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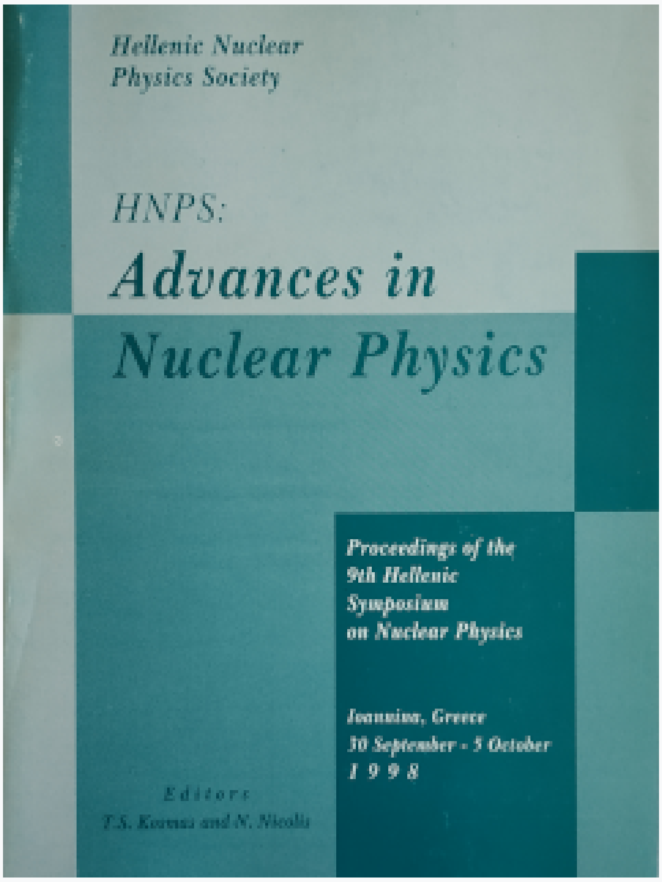

Study of the proton deformation using the Out-Of-Plane Spectrometers

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Abstract

Nucleon deformation can be studied through electro-excitation to the first nucleon resonance, the $\Delta^+(1232)$, and quantified through the quadrupole amplitudes in the $\gamma^* N \to \Delta$ transition. A search for these small amplitudes has been the focus of a series of measurements undertaken at Bates-MIT. A first set of in-plane data show evidence for strong resonant *and* non-resonant ("background") amplitudes in the longitudinal-transverse interference, which is sensitive to leading order to quadrupole contributions. Using beams of polarized electrons and the technique of out-of-plane detection, a second data set was collected on the two hadronic decay channels. It contains the first measurement of the fifth structure function on the nucleon, which provides an important theoretical constraint on the "background" amplitudes. Planned future measurements will focus on refining the resonance-background decomposition which is absolutely necessary before conclusions on the issue of nucleon deformation can be drawn.

1 Introduction

The possibility of nucleon deformation was first raised by Glashow 20 years ago [1] and has since remained an important open question. Because the static quadrupole moment of the nucleon vanishes identically, on account of its $J = 1/2$ nature, experimental and theoretical investigations have focused on the search for quadrupole strength in the $N \to \Delta$ transition. The physical origin of resonant quadrupole strength is however interpreted in different terms in the various nucleon models that predict such an effect. For instance, in "QCD-inspired" constituent quark models, it arises from intra-quark effective color-magnetic tensor forces [2,3], a situation analogous to that of the intra-nucleon tensor interaction in the deuteron which leads to its deformation.

