Eur. Phys. J. A **18**, 141–145 (2003)
DOI 10.1140/epja/i2002-10289-y

THE EUROPEAN
PHYSICAL JOURNAL A

Nucleon deformation

A status report

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Received: 30 September 2002 /
Published online: 22 October 2003 –

Abstract. The conjectured deformation of hadrons and its experimental verification offer a particularly fertile ground for understanding the intricate dynamics of their constituents and QCD at the confiment scale. The detailed study of the $N \rightarrow \Delta$ transition is viewed as the preferred method of experimental investigation of this central issue in hadronic physics. A brief overview of the field is presented, followed by a presentation of the most recent results from Bates $N \rightarrow \Delta$ program. The new Bates/OOPS data at $Q^2 = 0.127(\mathrm{GeV}/c)^2$ yield $R_{SM} = (-6.27 \pm 0.32_{\mathrm{stat+sys}} \pm 0.10_{\mathrm{model}})\%$ and $R_{EM} = (-2.00 \pm 0.40_{\mathrm{stat+sys}} \pm 0.27_{\mathrm{model}})\%$ and they exclude a spherical nucleon and/or Δ. The magnitude and the origin of the deformation is the focus of the ongoing and planned investigations.

PACS. 13.60.Le Meson production – 13.88.+e Polarization in interactions and scattering – 13.40.Gp Electromagnetic form factors – 14.20.Gk Baryon resonances with $S = 0$

1 Introduction

QCD inspired models [1–3] and recent lattice calculations [4,5] strongly suggest that the shapes of hadrons are expected to deviate from spherical symmetry. While the possibility of nucleon deformation was raised more than 20 years ago [6], 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, suggesting that the deviation from spherical symmetry is the result of several mechanisms. In "QCD-inspired" constituent quark models, it arises from the intra-quark effective color-magnetic tensor forces [1], while in chiral bag models [2] most of the deformation can be attributed to the asymmetric coupling of the meson cloud to the spin of the nucleon. 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) it is generated by intra-quark forces.

The vanishing of the static quadrupole moment of the nucleon due to its $J = \frac{1}{2}$ spin, precludes accesss to the most direct observable of deformation. As a result, the presence of resonant quadrupole amplitudes in the $N \rightarrow \Delta$ transition has emerged as the definitive experimental signature of deviation from the simplistic spherical models of the nucleon and/or the delta. This is easily understood in the spherical quark model of the nucleon, where the $N \rightarrow \Delta$ excitation is a pure $M1$ ($M_{1+}^{3/2}$) transition. The resonant quadrupole multipoles $E2$ ($E_{1+}^{3/2}$) and $C2$ ($S_{1+}^{3/2}$) contain the pertinent information, as they arise from D state admixtures in the wave functions —a case reminiscent of the deformation of the deuteron. In pion production the amplitudes are denoted by $M_{l\pm}^I$, $E_{l\pm}^I$, $S_{1\pm}^I$ and $L_{l\pm}^I$, indicating their character (magnetic, electric, scalar or longitudinal), their isospin I and their total angular momentum ($J = l \pm 1/2$).

Experimental and theoretical results are routinely quoted in terms of the Electric- and Scalar(Coulomb)-to-Magnetic-Ratios of amplitudes defined as $R_{EM} = \Re(E_{1+}/M_{1+})$ and $R_{SM} = \Re(S_{1+}/M_{1+})$, respectively. QCD-inspired models predict values of R_{SM} in the range from -0.1% to -8%, at low momentum transfers, $Q^2 \leq 1.0\ (\mathrm{GeV}/c)^2$. However, the isolation of the resonant R_{EM} and R_{SM} is complicated by the presence of the nonresonant "background processes" which are coherent with the resonant excitation of the $\Delta(1232)$. These interfering processes (such as the pion pole, Born terms, tails of higher resonances) need to be constrained in order to isolate the resonant contributions to R_{EM} and R_{SM} which contain the physics of interest. As a result, R_{EM} and R_{SM} are invariably extracted with model error which is often poorly known and rarely quoted.

