Electromagnetic Excitation of Baryon Resonances and the CLAS N^* Program.

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Abstract. The status of N^* physics with electromagnetic probes is discussed. The experimental program with CLAS and first preliminary data are presented.

1 Introduction

The goal of the N^* program at CEBAF (N^* is here used for N and Δ states) is to probe the internal structure of light quark baryons. This will be accomplished in various ways: (1) by studying the resonance transition formfactors in a large Q^2 range and for a large number of states. This will allow detailed tests of baryon structure models and probe the contributions from hard and soft processes. (2) by searching for the so-called "missing resonances", states which are predicted in the symmetric quark model but have not been seen so far, and (3) by searching for gluonic excitations of the nucleon ("hybrid baryons").

In this lecture I will use the constituent quark model [1, 2] (CQM) as a guide. The model predicts a large number of resonant light quark (u,d,s) baryon states within the symmetry group $SU(3)_{\text{flavor}} \otimes SU(2)_{\text{spin}} \otimes O(3)_{\text{space}}$. The states fall into supermultiplets with fixed orbital angular momentum and energy excitation level. The mass degeneracy within one supermultiplet is broken by the color magnetic hyperfine coupling between the quark spins.

2 Total absorption cross section

The total photon absorption cross section exhibits 3 or 4 enhancements associated with the excitation of some of the prominent resonances - the $\Delta_{\frac{1}{2}}^+(1232)$, $N(1520)$, $N_{\frac{5}{2}}^+(1680)$, and $\Delta_{\frac{7}{2}}^+(1950)$. From inclusive measurements we obtain

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only global information about the resonance form factors, and even this is only true in the region of the Δ resonance, a relatively isolated state. The higher mass states overlap, and since they have several hadronic decay channels open they are broad and do not appear as isolated states in the inclusive spectrum (Fig. 1). Three states are contributing to the enhancement around 1.5 GeV, at least seven to the bump at 1.7 GeV, and at least six are known in the mass region around 1.9 GeV. More are predicted with masses near 2 GeV.

Figure 1. Inclusive electron scattering. The spike is due to elastic ep scattering, the enhancements indicate resonance production.

The various states can only be separated if the hadronic final states are measured, e.g. $N\pi$, $N\eta$, $N\pi\pi$. Spin, parity and isospin of the intermediate state can be identified, and, using information on the hadronic decay vertex, the transverse ($\lambda_{\gamma N} = \frac{1}{2}, \frac{3}{2}$) and scalar ($\lambda_{\gamma N} = \frac{1}{2}$) electromagnetic transition amplitudes $A_{\frac{1}{2}}$, $A_{\frac{3}{2}}$, and $S_{\frac{1}{2}}$ can be determined and compared to model predictions. So far only single pion and single eta photo- or electroproduction data have been used in analyses.

3 Results of previous experiments

3.1 The $\gamma_p \Delta(1232)$ Transition

The lowest $I = \frac{3}{2}$ state is the $\Delta(1232)$, which may be excited by a magnetic dipole transition or through electric and Coulomb quadrupole transitions. In the symmetric quark model, a spin-flip in the ground state mediates the excitation. Dynamical model give small values for $R_{EM} = \frac{E_{1+}}{M_{1+}}$. However,

chiral invariance requires $R_{EM} \rightarrow 1$ for $Q^2 \gg M^2$.

Experimentally, such quadrupole contributions can be detected in distortions of the pion angular distribution. The electroproduction data (Fig. 2) have large systematic uncertainties. The $Q^2 = 0.5, 1.0, 3.2 \text{ GeV}^2$ points [3] indicate that R_{EM} may rise slowly with Q^2 . This is also seen in a recent dispersion relation analysis [4] of the same data, as well as of recent data at 2.8 and 4. GeV^2 from Jefferson Lab. However, the experimental analysis gives small negative values [6]. These discrepancies may be seen as a measure of model-dependencies in the analyses when only $p\pi^0$ data are used. Despite of these shortcomings the results clearly show that hard processes are not important at $Q^2 < 4.0 \text{ GeV}^2$ for this process.