Spin-parity selection rules in the $N(J^\pi = 1/2^+) \rightarrow \Delta(J^\pi = 3/2^+)$ transition allow magnetic dipole ($M1$) and electric quadrupole ($E2$) or Coulomb quadrupole ($C2$) multipoles. In pion production, amplitudes are denoted by $M^I_{l\pm}$, $E^I_{l\pm}$, and $S^I_{l\pm}$, thus indicating their character (magnetic, electric, or scalar), their isospin (I), and their total orbital angular momentum ($J = l \pm \frac{1}{2}$). Thus, the resonant photon multipoles $M1, E2$, and $C2$ correspond to the pion multipoles $M^{3/2}_{1+}$, $E^{3/2}_{1+}$, and $S^{3/2}_{1+}$, respectively. The Electric- and Scalar(Coulomb)-to-Magnetic-Ratios of amplitudes are defined as $EMR = R_{EM} = \mathrm{Re}\, e(E_{1+}/M_{1+})$ and $CMR = R_{SM} = \mathrm{Re}\, e(S_{1+}/M_{1+})$ respectively. In the spherical quark model of the nucleon, the $N \rightarrow \Delta$ excitation is a pure $M1$ transition. Early electroproduction experiments [4–7] indeed found the $M1$ amplitude to dominate. However, more refined models [8–10] predict values of R_{SM} in the range of -1% to -4%, at momentum transfer square $Q^2 \approx 0.1$ (GeV/c)^2.

The interpretation of the experimentally determined R_{EM} and R_{SM} is severely complicated by the presence of processes which are coherent with the resonant excitation of the $\Delta(1232)$. These processes (such as the pion pole, Born terms, tails of higher resonances, off-shell effects and pion loops) give rise to additional non-resonant quadrupole amplitudes which further complicate the isolation of the resonant quadrupole amplitudes. These interfering processes, termed "background contributions" therefore need to be constrained in order to isolate the resonant contributions to R_{EM} and R_{SM} which could then be interpreted as signals for "deformation". In our experimental program the separation of the "background" from the resonant terms plays a central role. It is attempted through measurements of the isolated responses over a wide range of the dynamic variables, where interference effects between different reaction mechanisms vary.

While real photons are used to extract R_{EM} at $Q^2 = 0$, the Q^2 evolution of R_{EM} and R_{SM} can be investigated only through electro-excitation. Recent precision measurements with polarized tagged photons have resulted in an $R^{3/2}_{EM} = \mathrm{Re}\, e(E^{3/2}_{1+}/M^{3/2}_{1+})$ at resonance of $(-3.0 \pm 0.3)\%$ [11] and $(-2.5 \pm 0.3)\%$ [12], in good agreement with theoretical calculations. The situation is quite different for electron scattering investigations and the resulting R_{EM} and R_{SM} determination. The first experiments conducted at Q^2 up to 1 (GeV/c)^2 have yielded an R_{SM} of around -7%, but with large statistical and systematic errors [4–7]. Exceptionally large values of around $R_{SM} \approx -13\%$, suggestive of a sharp dependence peaking near $Q^2 = 0.1$ (GeV/c)^2, have been reported [4,13]. Such

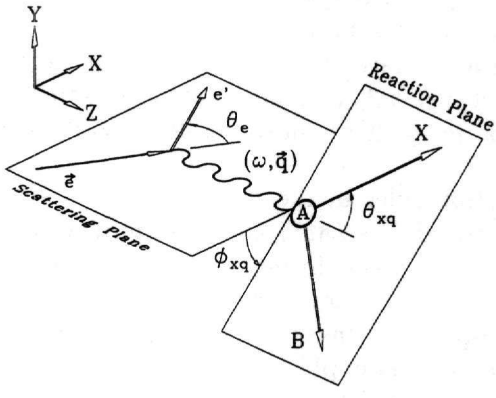

Fig. 1. Kinematic definitions for the A($\vec{e}, e'x$)B reaction.

large values and especially the presence of a large, rapid Q^2 variation cannot be accounted for in any known model. As a result, the recent claims drew considerable attention. The measurements reported here were performed at the same value of Q^2 in order to allow a direct comparison with the aforementioned data.

2 Experimental Method and Equipment

The experimental approach taken by the Out-Of-Plane Spectrometer (OOPS) collaboration is the isolation of all responses which manifest themselves in the $H(\vec{e}, e'x)$ reaction [14]. The program [15–17] is geared towards mapping these five responses over the dynamical variables (W, Q^2, θ_{pq}) for all possible Δ decay channels, *i.e.* $p\pi^0, n\pi^+$ and $p\gamma$. With this method, one obtains essential information on the isospin dependence of the process and another way of testing our understanding of "background" mechanisms as they have different manifestation in each of these channels, and different variations over the dynamical variables. The ultimate goal is to use such a data set in order to do a decomposition of the resonant and the important "background" multipoles.