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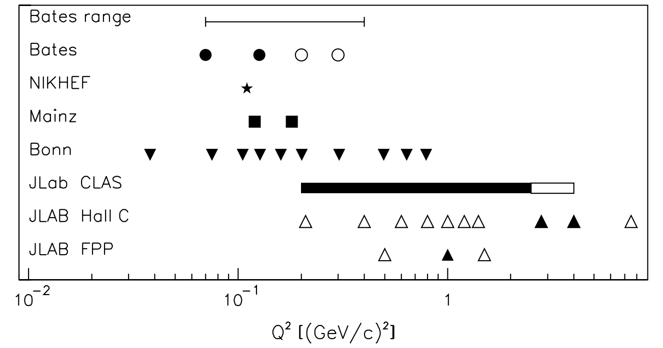

Fig. 1. Recently performed (filled symbols) and planned (open symbols) $N \to \Delta$ experiments at different laboratories for different Q^2. CLAS has a continuous coverage for $Q^2 > 0.35$ (GeV/c)^2.

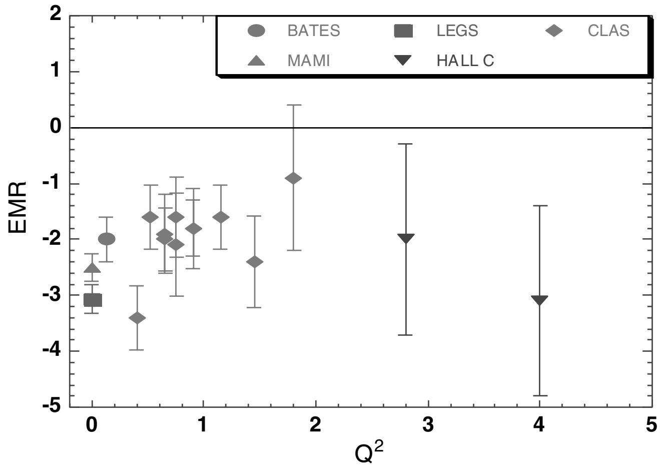

Fig. 2. Experimentally derived R_{EM} values.

2 Experimental landscape

Precision measurements with polarized tagged photons performed at Mainz and Brookhaven (LEGS) have converged at the level of asymmetries resulting in a resonant $R_{EM} = \mathrm{Im}E_{1+}^{3/2}/\mathrm{Im}M_{1+}^{3/2}$ of $(-3.0 \pm 0.3)\%$ [7] and $(-2.5 \pm 0.3)\%$ [8]. A number of theoretical calculations are in good agreement with the experimentally derived R_{EM}. However, important discrepancies still persist in the measurements of the two labs in the detailed angular and energy distributions.

The situation in electron scattering investigations is rapidly changing. Results are reported from several groups which are consistent and converging [9]. Figure 1 shows performed and programmed experiments exploring the issue of deformation through $N \to \Delta$ experiments at several laboratories [10–17]. The high-Q^2 range can only be reached by Jefferson, whereas Bonn, Mainz, and Bates are better suited to explore medium and low Q^2. Recent measurements at Bates [10,11,18], Bonn [15,14], and Mainz [13,12] demonstrate that observables sensitive to the R_{SM} can be obtained with the required high experimental precision.

The coincident $p(\boldsymbol{e}, e'\pi)$ cross-section in the one-photon-exchange approximation can be written as [19]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\omega \mathrm{d}\Omega_{\mathrm{e}} \mathrm{d}\Omega_\pi^{\mathrm{cm}}} = \Gamma_{\mathrm{v}}\ \sigma_{\mathrm{h}}(\theta,\phi)\,, \tag{1}$$
$$\sigma_{\mathrm{h}}(\theta,\phi) = \sigma_{\mathrm{T}} + \varepsilon\sigma_{\mathrm{L}} + \sqrt{2\varepsilon(1+\varepsilon)}\sigma_{\mathrm{TL}}\cos\phi + \varepsilon\sigma_{\mathrm{TT}}\cos 2\phi + hp_{\mathrm{e}}\sqrt{2\varepsilon(1-\varepsilon)}\sigma_{\mathrm{TL'}}\,,$$

where Γ_{v} is the virtual photon flux, $h = \pm 1$ is the electron helicity, p_{e} is the magnitude of the longitudinal electron polarization, ε is the virtual photon polarization, θ and ϕ are the pion CM polar and azimuthal angles relative to the momentum transfer $\boldsymbol{q}$, and σ_{L}, σ_{T}, σ_{TL}, and σ_{TT} are the longitudinal, transverse, transverse-longitudinal, and transverse-transverse interference cross-sections, respectively [19].