Figure 2. R_{EM} for the $\gamma N \Delta(1232)$. Symbols: squares - ref. [3], open circles - ref. [4], crosses - ref. [6], photon point - ref. [5]

3.2 Helicity Switch in $\gamma p \rightarrow N_{\frac{3}{2}}^-(1520), N_{\frac{5}{2}}^-(1680)$

Radiative transitions to the higher mass states $N(1520), N(1680)$ were found to be purely helicity $\frac{3}{2}$. In the quark model, this is explained by a cancellation between the spin-flip and the orbit-flip terms. However, in electroproduction such a cancellation is no longer possible, and the model predicts the $A_{\frac{1}{2}}$ amplitude dominates in both cases. In terms of the helicity asymmetry:

$$A_1 = \frac{A_{\frac{1}{2}}^2 - A_{\frac{3}{2}}^2}{A_{\frac{1}{2}}^2 + A_{\frac{3}{2}}^2} \quad (2)$$

a "switch" from $A_1 = -1$ at $Q^2 = 0$ to $A_1 \rightarrow +1$ at $Q^2 \gg 1 \text{ GeV}^2$ is predicted. This has been seen for the $N(1520)$, however, the data for the $N(1680)$ are too poor for a definite conclusion.

3.3 The Transition $\gamma p \rightarrow N_{\frac{1}{2}}^{-}(1535)$

Perhaps the most consistent data are available for the $N(1535)$ resonance, which is the $SU(6)$ partner of the $N(1520)$. This transition is most cleanly measured in the ηp channel which also isolates isospin $\frac{1}{2}$ states. Since no other near by state has a significant decay to ηp , and non-resonant amplitudes are small, this channel can be used to 'tag' the $N(1535)$ resonance. While photoproduction experiments indicate some D-wave contribution, electroproduction of $p\eta$ is consistent with s-wave only. This may be simply due to the fast drop of the $A_{\frac{3}{2}}$ amplitude for the $\gamma p N(1520)$ transition with Q^2 .

3.4 Limits of the Constituent Quark Model

One way of testing the CQM is to study ratios of transition amplitudes of states belonging to the same supermultiplet. In the ratio

$$\frac{A_{\frac{1}{2}}(N(1520))}{A_{\frac{1}{2}}(N(1535))}$$

effects of the radial wave function drop out, and since both states have the same mass, kinematical effects should be small. Fig. 3 shows the data in comparison with model predictions. This ratio is rather insensitive to relativistic effects and other model ingredients. At high Q^2 , the predictions are close to the $SU(6)$ limit for pure spin transitions, which are expected to dominate. While the data agree very well at low Q^2 , the highest Q^2 point indicates a significant deviation. If this is a sign for a non-trivial breakdown of the CQM at small distances remains to be seen with improved data.

Figure 3. Test of the CQM symmetry structure; the curves are from ref. [9].

Using experimental information on states belonging to the same supermultiplet, one can test symmetry properties of the electromagnetic transition be-

tween supermultiplets. In a single quark transition model, radiative transitions from the ground state to the $[70, 1^-]$ supermultiplet are described by a one-body current operator [8] :

$$J_+^{em} = A \cdot L_+ + B \cdot S_+ + C \cdot L_+ S_z \quad , \quad (3)$$

corresponding to orbit, spin, and combined spin-orbit coupling, respectively. Deviations from the SQTm predictions may therefore yield information about multiple quark contributions. Using the data on the $N(1535)$ and $N(1520)$ we can determine A , B , C as a function of Q^2 , and predict transition amplitudes to all other states belonging to $[70, 1^-]$. The predictions agree quite well with the data at the photon point, showing that $SU(6)$ symmetry is approximately correct. However, this symmetry might break down at high Q^2 . This can presently not be tested as electroproduction data on most of the higher mass states are lacking.

3.5 "Missing" Quark Model States

The symmetric quark model predicts many states with masses above 1.8 GeV which have not been observed in $\pi N \rightarrow \pi N$ reactions. Many of the "missing" states are predicted to decouple from the πN channel, however, they may couple to channels such as ρN , ωN , or $\pi \Delta$. Some may also couple to photons. Electromagnetic production of these channels may therefore be the only way to search for the "missing" states. Obviously, our picture of baryon structure could change dramatically if these states do not exist. Production of vector mesons or $\Delta^{++}\pi^-$ should provide a definite answer regarding the existence of at least some of these states [10]. For example, at forward angles the process $\gamma p \rightarrow p\omega$ is dominated by diffractive production, while resonance contributions would dominate at large angles. In electroproduction one expects the diffractive contribution to be reduced relative to the resonance contribution due to the increasing virtuality of the vector meson propagator involved.

3.6 Electro-Quenching of the Roper $N_{\frac{1}{2}}^+(1440)$

Existing data indicate a very fast drop of the transverse transition amplitude for the Roper resonance. There have been suggestions that this fast drop may be explained by pionic contributions, which die out fast with increasing Q^2 and are not explicitly included in the quark calculations [9]. The non-relativistic quark model predicts for the neutron/proton ratio: $A_{\frac{1}{2}}^n/A_{\frac{1}{2}}^p = -0.67$. In chiral bag model calculations [11], contributions from the pion cloud of the proton bring this ratio closer to -1 at $Q^2 = 0$, while the averaged experimental value is -0.60 ± 0.15 , making an interpretation in terms of pion contributions rather unlikely, at least within the CBM.

