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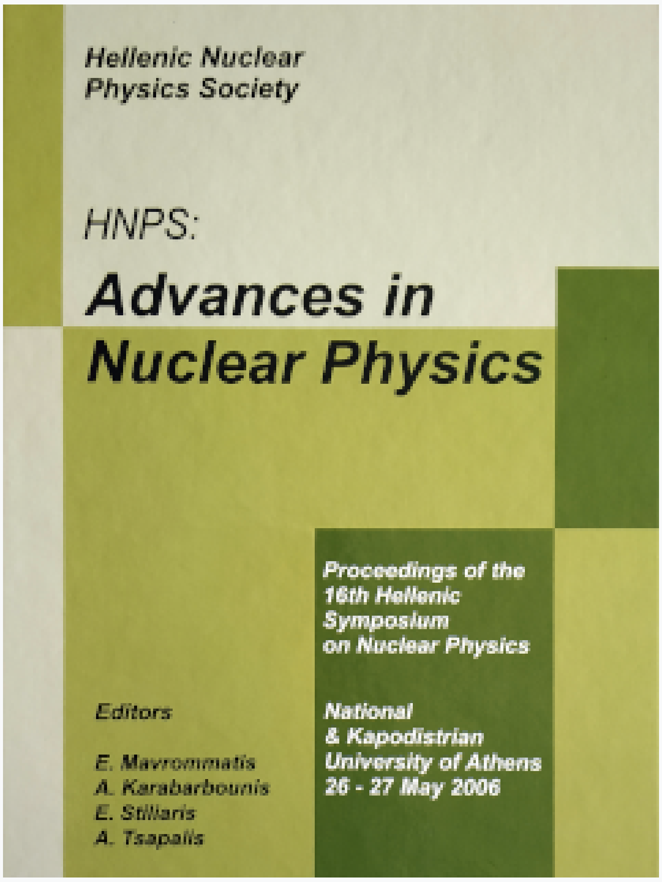

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N. F. Sparveris

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Measurements of the quadrupole strengths in the $N \rightarrow \Delta$ transition at Mainz and Bates

N.F. Sparveris [a]

[a]Department of Physics, University of Athens, Greece

The issue of hadron deformation has been a subject of intense scientific interest during the last two decades. The detailed study of the $N \rightarrow \Delta$ transition is the best method of experimental investigation of this issue. The most recent results from the Bates and Mainz $N \rightarrow \Delta$ programs will be presented which focus at the low Q^2 region. The experimental data yield precise non zero quadrupole to dipole amplitude EMR and CMR ratios, giving credence to the conjecture of deformation in hadrons favoring the attribution of the origin of deformation at the low Q^2 region to the dominance of mesonic effects.

1. Introduction

Hadrons are characterised by complex quark-gluon and meson cloud dynamics which give rise to non spherical component in their wavefunction which in a clasical limit and at large wavelengths will correspond to "deformation". Proton, the only stable hadron, is a quite composite system with complex quark - gluon dynamics. Experimental confirmation of the deviation of the proton structure from spherical symmetry is fundamental and has been the subject of intense experimental and theoretical interest [1] since this possibility was originally raised by Glashow [2].

Recent lattice calculations [3] and QCD inspired models strongly suggest that the shapes of hadrons are expected to deviate from spherical symmetry. It is only recently that results of exclusive experiments of high precision are able to confirm the deviation from spherical shape. The origin of deformation is attributed to different mechanisms in the various nucleon models. In the constituent-quark picture of hadrons, it arises as a consequence of the non-central color-hyperfine interaction among quarks [4,5], while in dynamical models of the πN system, deformation also arises from the asymmetric coupling of the pion cloud to the quark core. Our current understanding of the nucleon indicates that most of the deformation at long distances (low momenta) is driven by the pionic cloud while at short distances (high momenta) is generated by intra-quark forces.

