Electromagnetic Transition Form Factors of Nucleon Resonances.

Volker D. Burkert

Jersey Laboratory
12000 Jersey Avenue, Newport News, VA 23606
E-mail: burkert@jlab.org

Abstract. Recent measurements of nucleon resonance transition form factors with CLAS at Jersey Lab are discussed. The new 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 data on high Q^2 n^+ production confirm the slow fall-off of the S_11 (1535) transition form factor with Q^2, and better constrain the branching ratios \eta = 0.50 and \xi = 0.45. For the first time, the longitudinal transition amplitude to the S_11 (1535) was extracted from the n^- 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.

PACS. 13.60.Le, 13.88.+e

1 Introduction

Electroexcitation of nucleon resonances has long been recognized as a sensitive 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. More than 80% of the helicity-dependent integrated total photoboson cross section difference (GDH integral) are the result of the N (1232) transition [1,2], and at a photon virtuality Q^2 = 1 GeV^2 m ore than 50% of the rst moment \int_0^1 g_1(x,Q^2) dx of the spin structure function g_1 for the proton are due to contributions of the resonance region at W < 2 GeV [3], and are crucial for describing the entire Q^2 range of \int f (Q^2) and \int n (Q^2) for the proton and proton-neutron difference respectively [4,5,6].

Nucleon resonances are of high interest in their own right. Electroexcitation 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 in plane extrapolation of the symmetric constituent quark model based on broken SU(6) symmetry [8]. Other models predict a di erent excitation spectrum, e.g. through a diquark-quark picture, or through dynamical baryon-meson interactions. The di erent resonance models not only predict di erent excitation spectra but also di erent 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.

CLAS is the rst full acceptance instrument with sufficient resolution to measure exclusive electroproduction 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-nucleon states are measured simultaneously.

Fig. 1. R_E and R_M extracted from exclusive reactions p(ee'p) using modern analysis tools, e.g. unitary isobar models and dispersion relations. Recent quenched Lattice QCD points are shown as well.
In this talk I discuss recent results from the electroproduction of single pions to study several well-known excited states.

2 The N (1232) transition

An interesting aspect of nucleon structure at low energies is a possible quadrupole deformation of the nucleon's lowest excited state, the (1232). Such a deformation would be evident in non-zero values of the quadrupole transition amplitudes $E_{1+}$ from the nucleon to the (1232) [10]. In models with SU(6) spherical symmetry, the N transition is simply due to a magnetic dipole $M_1$, mediated by a spin $1/2$ and $E_{1+} = S_{1+} = 0$. Dynamically, quadrupole deformations are generated through the interaction of the photon with the pion cloud [11,12] or through the one-gluon exchange mechanism [3]. At asymptotic momentum transfers, a model-independent prediction of helicity conservation requires $R_{EM} = E_{1+} = M_1 = 1$. An interpretation of $R_{EM}$ in terms of a quadrupole deformation can only be valid at low momentum transfer.

Results of the multipole analysis of the JLab data [13,14,19,20] as well as low $Q^2$ data from MAMI [13,21,22] and CLAS [23] are shown in Fig. 1. A consistent picture emerges from these precise data.

- $R_{EM}$ remains negative, small and nearly constant in the entire range $0 < Q^2 < 6$ GeV$^2$.
- There are no indications that leading pQCD contributions are important as they would result in $R_{EM} = 1$ [24].

Comparison with microscopic models shows that a simultaneous description of both $R_{EM}$ and $R_{SM}$ is achieved with dynamical ISJOM models that include pion-nucleon interactions explicitly. This supports the claim that most of the quadrupole strength in the N (1232) transition is due to pion e ections which are usually not included in quark models. From Fig. 3 we conclude that at the real photon point 1/3 of the transition strength is due to pion e ections, which extends to rather high $Q^2$, although with decreasing relative strength.

The MAMI unitary isobar model has been frequently used in the analysis of pion electroproduction data. I want to comment on one aspect of the 2007 version MAMI 07 that has generated some confusion regarding the results of analysis compared to the 2003 version MAMI 03. Independent analyses of the JLab data from CLAS and Hall C have been carried out with the MAMI framework and MAMI 07 [17]. MAMI 03 parameters were adjusted by analysing the 2001 CLAS cross section data [19] and the higher $Q^2$ Hall C data [23]. In Fig. 3 the MAMI 03 parameters are used and the predictions compared with the CLAS data published in 2006 [19] for the response function $R_{EM}$ in the (1232) mass region showing excellent agreement. The extracted $R_{EM}$ ratio showed a strong rise in magnitude with $Q^2$ consistent with the values shown in Fig. 3 from the CLAS 2006 data that were not included in the fit. In MAMI 07 a new set was made that now included the CLAS 2006 data but did not include the previ-
ously used HallC data. The results of that are shown in the right panels in Fig. 4, and clearly compare much less favorably with the measured elastic resonance function. It also results in an almost Q^2-independent behavior at high Q^2, in clear contradiction to the previously obtained strong rise in magnitude with Q^2. It appears that this discrepancy is an artifact of the parametrization used in MAID 07 for the R_{SM} ratio, which includes the constraint R_{SM} = constant, the asymptotic limit for Q^2 = 1. However, this constraint is not justified as there are no indications that asymptotic behavior is relevant even in R_{EM} (which would require R_{EM} = 1, while the data show R_{EM} < 0.5), or in the extraction of R_{SM} when not constrained by the presumed asymptotic behavior.