Progress in describing the transition amplitude of the Roper has been reported at this workshop using relativized models, e.g. the light cone model and by introducing quark formfactors [17].

3.7 Gluonic Excitations of the Nucleon

In the past decade there have been speculations about the existence of gluonic baryon states $|q^3 G\rangle$ consisting of three constituent quarks and constituent glue [12, 13]. QCD lattice simulations indicate that such configurations must exist for mesons, whereas no such calculations have been performed for baryons. Estimates within the framework of QCD sum rules [15] yield masses for the lowest gluonic baryon state P_{11}^G around 1.5 GeV.

Unfortunately, gluonic baryons cannot be distinguished from ordinary $|q^3\rangle$ states in hadronic production because they are, unlike some gluonic mesons, characterized by quantum numbers which are also possible for the normal $|q^3\rangle$ baryon states. However, as their internal structure must be quite different from ordinary baryons, measurement of their transition form factors in electroproduction could be a powerful tool in these studies. A study of the Roper states $N_{\frac{1}{2}}(1440)$ and $\Delta_{\frac{3}{2}}(1600)$ as radial excitations of the 3-quark system or as gluonic excitation shows the transition formfactors may be quite different for these alternative models. Moreover, because gluons have only transverse excitation modes, the longitudinal coupling is absent for gluonic excitations, and $S_{\frac{1}{2}}(Q^2) \equiv 0$.

4 The N^* program with CLAS

The study of electro-excitation of N^* resonances in the past has suffered from several shortcomings, such as: (1) lack of theoretical guidance, as most measurements were completed in the pre-QCD, (2) limitations of single pion production experiments with small solid angle spectrometers, and (3) the complete lack of polarization measurements.

The CLAS program [16] is aimed at improving this situation quantitatively as well as qualitatively. Several experiments focus on the precise measurement of the multipoles for the $\Delta(1232)$ in a large Q^2 range, by measuring the unpolarized differential cross section for charged and neutral pion production: $ep \rightarrow e'p\pi^0$, $ep \rightarrow e'n\pi^+$, and $en \rightarrow e'p\pi^-$, with high statistics, and by covering the full azimuthal and polar angular ranges. Also, detailed measurements of polarization observables are in preparation.

Another focus is the region of the second enhancement in the cross section. Of particular interest is the measurement of the transverse and longitudinal transition amplitudes of the Roper over a large Q^2 range. These measurements will help clarify the nature of this state.

The region of the third enhancement contains several states belonging to the $[70, 1^-]_1$ supermultiplet, whose photocouplings are virtually unknown for $Q^2 > 0$, such as $\Delta_{\frac{1}{2}}^-(1620)$, $N_{\frac{3}{2}}^-(1700)$, $\Delta_{\frac{3}{2}}^-(1700)$, and $N_{\frac{5}{2}}^-(1675)$. Also, there exist only few data on electroproduction of neutron resonances. Experiments to study channels such as $ep \rightarrow e'\Delta\pi$, $ep \rightarrow e'N\rho$ are expected to generate much improved data on several of these states, therefore allowing accurate tests of the SQTm assumption, as well as tests of the validity range of the constituent quark model. These channels, as well as $ep \rightarrow e'p\omega$, and $\gamma p \rightarrow p\pi^+\pi^-$ are

sensitive to many of the “missing” $|q^3 >$ states, and will be extensively studied with CLAS.

The reactions $ep \rightarrow ep\eta$, $\gamma p \rightarrow p\eta$ will be used to study the $N_{\frac{1}{2}}(1535)$ and $N_{\frac{1}{2}}(1710)$ states, as well as to search for other isospin $\frac{1}{2}$ excitations. The $\gamma p \rightarrow p\eta'$ reaction might be sensitive to gluonic baryon excitations at higher masses.

Most of the experimental studies of N^* transitions have focussed on the vector structure of the hadronic current. Electroproduction of resonances in coincidence with a pion allow access to the axial structure of the hadronic current. For example, the process $ep \rightarrow e'\Delta^{++}\pi_{soft}^-$, where the π^- is produced near threshold, is related to the axial vector transition form factor G_A^{Δ} from the nucleon to the $\Delta(1232)$ via current algebra and PCAC theorem[19].