For the case of polarized beam and out-of-plane detection (Fig. 1) the cross section for the A($\vec{e}, e'x$)B reaction is [14]:

$$d\sigma = d\sigma_{\text{Mott}}(v_L R_L + v_T R_T + v_{LT} R_{LT} \cos\phi_{xq} + v_{TT} R_{TT} \cos 2\phi_{xq} + h v'_{LT} R'_{LT} \sin\phi_{xq}) \quad (1)$$

where ϕ_{xq} is the azimuthal reaction angle for the detected particle, $v_{\alpha\beta}$ is the lepton tensor and h is the beam helicity. The longitudinal-transverse (R_{LT}) and transverse-transverse (R_{TT}) structure functions contain the interference terms $\mathrm{Re}\, e(S^*_{1+}M_{1+})$ and $\mathrm{Re}\, e(E^*_{1+}M_{1+})$ respectively. They are thus sensitive to the small quadrupole multipoles by amplifying their contribution through their interference with the the large and reasonably well-understood M_{1+}. The so-called 'fifth' structure function (R'_{LT}) is the imaginary analog to R_{LT}. It contains the term $\mathrm{Im}\, m(S^*_{1+}M_{1+})$ and is therefore sensitive to the relative phase of the resonant amplitudes. Because for an isolated resonance this observable would be zero, it plays a key role in the separation of resonant from competing channels in the study of nucleon resonances. It can be only measured if the incident electrons are longitudinally polarized and out-of-plane detection is implemented.

The isolation of all five responses of Eq. 1 is possible by placing detectors at optimally chosen positions, using ϕ_{xq} as a lever arm. If, in addition, the measurements are performed simultaneously with multiple detectors, systematic errors can be substantially reduced, as the structure functions are derived - up to a normalization factor - from cross section ratios. It is often useful to form the asymmetries A_{LT}, A_{TT} and A'_{LT} which are related to the corresponding structure functions LT, TT and LT'. The helicity asymmetry and response are related by

$$A_h = A'_{LT} = \frac{d\sigma(+h) - d\sigma(-h)}{d\sigma(+h) + d\sigma(-h)}. \tag{2}$$

The measurement scheme described above has been realized at Bates-MIT in the OOPS facility. Four identical spectrometers [18,19] have been constructed, so that they can be positioned in a cluster symmetrically around the momentum transfer axis in a $\times$ or a $+$ configuration. The OOPSs are 16-ton 850 MeV/c magnetic spectrometers of momemtum resolution of $\Delta P/P = 0.5\%$ and a large flat bite of $\pm 10\%$. They can be placed with position and orientation accuracies of better than 1 mm and 1 mr respectively. The focal plane instrumentation of an OOPS spectrometer consists of three horizontal drift chambers for track reconstruction and three scintillators for triggering.

3 The $\Delta \to p\pi^0$ Channel

The $\Delta \to p\pi^0$ channel was the first to be measured because it has the highest branching ratio (66%) and the "background" is lower than in the $n\pi^+$ channel. Conventional in-plane spectrometers, unpolarized beam and, in one case, a focal plane polarimeter (FPP) were used. A second data set was collected using polarized beams and three OOPS spectrometers. The main kinematic quantities are summarized in Table 1.

Table 1
Reactions and kinematics

Reaction	Q^2 $(GeV/c)^2$	W (MeV)	θ_{xq}^{cm} (deg.)	ϕ_{xq}^{cm} (deg.)
$H(e,e'\vec{p})\pi^0$	0.126	1232	0.0	0
$H(e,e'p)\pi^0$	0.126	1172	0–39.9	0, 180
$H(e,e'p)\pi^0$	0.126	1232	0–28.1	0, 180
$H(e,e'p)\pi^0$	0.126	1292	0–9.5	0, 180
$H(e,e'p)\pi^0$	0.071	1155	55.2	45, 135
$H(\vec{e},e'p)\pi^0$	0.127	1170	61.5	45, 135
$H(\vec{e},e'p)\pi^0$	0.127	1232	49.5	45, 135
$H(\vec{e},e'\pi^+)n$	0.127	1232	26.4	45, 135