The most direct and reliable measurement of deformation is provided through the spectroscopic quadrupole moment. Since for the proton it vanishes identically because of its spin 1/2 nature, the signature of the deformation of the proton is sought instead in the presence of resonant quadrupole amplitudes (E2, C2) in the predominantly M1 (magnetic dipole -quark spin flip) $N \rightarrow \Delta$ transition. Non vanishing resonant quadrupole amplitudes will signify that either the proton or the delta and more likely both are deformed. Thus measurements of the E2 and C2 amplitudes represent deviations from spherical symmetry of the N,Δ system and not the nucleon alone; moreover their Q^2 evolution is expected to provide insights on the mechanism that generates the deformation.

The isolation of the resonant amplitudes E2 and C2 is complicated by the presence of the nonresonant background processes which are coherent with the resonant excitation of the $\Delta(1232)$. The experimental difficulty is that the E2/M1 and C2/M1 ratios are small (typically -2 to -8 % at low Q^2). In this case the non-resonant (background) and resonant quadrupole amplitudes are the same order of magnitude and it is for this reason that experiments have to be designed to attain the required precision to separate the signal and background contributions.

2. The Bates $N \rightarrow \Delta$ Program

The Bates $N \rightarrow \Delta$ program from its very inception back in 1987 relies on a major instrumentation initiative, the Out-Of- Plane Spectrometer (OOPS) system [19] . The OOPS facility, fully developed and commissioned [20–22], was explicitly designed to take advantage of the azimuthal angle dependence of the cross section which acts as lever arm for isolating the interference responses. It consists of an electron spectrometer used in conjunction with four relatively light spectrometers which can be deployed at a fixed polar angle, relative to the momentum transfer q to detect the emitted proton.

The cross section of the H$(e, e'p)\pi^0$ reaction is sensitive to independent partial cross sections ($\sigma_T, \sigma_L, \sigma_{LT}, \sigma^{'}_{LT}$ and σ_{TT}) which are proportional to the corresponding response functions [13] :

$$\frac{d^5\sigma}{d\omega d\Omega_e d\Omega^{cm}_{pq}} = \Gamma(\sigma_T + \epsilon\cdot\sigma_L - v_{LT}\cdot\sigma_{LT}\cdot \cos\phi_{pq} + \epsilon\cdot\sigma_{TT}\cdot \cos 2\phi_{pq} + h \cdot v^{'}_{LT}\cdot\sigma^{'}_{LT}) \quad (1)$$

where ϵ is the transverse polarization of the virtual photon, Γ the virtual photon flux and ϕ_{pq} is the proton azimuthal angle with respect to the momentum transfer direction.

By deploying multiple (3 or 4) spectrometers at different azimuthal angles Φ_{pq}, the combination of $\sigma_0 = \sigma_T + \epsilon \cdot \sigma_L$, σ_{TT} and σ_{TL} can be simultaneously measured in one run, which reduces the systematic errors caused by luminosity measurement errors. Furthermore, when polarized electron beams are employed, measurements of the fifth structure function $\sigma^{'}_{TL}$, which require out-of-plane hadron detection, become possible.

The first $N \rightarrow \Delta$ measurements [9] at Bates, involving only in-plane detection, resulted in the precise determination of the cross section in parallel kinematics, σ_0, the σ_{LT} response and the measurement of the induced proton polarization P_n. The precise σ_{LT} results demonstrated the sensitivity of the data to the deformation [9]. P_n is proportional to the σ^n_{LT} response and it would be identically zero in the absence of background. It was found [8] to be $-0.397 \pm 0.055 \pm 0.009$ which established the importance of the background contributions. Quadrupole amplitudes [9] were determined but with a significant model error. The first out-of-plane $N \rightarrow \Delta$ measurements [23] were performed in year 1998 while year 2000/2001 was marked by major technical achievements for the OOPS program which led to production runs for the VCS and $N \rightarrow \Delta$ experiments. A 950 MeV beam energy, with currents up to $7\mu A$ and a duty-factor in excess of 50% was used in conjunction with the completed and commissioned 4-OOPS cluster. During this series of measurements the TT response which is sensitive to the electric quadrupole amplitude was isolated for the first time [10] while at the same time measurements of the σ_{LT} response were extended to proton angles up to 95^o. The response functions σ_0 and σ_{TT} contain the term $|E1_+M_{1+}|$ but also the dominant term $|M1+|^2$. The influence of the dominant $|M1+|^2$ term can be diminished by measuring the following combination [24] of the σ_0 and σ_{TT} responses:

$$\sigma_{E2}(\theta^*_{pq}) \equiv \sigma_o(\theta^*_{pq}) + \sigma_{TT}(\theta^*_{pq}) - \sigma_o(\theta^*_{pq} = 0^\circ) =$$

$$2Re[E^*_{o+}(3E_{1+} + M_{1+} - M_{1-})](1 - cos\theta^*_{pq}) - 12Re[E^*_{1+}(M_{1+} - M_{1-})]sin^2\theta^*_{pq} \quad (2)$$

The term of interest $|E1_+M_{1+}|$ is enhanced by a factor of twelve (12) while the leading term $|M1+|^2$ is eliminated. The cross sections needed to derive this quantity were measured leading to a most precise measurement of R_{EM} at $Q^2 = 0.126(GeV/c)^2$. The sensitivity to the EMR is maximized at the measured kinematics as shown in Fig. 1.

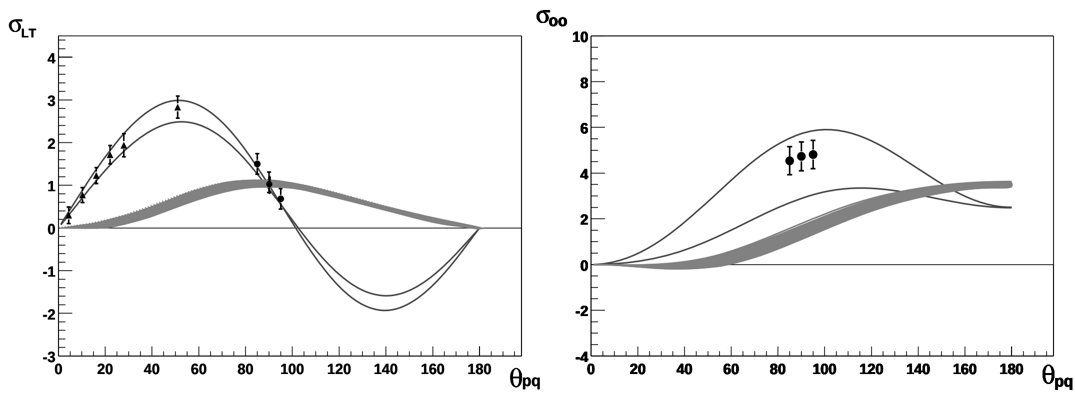

Figure 1. The Nucleon is deformed: The σ_{LT} and σ_{00} responses measured by the OOPS collaboration at W = 1232 MeV. The shaded band represents the allowed uncertainty for a spherical Nucleon (both N(938) and $\Delta(1232)$). The band ecompassing the data represents the uncertainly allowed by all of our data analyzed simultaneously.

A combined analysis of all the available OOPS data has been performed [10]. The data base at $Q^2 = 0.126(GeV/c)^2$ is quite rich allowing for a most precise extraction of the R_{EM} and R_{SM} values characterized by a very small model uncertainty thus indicating that apart from the resonant amplitudes of interest the background contribution multipoles are significantly constrained by the data as well. This analysis which has yielded the results in Fig. 1 demonstrated beyond any doubt that both the R_{EM} and R_{SM} yield incompatible results with a spherical nucleon. The derived values for the quadrupole to amplitude ratios derived from an adjustment of MAID to the extracted cross sections [10] are $R_{SM} = (-6.1 \pm 0.2_{stat+sys} \pm 0.5_{mod})\%$ and $R_{EM} = (-2.3 \pm 0.3_{stat+sys} \pm 0.6_{mod})\%$. Both ratios are dramatically bigger than the values predicted by quark models on account of the non central color hyperfine interaction [5]. They are consistent in magnitude, but not in detail, with the values predicted by models [15–17] taking into account the mesonic degrees of freedom. This we interpret as a validation of the crucial role the pion cloud plays in nucleon structure, a consequence of the spontaneous breaking of chiral symmetry [25]. The derived results are consistent with the interpretation of Buchmann [26] and coworkers suggesting a prolate nucleon and an oblate Δ.