The resonant quadrupole multipoles $(E_{1+}^{3/2})$ and $(S_{1+}^{3/2})$ which are small are investigated in the interference responses σ_{LT} and σ_{TT}, where the small amplitudes are exposed by interfering with the dominant $M1$ amplitude. From these responses R_{SM} and R_{EM} are extracted through one of the following two approaches: a) In the Truncated Multipole Expansion (TME) approximation, most or all of the nonresonant multipoles are neglected (*e.g.*, see [14–16]) assuming that at resonance only the resonant terms contribute significantly. b) A phenomenological reaction framework with adjustable quadrupole amplitudes is used to perform a model extraction (*e.g.*, see [16, 11]). It is assumed that the reaction is controlled at the level of precision required for the disentanglement of the background from the resonance.

The TL and the TL′ (transverse-longitudinal) response functions are the real and imaginary parts of the same combination of multipole amplitudes. In the TME approximation they can be written as [19]

$$\sigma_{\mathrm{TL}}(\theta) = -\sin\theta \mathrm{Re}[A_{\mathrm{TL}} + B_{\mathrm{TL}}\cos\theta]\,, \tag{2}$$
$$\sigma_{\mathrm{TL'}}(\theta) = \sin\theta \mathrm{Im}[A_{\mathrm{TL}} + B_{\mathrm{TL}}\cos\theta]\,,$$
$$A_{\mathrm{TL}} \approx -L_{0+}^* M_{1+}\,,$$
$$B_{\mathrm{TL}} \approx -6L_{1+}^* M_{1+}\,.$$

The two responses are particularly valuable because σ_{LT} is most sensitive to the presence of resonant quadrupole amplitudes, while σ_{LT}' is particularly sensitive to the background contributions, thus providing information on the two key experimental issues being explored.

The importance of background is clearly seen in the W behavior of the responses [11] and the nonvanishing recoil polarization P_n [10,12]. New precise results of R_{EM} have recently been published from CLAS (Jefferson) [17] and been reported by Bonn [14]. It will be interesting to ascertain whether the R_{EM} at the low and intermediate Q^2 values studied assumes positive values or it stays negative (as at the precisely known photon point [7,8]). We should also point out that the transverse background contributions at finite Q^2 are even less understood than the scalar ones.

Figures 2 and 3 offer a recent compilation of the current status of R_{EM} and R_{SM} as a function of Q^2. It can be observed that both R_{EM} and R_{SM} are small and negative in the region where they have been measured. At

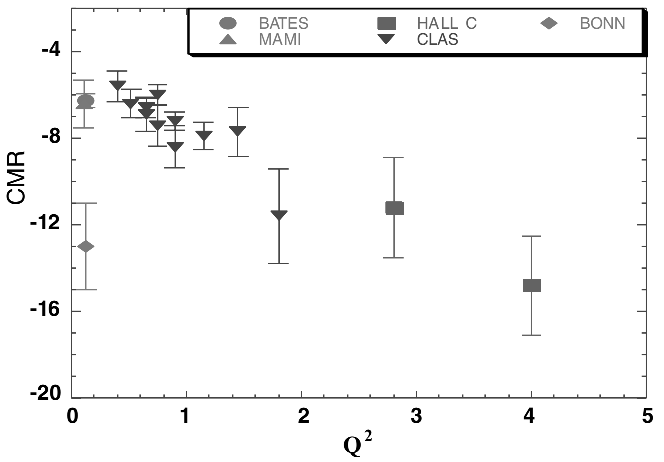

Fig. 3. Experimentally derived R_{SM} values.

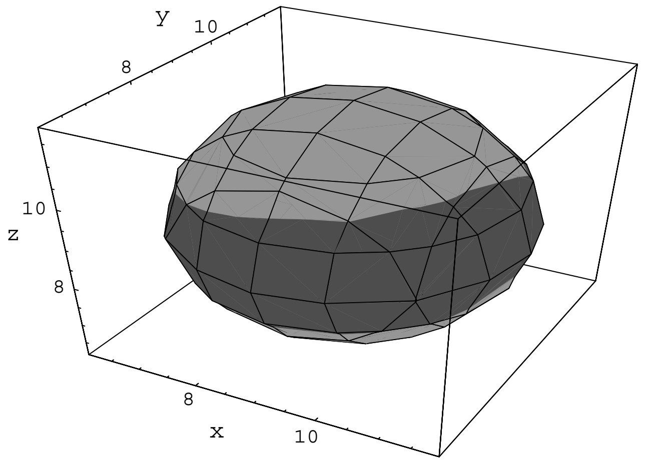

Fig. 4. The shape of the Δ in lattice gauge calculation [4] which predicts an oblate shape.

asymptotic values of Q^2, helicity conservation [20] requires that $R_{EM} \rightarrow 1.0$ and that $R_{CM} \rightarrow$ constant. Clearly, this regime has not been reached.