Ultimately, we want to come to a QCD description of these important nucleon structure quantities. In recent years significant effort has been extended towards a lattice QCD description of the N transition. With the still large error bars, both quenched and unquenched calculations at Q^2 < 1.5 GeV^2 with pion masses of 400 M eV are consistent with a constant negative value of R_{EM} = 0.2, in agreement with the data. For the R_{SM} ratio there is a clear discrepancy at low Q^2 in both quenched and unquenched QCD calculation while the rise in magnitude of R_{SM} with Q^2 observed in the data is quantitatively reproduced in full QCD at the Q^2 > 1 GeV^2.

The measured N transition form factors extend to Q^2 = 6 GeV^2, and show no sign of the expected asymptotic behavior. It would be very interesting to see if lattice QCD calculations can describe the observed strong Q^2 dependence of R_{SM}, and the near lack of Q^2 dependence of R_{EM} at high Q^2.

3 The second resonance region

Three states, the Roper P_{11}(1440), and two strong negative parity states, D_{13}(1520), and S_{11}(1535) make up the second enhancement seen in inclusive electron scattering.

![Figure 4](https://example.com/figure4.png)

Fig. 4. W dependence of the three lowest Legendre moments from n^- angular distributions at xed Q^2 = 2.05 GeV^2. The dotted line indicates the cross section when the amplitudes of the P_{11}(1440) are set equal to 0.

3.1 The Roper resonance P_{11}(1440) - a puzzle resolved

The P_{11}(1440) resonance has been a focus of attention for the last decade, largely due to the inability of the standard constituent quark model to describe basic features such as the mass, coupling, and Q^2 evolution. This has led to alternate approaches where the state is treated as a quark excitation of the nucleon, or a small quark core with a large meson cloud, or a hadronic molecule of a nucleon and a meson. Quenched lattice QCD calculations indicate that the state has a significant 3-quark component, and calculate the mass to be close to the experimental value.

Given these different theoretical concepts for the structure of the state, the question "What is the nature of the Roper state?" has been a focus of the N program with CLAS. The state couples to both N and N* states. It is also a very wide resonance with about 350 M eV total width. Therefore single and double pion electroproduction data covering a large range of the invariant mass W, with full center-of-mass angular coverage are crucial in extracting the transition form factors in a large range of Q^2. A spin-isospin I = 1/2 state, the P_{11}(1440) couples more strongly to n^- than to p^+. The low contributions of the high energy tail of the (1232) are much reduced in that channel due to the I = 3/2 of the (1232).

Over 33,000 di erential cross section data points and polarized beam asymmetries from CLAS have been analyzed using a self-consistent reaction approach and a unitary isobar model. Some of the features of the data may be best seen in the Legendre moment decomposition. Response functions can be expressed in terms of Legendre polynomials, e.g., the azimuthal angle independent part of the di erential cross section can be written as:

\[ T = \sum_{l=0}^{\infty} \frac{\alpha}{\beta} D_{l}^T \cos \theta. \]

Figure 5 shows the lowest Legendre moments for this response function. The transverse and longitudinal electrocoupling amplitudes for the P_{11}(1440) resonance are extracted from the data. They are shown in Fig. 5. 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 o
at high $Q^2$. This remarkable behavior of a significant change with $Q^2$ has not been seen before for any nucleon transition form factor or elastic form factor. The longitudinal amplitude $S_{1\to 2}$ is large at low $Q^2$ and drops smoothly with increasing $Q^2$. The bold curves are all relativistic light front quark model calculations [21]. The thin solid line is a non-relativistic quark model with a vector meson cloud [22], and the thin dashed line is for a gluonic excitation [23]. The rst results for the transition form factors of the $R$ oper have recently been obtained in unquenched QCD [24].

The hybrid baryon model is clearly ruled out for both amplitudes. A high $Q^2$ both amplitudes are qualitatively described by the light front quark model, which strongly suggests that the $R$ oper is a radial excitation of the nucleon. The low $Q^2$ behavior is not well described by the LF model 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 may be missing.