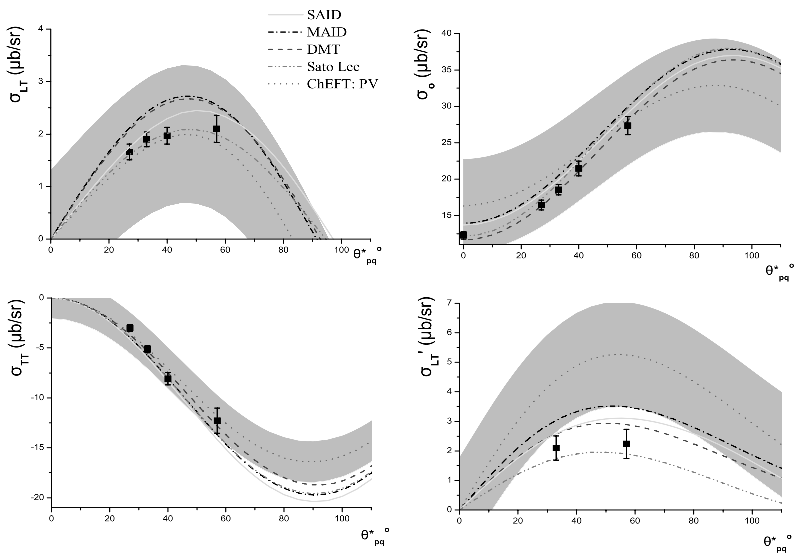

Figure 2. The measured $\sigma_o = \sigma_T + \epsilon \cdot \sigma_L$, σ_{LT}, σ_{TT} and $\sigma_{LT'}$ partial cross sections as a function of θ^*_{pq} at central kinematics of W=1221 MeV and $Q^2 = 0.20$ (GeV/c)^2. The theoretical predictions of MAID, DMT, SAID, Sato Lee and the ChEFT of Pascalutsa and Vanderhaegen (with the corresponding error band) are also presented.

3. $N \to \Delta$ measurements at Mainz

The $N \to \Delta$ measurements at Mainz, more resent than the Bates ones, took place during year 2003. The aim of this experimental program was to focus at the low Q^2 region and to explore the Q^2 evolution of the quadrupole amplitudes in a region where the pionic contribution is predicted to play a dominating role [15–17]; Understanding the magnitude and Q^2 dependence of the quadrupole amplitudes is expected to provide valuable insights on the mechanism that generates the deformation.

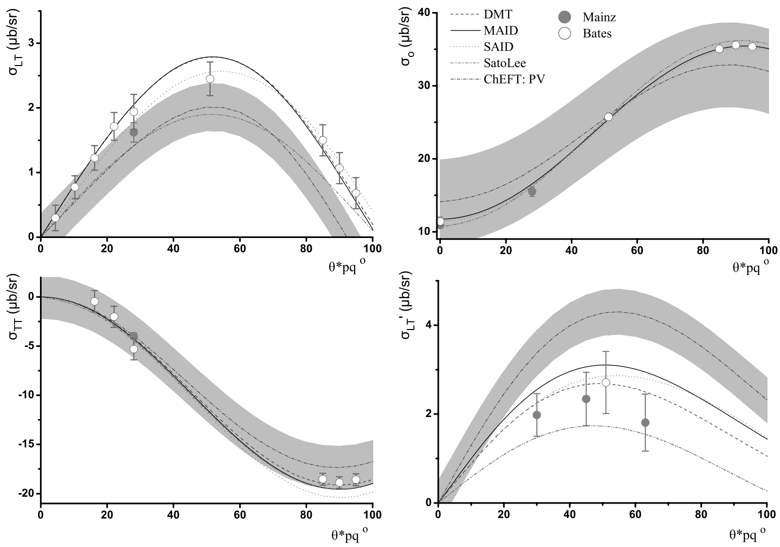

Figure 3. The measured partial cross sections as a function of θ^*_{pq} at central kinematics of W=1232 MeV and $Q^2 = 0.127$ (GeV/c)^2 along with the corresponding ones from Bates.