3 Theoretical developments

While direct links to QCD only very recently appear to be within reach, QCD-inspired models have provided since the very beginning schemes for both guiding the experimental programs and for interpreting their results. The very fertile and strong interplay between theory and experiment is a key feature of the field. Nucleon models are continuously being refined providing valuable guidance as to the magnitude of the resonant amplitudes. The overwhelming majority of nucleon models have a definite prediction for the value of R_{EM} and often of the Q^2 evolution of R_{EM} and R_{SM}.

The development of phenomenological reaction models, which in addition to the resonant amplitudes can calculate in a consistent fashion the contribution of the background, has been crucial to the development of the field. They provide predictions for the responses and the cross-sections which allows the interpretation of experimental data in a meaningful and consistent way. Prominent in this category are the models of RPI [21], MAID [22] SL [2] and the DMT [23]; they offer a rich and yet flexible phenomenology that allows for the extraction from the data of the amplitudes of interest (albeit model dependent). Deficiencies of the models that emerge as a result of the comparison with the data are rectified by re-adjustments of the parameters and/or by modifying the phenomenology. This results in an improved understanding of the underlying physics and gradual reduction of the model error.

Important is the $H(\boldsymbol{e}, e'p)\gamma$ channel which has not been exploited experimentally yet. The new dispersion theory [24] of the Mainz group, taken in conjunction with the previous work of Vanderhaegen *et al.* [25] allows to addresses the physics of "deformation" and of nucleon polarizabilities in the region above pion threshold simultaneously.

The prediction of the DMT [3,23] and of SL [2] that most of the responses and the R_{EM} and R_{SM} exhibit a distinct structure at very low Q^2 values (below 0.10 GeV^2/c^2) which arises as manifestation of the mesonic degrees of freedom is most intriguing. We may thus have for the first time a clear signature of the manifestation of the pion cloud at low Q^2 which paves the way for the experimental exploration of this effect.

Finally, it is very exciting that remarkable progress in recent years both in the theoretical understanding but also in computational techniques and computing power has allowed the first results with direct connection to QCD to emerge. Recent results from chiral perturbation theory [26] or lattice gauge theory calculations [4] are clearly indicating that we can expect to establish for the first time contact between QCD theory and experiment in immediate future. It is remarkable that very recently lattice gauge calculations, both in quenched and unquenched approximations, have yielded R_{EM} and R_{SM} values with acceptable uncertainties and within the range of the experimental results [4]. They have also measured on the lattice and shown for the first time the shape of hadrons; in fig. 4 the calculated shape of the Δ is shown, which is found to be oblate, consistent with the experimental findings.

4 The Bates γ^*N $\rightarrow \Delta$ program

The Bates $\gamma^* N \rightarrow \Delta$ from its very inception back in 1997 relies on a major instrumentation initiative, the Out-Of-Plane Spectrometer (OOPS) system. The OOPS facility is now fully developed and commissioned. It exceeds all design requirements [27,28]. It was explicitly designed to take advantage of the ϕ-dependence of the cross-section which acts as lever arm for isolating the interference responses. It also allows access to the fifth response, which requires both polarized beam and out-of-plane detection. The so-called "+" configuration, schematically depicted in fig. 5, has been mostly employed in recent runs. The four spectrometers measure the coincidence cross-section

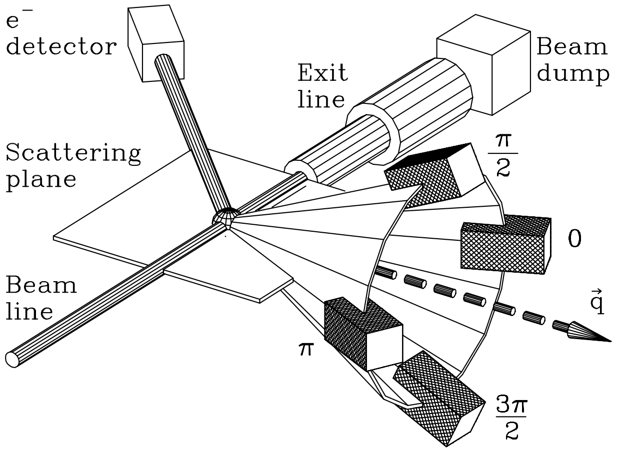

Fig. 5. A schematic diagram of the "+" configuation of the Bates OOPS spectrometer.