3.2 The $S_{1\to 1}$ ($1535$) state

The $S_{1\to 1}$ ($1535$) state was found to have an unusual and hard behavior, i.e., the $Q^2$ evolution shows a slow falloff. This state has only been studied in the $p$ channel where the $S_{1\to 1}$ ($1535$) appears as a rather isolated resonance near the $N$ threshold and with very little nonresonant background. Data from JLab using CLAS [25, 26] and HallC [27] have provided a consistent picture of the $Q^2$ evolution from elastic electroproduction data alone, confirming the hard form factor behavior with precision. There are two remaining significant uncertainties in the electromagnetic couplings of the $S_{1\to 1}$ ($1535$) that need to be examined. The rst one is due to the branching ratio of the $S_{1\to 1}$ ($1535$), i.e., the second one is due to the lack of precise information on the longitudinal coupling, which in the $p$ channel is usually neglected.

The $p$ data have been normalized using a branching ratio $N_N = 0.52$, while the PDG gives a range of $0.45 - 0.60$. This state is not coupled to other channels than $N$ and $N'$ and an measurement of the reaction $p + n \to p' + n'$ will reduce this uncertainty. A second, the $N'$ state is much more sensitive to the longitudinal amplitude than the $p$ channel. Data in Ref. 20 have been used to determine the electrocoupling amplitudes for the $S_{1\to 1}$ ($1535$). Using the average values $N_N = 0.45$ and $N_N = 0.52$, the $S_{1\to 1}$ ($1535$) data fall systematically above the $p$ data set. Adjusting $N_N = 0.50$ and $N_N = 0.45$ brings the two data sets into excellent agreement for the higher $Q^2$ data, as shown in Fig. 6. The clean channel sym boles show the results in the $p$ channel. The full circles are from the analysis of the CLAS $S_{1\to 1}$ data [28]. The square sym boles are from the analysis of earlier CLAS $p - p$ data [29].

The theory curves are from various constituent quark model calculations and quark model calculations [42]. There could be a 10-20% difference between the $N$ and $N'$ for the $Q^2 = 0.4$, $0.6$ GeV$^2$ points. This indicates that meson-cloud effects may play some role at low $Q^2$, possibly affecting the results differently in the two channels. Analyses that take coupled-channel effects into account are needed to fully clarify the low $Q^2$ behavior. As mentioned above, the $p$ channel in studying the $S_{1\to 1}$ ($1535$) is not sensitive to the longitudinal transition form factor, while the $N$ channel has little sensitivity and requires a Rosenbluth separation to separate the transverse and longitudinal components. In the $N'$ case, the sensitivity is due to a significant wave interference with the nearby $p$-wave amplitudes of the $P_{1\to 1}$ ($1440$). This can be seen in the multipole expansion of the lowest Legendre moment of the $L_T$ response function:

$$D_{1\to 1}^{L_T} = \frac{2}{K} R(\omega, S_1 + S_0, M_1).$$

The second term is very sensitive to the $S_{0\to 1}$ multipole of the $S_{1\to 1}$ ($1535$) due to the strong transverse $R$-oper multipole ($M_1$), especially at high $Q^2$. Preliminary results show significant negative values for the $S_{1\to 2}$ amplitudes of the $S_{1\to 1}$ ($1535$).

3.3 Helicity structure of the $D_{13}$ ($1520$)

A longstanding prediction of the dynamical constituent quark model is the rapid helicity switch from the dominance of the $A_{3\to 2}$ at the real photo point to the dominance of the $A_{1\to 2}$ amplitudes at $Q^2 > 1$ GeV$^2$. In the simple non-relativistic harmonic oscillator model with spin and orbit, $L_T$ amplitudes only, the ratio of the two amplitudes is...
given by:

\[ A_{3/2}^{1/2} = \frac{Q^2}{3} - 1 \]

where \( Q \) 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 7 shows the results for the two transverse amplitudes. We see the \( A_{3/2} \) amplitude decreasing rapidly in strength with 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. \( A_{1/2} \) completely dominates at \( Q^2 > 2 \) GeV^2.

4 Conclusions

With the recent precise data on pion and eta electroproduction, combined with the large coverage in \( Q^2, W \), and center-of-mass angle, 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. We have learned that the (1232) exhibits an obvious deformation. The multipole ratios \( R_{EM} \) an \( R_{SM} \) show no sign of approaching the predicted asymptotic behavior, which provides a real challenge for model builders. The latest data from CLAS on charged pion production reveals a sign change of the transverse amplitude for the N-rod transition near \( Q^2 = 0.5 \) GeV^2, and gives strong evidence for this state as the first radial excitation of the nucleon. The hard transition form factor of the \( S_1(1535) \) previously observed only in the p wave channel is confirmed in the n wave channel, which also allows us to extract the so far unknown longitudinal amplitude \( S_{1/2} \). The \( D_13(1520) \) clearly exhibits the helicity behavior long ago predicted by the constituent quark model.