The experiment was performed using the A1 magnetic spectrometers [27,28] and covering the kinematical range from $Q^2 = 0.06$ (GeV/c)^2 to $Q^2 = 0.20$ (GeV/c)^2. An 855 MeV polarized electron beam with a 75% polarization was employed on a liquid-hydrogen target where the beam average current was 25 μA. Electrons and protons were detected in coincidence with spectrometers A and B respectively, both using two pairs of vertical drift chambers for track reconstruction and two layers of scintillator detectors for timing information and particle identification [28]. Measurements with the proton spectrometer at three different azimouthal angles ϕ_{pq} for the same central kinematics allowed the extraction of all three unpolarized partial cross sections σ_{TT}, σ_{LT} and $\sigma_o = \sigma_T + \epsilon \cdot \sigma_L$ while through the out of plane measurements it became possible to extract the $\sigma_{LT'}$.

The experimental results [12] along with all resent theoretical model calculations are presented in Figures 2,3 and 4. The measurements at $Q^2 = 0.06$ (GeV/c)^2 and $Q^2 = 0.20$ (GeV/c)^2 provided a rich and precise data base to allow the accurate extraction of the quadrupole amplitudes at this kinematics. Measurements were also taken at $Q^2 = 0.127$ (GeV/c)^2 to allow the comparison between the Bates and the Mainz results. As can be seen from Fig. 3 the results are found to be in excellent agreement among the two labs.

The resonant $M^{3/2}_{1+}$, $S^{3/2}_{1+}$ and $E^{3/2}_{1+}$ have been extracted from the measured partial cross sections through a fit to the three resonant amplitudes while taking into account

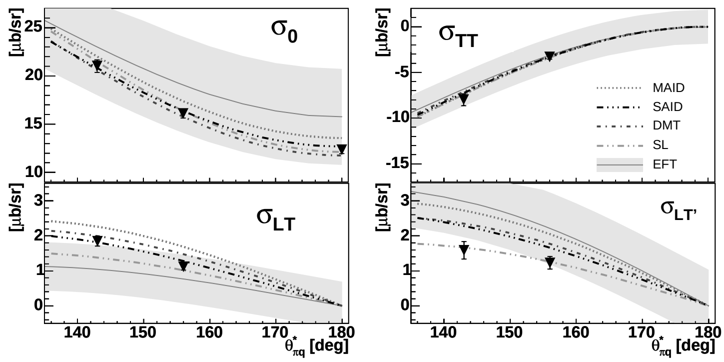

Figure 4. The measured partial cross sections as a function of θ^*_{pq} at central kinematics of W=1221 MeV and $Q^2 = 0.06$ (GeV/c)^2 along with the theoretical model predictions.

the contributions of background amplitudes from MAID, DMT, SAID and Sato Lee model predictions. The values adopted come from the average of the fit results while the model uncertainty is obtained by taking their RMS deviation. The values for the quadrupole to dipole ratios are found to be $CMR = (-5.08 \pm 0.28_{stat+sys} \pm 0.34_{model})\%$ and $EMR = (-1.94 \pm 0.68_{stat+sys} \pm 0.44_{model})\%$ at $Q^2 = 0.20$ (GeV/c)^2 and $CMR = (-4.81 \pm 0.27_{stat+sys} \pm 0.26_{model})\%$ and $EMR = (-2.28 \pm 0.29_{stat+sys} \pm 0.20_{model})\%$ at $Q^2 = 0.06$ (GeV/c)^2. The derived quadrupole to dipole ratios are presented in Fig. 5 along with the corresponding theoretical model calculations.