5 A first look at CLAS data

As of September '98 CLAS has accumulated about 5% of the expected N^* data using electron beams at 1.6, 2.4, and 4 GeV, and about 10% of the expected photon data. Some of the electron scattering data have been analyzed using preliminary reconstruction software and calibration procedures. Although the current status of the analysis is still extremely preliminary, some features of the data will not change significantly in course of the analysis, and I will briefly discuss some of them.

An important features of CLAS is its capability to detect nearly the entire phase space of a reaction simultaneously. Identification of charged particles is provided by the combination of time-of-flight from the target to the scintillation counters with momentum measurements in the drift chamber/magnet system. Neutral particles can be identified by missing mass techniques or, in a limited phase space region, by detection in the electromagnetic calorimeters. Fig. 4 shows a missing mass distribution M_X for $ep \rightarrow epX$ and $ep \rightarrow e\pi^+X$. The π^0 , η and ρ, ω and neutron bands, respectively are clearly visible, indicating strong production of these channels. An important part is also due to two-pion production, e.g. $ep \rightarrow ep\pi^+\pi^-$, which requires detection of at least 2 hadrons in the final state. All these channels will be analyzed as part of the N^* program.

Fig. 5 shows the relative yields of various exclusive reactions as a function of the invariant hadronic mass W . Nearly all processes ($\rho\omega$ needs more statistics) show clear resonance contributions, and the isospin structure of the dominant resonances with masses < 1.75 GeV are revealed when comparing charged and neutral pion production - the $\Delta(1232)$ being isospin $\frac{3}{2}$ and dominantly decaying to $p\pi^0$, the $N(1520)$ and $N(1535)$ and $N(1680)$ with strong $n\pi^+$ as well as $p\pi^+\pi^-$ decays.

6 Conclusions and Outlook

The study of photo- and electroproduction of pseudoscalar and vector mesons from nucleons, provides rich information on the excitation of N^* and Δ reso-

Figure 4. Missing mass for $ep \rightarrow epX$ (left), and $ep \rightarrow e\pi^+X$ (right). The peaks correspond to the π^0 , η , ρ/ω , and neutron mass, respectively

Figure 5. Some of the exclusive reactions recorded in CLAS at 4 GeV beam energy.

nances, their structure, and the strong interaction force in the non-perturbative regime. The utilization of state-of-the-art experimental equipment and data processing techniques has opened up the unique opportunity to collect the data needed for a comprehensive study of the structure of the nucleon in the confinement regime. CLAS has started to take data related to the N^* program in December 1997. The analysis is progressing rapidly and more data taking is scheduled for the year 1999.

References

1. N. Isgur, G. Karl, *Phys. Lett.* 72B, 109 (1977); *Phys. Rev.* D23, 817 (1981)
2. S. Capstick, N. Isgur, *Phys. Rev.* D36, 2800 (1987)
3. V.D. Burkert and L. Elouadrhiri, *Phys. Rev. Lett.* 75, 3614 (1995)
4. I. Aznauryan and S. Stepanyan, private communication
5. R. Beck et al., *Phys. Rev. Lett.* 78, 606 (1997)
6. P. Stoler, contribution presented at this workshop
7. F.E. Close, F.J. Gilman, *Phys. Letts.* 38B, 541 (1972)
8. A.J.G. Hey, J. Weyers, *Phys. Letts.* 48B, 69 (1974)
9. S. Capstick, *Phys. Rev.* D46, 2864 (1992)
10. M. Ripani, lecture presented at this workshop
11. K. Bermuth et al., *Phys. Rev.* D37, 89 (1988)
12. T. Barnes, F.E. Close, *Phys. Letts.* 123B, 89 (1983)
13. E. Golowich, E. Haqq, G. Karl, *Phys. Rev.* D28, 160 (1983)
14. Z.P. Li, V. Burkert, Z. Li, *Phys. Rev.* D46, 70 (1992)
15. L. Kisslinger, talk presented at the CEBAF/INT Workshop on N^* physics, Seattle, Washington, September 9 - 13, 1996.
16. See also: http://www.cebaf.gov/exp_prog/generated/meson.html
17. F. Cardarelli, E. Pace, G. Salme, S. Simula, *Phys. Lett.* B371, 7 (1996)
18. V. Burkert and B. Mecking, *Large Acceptance Detectors for Nuclear Physics*, in: *Modern Topics in Electron Scattering*, eds. B. Frois, I. Sick, World Scientific, Singapore, 1991
19. S. Adler and W. Weisberger, *Phys. Rev.* 169, 1392 (1968)