References

1. V. D. Burkert, Zh. Li, Phys. Rev. D 47, 46, 1993.
2. J. Ahrens et al., Phys. Rev. Lett. 87, 022003, 2001.
3. R. Fatemi et al., Phys. Rev. Lett. 91, 222002, 2003.
4. Y. Prok et al., [arXiv:0802.2232 [nucl-ex]]
5. V. D. Burkert and B. Li, Phys. Lett. B 296, 223, 1992; J. Exp. Theor. Phys. 78, 619, 1994.
6. A. Deur et al., Phys. Rev. Lett. 93, 212001, 2004; A. Deur et al., [arXiv:0802.3198]
7. V. Burkert, T. S. Lee, Int. J. Phys. E13, 1035, 2004.
8. N. Isgur and G. Karl, Phys. Rev. D 18, 4187, 1978; Phys. Rev. D 19, 2653, 1979.
9. R. Konig and N. Isgur, Phys. Rev. D 21, 1868, 1980.
10. A. Buchmann and E. Henley, Phys. Rev. D 65, 073017, 2002.
11. T. Sato and T. S. Lee, Phys. Rev. C 63, 055201, 2001.
12. S. S. Kamalov and S. N. Yang, Phys. Rev. Lett. 83, 4494, 1999.
13. S. Stave et al., [arXiv:0803.2496 [hep-ex]], N. F. Sparveris et al., Phys. Lett. B 561, 102, 2007.
14. N. F. Sparveris et al., Phys. Rev. Lett. 94, 022003, 2005.
15. S. S. Kamalov et al., Phys. Rev. C 64, 033201, 2001.
16. L. Tiator et al., Eur. Phys. J. A 19, 55, 2004.
17. D. Derchen et al., Eur. Phys. J. A 34, 69, 2007.
18. K. Joo et al., Phys. Rev. Lett. 88, 122001, 2002.
19. M. Ungaro et al., Phys. Rev. Lett. 97, 112003, 2006.
20. J. J. Kelly et al., Phys. Rev. Lett. 95, 102001, 2005.
21. R. Beck et al., Phys. Rev. C 61, 035204, 2000.
22. G. Banoji et al., Phys. Rev. C 64, 025203, 2001.
23. V. V. Frolov et al., Phys. Rev. Lett. 82, 45-48, 1999.
24. G. A. W. arren, C. E. Carlson, Phys. Rev. D 42, 3020, 1990.
25. I. A. Znaur, Z. Phys. A 346, 297, 1993.
26. C. A. Lassou et al., Phys. Rev. Lett. 94, 021601, 2005.
27. C. A. Lassou et al., Phys. Rev. D 77, 085012, 2008.
28. Z. P. Li, V. Burkert, Zh. Li, Phys. Rev. D 46, 70, 1992.
29. F. Cano and P. Gonzalez, Phys. Lett. B 431, 270, 1998.
30. O. Krehl et al., Phys. Rev. C 62, 052207, 2000.
31. H. Egyan et al., Phys. Rev. C 73, 025204, 2006.
32. I. A. Znaur, Phys. Rev. C 71, 015209, 2005.
33. I. A. Znaur et al., arXiv:0804.0447
34. I. A. Znaur et al., Phys. Rev. C 71, 015201; Phys. Rev. C 72, 045201, 2005.
35. N. M. Mathur et al., Phys. Lett. B 605, 137, 2005.
36. For an overview, see: I. A. Znaur, Phys. Rev. C 76, 025212, 2007.
37. H. H. Lin et al., [arXiv:0803.3020 [hep-lat]]
38. R. T. Thompson et al., Phys. Rev. Lett. 86, 1702, 2001.
39. H. Densil et al., Phys. Rev. C 76, 015204, 2007.
40. C. A. N. strong et al., Phys. Rev. D 60, 052004, 1999.
41. S. Caspian and B. D. Keister, Phys. Rev. D 51, 3507, 1995.
42. E. Pace, G. Salm e, and S. Simula, Few Body Syst. Suppl. 10, 407, 1999.
43. D. M. Ewens et al., Eur. Phys. J. A 14, 77, 2002.
44. M. A. Izzo, M. M. Gannini, and E. Santopinto, J. Phys. G 24, 753, 1998.
45. M. Wams et al., Z. Phys. C 45, 627, 1990.