A comparison with the various theoretical calculations allows an overall assessment of our understanding of the issue of nucleon deformation. The SAID, MAID, DMT and Sato Lee models perform satisfactory considering the full Q^2 range and they are able to describe adequately the very precise experimental results, with Sato Lee and DMT to both find that a large fraction of the $E2$ and $C2$ multipole strength arises due to the pionic cloud with the effect reaching a maximum value in the region $Q^2 = 0.15$ (GeV/c)^2. At the same time though, all modles exhibit some small deficiencies at certain kinematics thus indicating that improvements could and should be implemented to these models.

The effective field theoretical (chiral) calculation [18] that is solidly based on QCD also successfully accounts for the magnitude of the effects giving further credence to the dominance of the meson cloud effect, although the rather large uncertainties that are associated with this calculation render the prediction compatible with the measurements while at the same time making the need for the next order calculation obvious.

The recent results from lattice QCD [3] are also of special interest since they are for the first time accurate enough to allow a meaningful comparison to experiment. The chirally extrapolated [18] values of CMR and EMR are found to be non zero and negative at the low Q^2 region, in good agreement with the experiment results thus linking the experimental evidence for deformation directly to QCD.

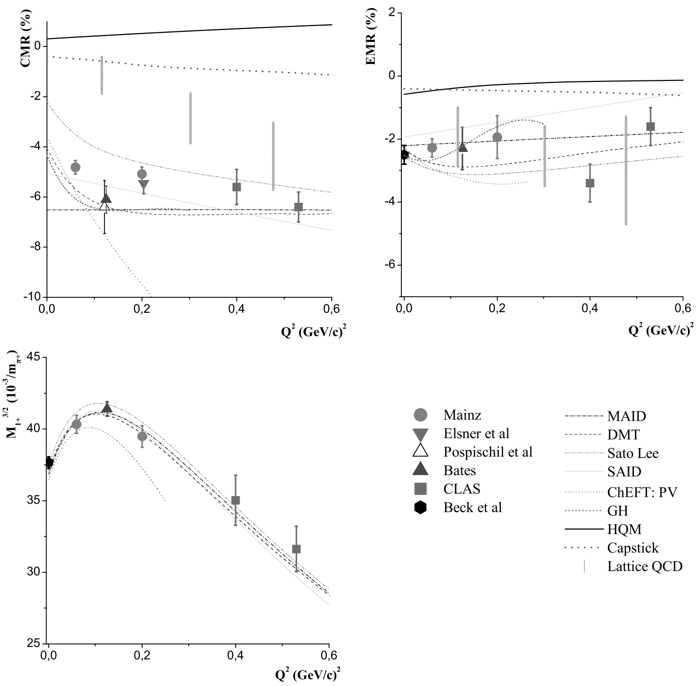

Figure 5. The extracted values for CMR, EMR and $M_{1+}^{3/2}$ as a function of Q^2. The theoretical predictions of MAID, DMT, SAID, Sato Lee, ChEFT of Pascalutsa-Vanderhaegen and the Gail-Hemmert and the experimental results from [7,10–12,29,30] are shown.

4. Conclusions

The experimental results provided by the Bates and Mainz measurements complete the experimental investigation of the issue of nucleon deformation at low Q^2. The non zero values of the resonant quadrupole amplitudes determined support the conjecture of nucleon deformation. Taken together with the results from the photon point allow certain conclusions to be drawn concerning the mechanisms that may be responsible for causing deviation from sphericity and to evaluate the role of the pion cloud which is expected to be dominant at low Q^2. The EMR and CMR ratios have been determined precisely and their values vary smoothly as a function of Q^2 (see Fig. 5) as expected. The quadrupole to dipole amplitude ratios are found to be bigger by an order of magnitude than the values predicted by quark models on account of the noncentral color-hyperfine interaction [5] and consistent in magnitude with the ones predicted from models that take into account the mesonic degrees of freedom [15–17]. Finally, resent chiral effective [18] and lattice calculations [3] which provide a direct link to QCD are in agreement with the experimental values.

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