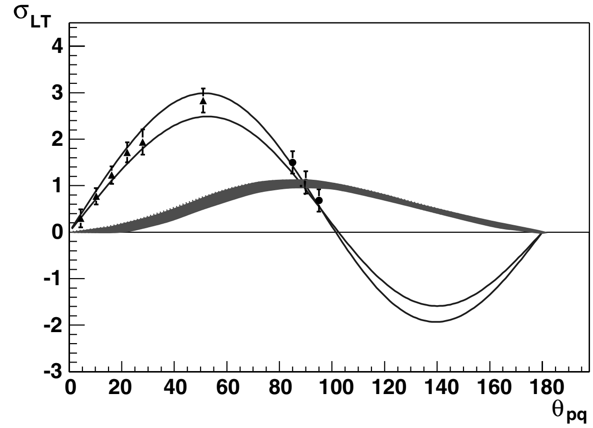

Fig. 6. The nucleon is deformed: The σ_{LT} response measured by the OOPS Collaboration at $W = 1232$ GeV. The shaded band represents the allowed uncertainty for a spherical nucleon (both $N(938)$ and $\Delta(1232)$). The band ecompassing the data represents the uncertainly allowed by all of our data analyzed simultaneously (see the discussion in the text).

at four different azimuthal angles but at the same θ^*_{pq} simultaneously thus allowing the extraction of the interference responses with minimal systematic uncertainty.

The first $\gamma^* N \to \Delta$ measurements [10,11,29] resulted in the precise determination of the cross-section in "parallel kinematics", σ_0, of the LT-asymmetry, A_{LT}, and response σ_{LT} and the measurement of the induced proton polarization P_n. P_n is proportional to the σ^n_{LT} response and it would be identically zero in the absence of background. It was found [10] to be $-0.397 \pm 0.055 \pm 0.009$ which established the importance of the background contributions. Recent FPP measurements at Mainz [13] of higher statistical precision and which measured all three polarization responses, both confirmed the above measurement but in addition were able to determine the magnitude of the R_{SM}, the point shown in fig. 3.

The coincident cross-section in parallel kinematics was measured from $W = 1155$ to $W = 1320$ MeV; however, it was the precise R_{LT} results that amply demonstrated the sensitivity of the data to the "deformation" [11]. All available models fail dramatically to predict the behavior of the data unless nonzero resonant quadrupole amplitudes are introduced. Reasonable agreement is achieved when the parameters of the models are adjusted allowing for their determination either through a variant of the $M1$ dominance TME fit or through model extraction. By adjusting the relevant parameters in the models of MAID [22], of RPI [21] and of SL [2], values for R_{SM} and R_{SM} have been derived [11]. The dynamical Models of SL [2] and DMT [3] provide acceptable description, while the RPI [21] model could not account for all the measured responses simultaneously.

The first out-of-plane $N \to \Delta$ measurements [30] were performed for proton or pion detection. In addition to measuring the σ_{LT} response at a larger angle, the data allowed for the extraction of the helicity asymmetry A_{h} and the $R_{\mathrm{LT}}{}'$ response. A_{h} has analogous significance to P_n in isolating the background contributions, as they both are an imaginary part of a LT interference.

The year 2000/2001 was marked by major technical achievements for the OOPS program which led to production runs for the VCS and $N \to \Delta$ experiments. A 950 MeV beam energy, with currents up to 7 μA and a duty-factor in excess of 50% was used in conjunction with the completed and commissioned 4-OOPS cluster.

