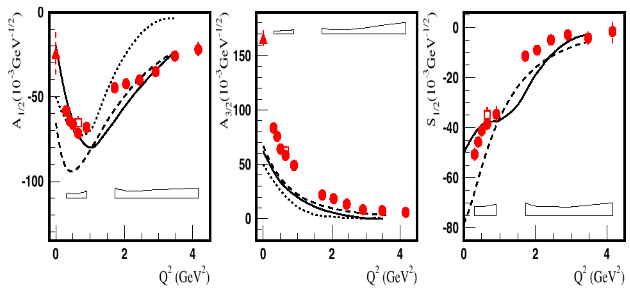

Figure 3: (color online) Transverse helicity amplitudes $A_{1/2}$ (left), $A_{3/2}$ (middle) and $S_{1/2}$ (right) for the $D_{13}(1520)$. The helicity switch is clearly visible. Model curves are the same as in Fig. 2

3. Conclusions

The hadron structure investigation is directly linked to the study of effective degrees of freedom at varying distance scales. With the recent precise data on pion and eta electro-production, combined with the large coverage in Q^2, W, and center-of-mass angles, the study of nucleon resonance transitions has become an effective tool in the exploration of nucleon structure in the domain of strong QCD and confinement. The latest data from CLAS on charged pion production reveal a sign change of the transverse amplitude for the $P_{11}(1440)$ transition near $Q^2 = 0.5$ GeV^2 and slow fall off in high Q^2 give strong evidence for this state as the first radial excitation of the nucleon. The hard transition form factor of the $S_{11}(1535)$ previously observed only in the $p\eta$ channel is confirmed in the $n\pi^+$ channel, which also allows us to extract the so far unmeasured longitudinal amplitude $S_{1/2}$. The $D_{13}(1520)$ clearly exhibits the helicity flip behavior by observing the A_{hel}, which is consistent prediction by the constituent quark model. In the LF system the Dirac and Pauli form factors $F1$ and $F2$ can be interpreted as two-dimensional charge densities by Fourier transformation. Figure 4 shows the transition charge density in transverse impact parameter space for the $P_{11}(1440)$ and $D_{13}(1520)$ states [20]. It is also important to achieve the successful combined description of all observable s in the single- and double-pion electro-production off the nucleon for a common set of N^* helicity coupling amplitudes and hadronic parameters, because it would ensure a reliable separation between non-resonant and resonant contributions in both channels. Such a successful combined CLAS analysis in both exclusive channels for a common set of N^* electro-coupling and hadronic parameters has been achieved at $Q^2 = 0.4,\ 0.65\text{GeV}^2$.

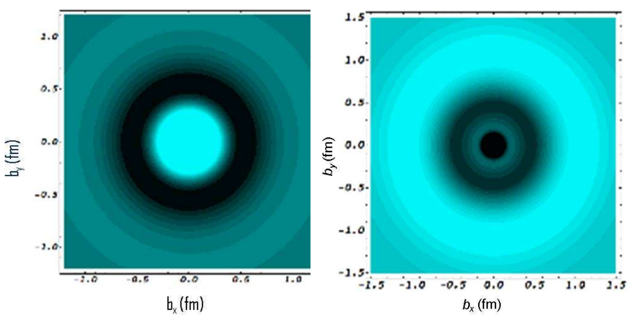

Figure 4: (color online) Transverse transition charge densities in the light front system for the proton to $P_{11}(1440)$ (left) and $D_{13}(1520)$ (right) transitions in the light-front helicity $+1/2 \rightarrow +1/2$. The light area indicates dominance of up quarks(positive charge), the dark area is down quark(negative charge) dominance.

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