The TT response which is sensitive to the electric-quadrupole amplitude, and of which little is known at nonzero Q^2 was isolated for the first time [18]. The response functions σ_{T} and σ_{TT} contain the term $\Re[E^*_{1+} M_{1+}]$ but also the dominant term $|M_{1+}|^2$. The influence of the dominant $|M_{1+}|^2$ term can be diminished by measuring the following combination of the σ_{T} and σ_{TT} responses:

$$\begin{aligned}\sigma_{00}(\theta^*_{pq}) = \sigma_{\mathrm{T}}(\theta^*_{pq}) + \sigma_{\mathrm{TT}}(\theta^*_{pq}) - \sigma_{\mathrm{T}}(0) = \\ 2\Re[E^*_{0+}(3E_{1+} + M_{1+} - M_{1-})](1 - \cos\theta^*_{pq}) \\ -12\Re[E^*_{1+}(M_{1+} - M_{1-})]\sin^2\theta^*_{pq}\,. \qquad (3)\end{aligned}$$

The term of interest $\Re[E^*_{1+} M_{1+}]$ is enhanced by a factor of twelve (12)! while the leading term ($|M_{1+}|^2$) is eliminated. The cross-sections needed to derive this quantity were measured; as a result, we expect to extract a most precise measurement of R_{EM} at $Q^2 = 0.126$ GeV^2. The sensitivity to the EMR is maximized at the measured kinematics as shown in fig. 7.

A very recent combined analysis of all the available OOPS data has been performed by Sparveris [18]. The data base at $Q^2 = 0.126$ is quite rich allowing for a "model independent" extraction of the R_{EM} and R_{SM} values. This analysis which has yielded the results in fig. 6 and fig. 7 demonstrated beyond any doubt that both the R_{EM} and R_{SM} yield incompatible results with a spherical nucleon. Based on this same analysis, we have derived [18] $R_{SM} = (-6.27 \pm 0.32_{\mathrm{stat+sys}})\%$ and $R_{EM} = (-2.00 \pm 0.40_{\mathrm{stat+sys}})\%$. We assign model uncertainties of 0.10% and 0.27% to R_{SM} and R_{EM}, respectively. This

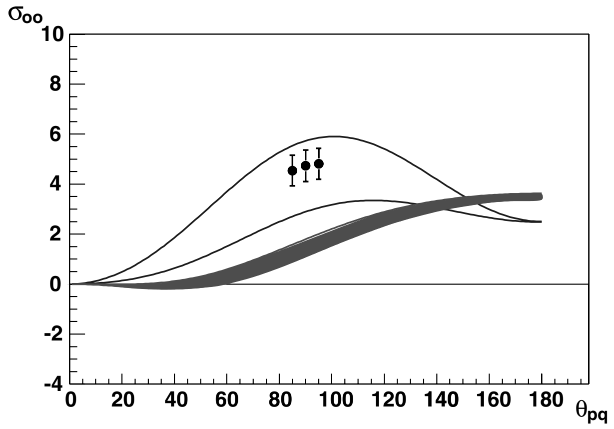

Fig. 7. The measured σ_{00} exhibits high sensitivity to R_{EM} allowing the exclusion of a "spherical nucleon". See text. The error bands have the same meaning as in fig. 6.

is to contrasted with the similar analysis of then available data which resulted in [11] in model uncertainties of 2.5% and 2.0% to R_{SM} and R_{EM}, respectively. The derived results are consistent with the interpretation of Buchmann [31] and coworkers suggesting a prolate nucleon and an oblate Δ.

During the same running period we were able to access the low-momentum branch of the recoiling protons by tuning the OOPS spectrometers to very low-momentum detection. We thus accessed $\theta^*_{pq} = 151°$ and at $\theta^*_{pq} = 180°$ for an $\sigma_{\rm LT}$ measurement. The high duty cycle extracted beam also provided a significant advantage for studies of the π^+ channel dramatically reducing the experimental background. The $p(e, e'\pi^+)n$ reaction was measured at $W = 1232$ MeV, $Q^2 = 0.127$ GeV^2 and $\theta^*_\pi = 44.5°$. All three unpolarized response functions could be determined. In addition, we measured the cross-section in parallel kinematics. These results are currently in the final stages of analysis.

5 Future prospects

A new level of sophistication and precision is emerging from the experimental programs in pursuit of the issue of hadron deformation through the $N\to\Delta$ transition. It is apparent that in the next few years the definitive signature will be established and we can hope to achieve firm contact with QCD. Of immediate concern is the role of the pion cloud at low momentum transfers and the quantification of model error in the extracted quantities.

I want to thank the organizers for their invitation to this exciting conference and Prof. S. Stiliaris, C. Alexandrou and N. Sparveris for contributing significantly to this paper. I am indebted to the Bates community and to the OOPS Collaboration and to Drs S. Kamalov, L.Tiator for many useful suggestions. This work was supported in part by E.U. RTN HPRN-CT-2000-00130 and Athens University.

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