3.1 In-plane Measurements of $d\sigma_{||}$, R_{LT}, A_{LT} and P_n

This experiment [20] was conducted with beams of 1% duty factor and at energies of 719 and 799 MeV. A liquid H_2 target was used in a cylindrical cell of 3-cm diameter with a 10-μm-thick Havar wall. The scattered electrons were detected in the Medium Energy Pion Spectrometer (MEPS) and the coincident protons in the One Hundred Inch Proton Spectrometer (OHIPS). The total efficiency of the system was calibrated by using elastic electron scattering data from the liquid H_2 target. The phase-space normalization of the cross section and various corrections that need to be applied to the data, including radiative corrections, have been implemented with the aid of a Monte Carlo simulation model.

The differential cross section for proton detection along the momentum transfer direction is shown in Fig.1. For such 'parallel' kinematics, R_{LT} and R_{TT} vanish, and the cross section ($d\sigma_{||}$) is dominated by R_T, which contains the term $|M_{1+}|^2$. The data are shown as a function of invariant mass W and exhibit a distinct resonant shape peaking at 1203.4 ± 1.3 MeV. The data are compared with predictions of the model of Sato and Lee, which is an extension of their photo-production model [9], of Mehrotra and Wright [21], and of Drechsel *et al.* [10]. All calculations predict the position of the maximum correctly, although they differ in their detailed shape and especially in magnitude. The 'deformed' (non-zero quadrupole $\gamma^* N \to \Delta$ form factors) model of Sato and Lee [9] is the one closest to these data.

The longitudinal-transverse interference response R_{LT} and the related asymmetry A_{LT} for this in-plane case are related by

$$A_{LT} = \frac{d\sigma(\phi=0) - d\sigma(\phi=\pi)}{d\sigma(\phi=0) + d\sigma(\phi=\pi)} = \frac{v_{LT} R_{LT}}{v_L R_L + v_T R_T + v_{TT} R_{TT}}. \qquad (1)$$

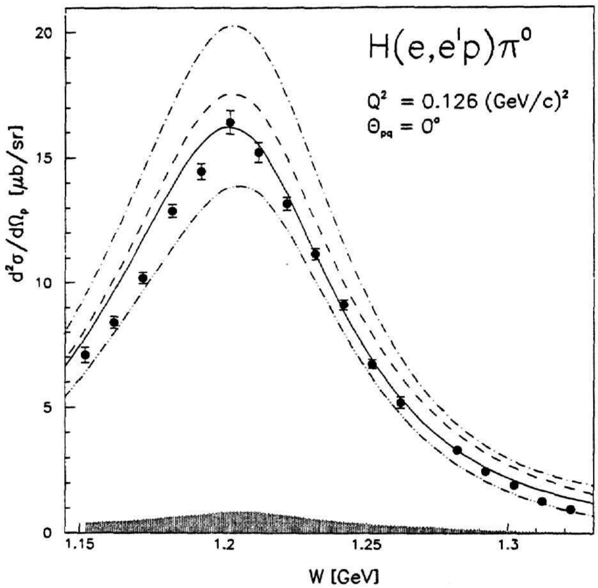

Fig. 1. The CM cross section in parallel kinematics $d\sigma_{||}$ [20]. The solid curve is the "deformed" and the dashed curve the "non-deformed" prediction of Ref. [9]. The dot-dashed and dot-dot-dashed curves are the calculation of Refs. [21] and [10] respectively. The shaded band shows the value of the systematic error.

Fig. 2 shows R_{LT} and A_{LT} plotted vs. the proton angle to the momentum transfer axis θ_{pq} in the CM frame. Clearly, a consistent description of the small amplitudes which build the longitudinal-transverse interference response is not given by any of the available theoretical models. Our results are also compared against those of another experiment [13], where A_{LT} was measured at a CM-backward angle, and a value of $R_{SM} = -13\%$ was extracted at $W = 1232$ MeV. Using their measured asymmetry and assumption that only the resonant amplitudes contribute, we projected the hatched band in Fig. 2. The disagreement with our data is a strong indication that "background" contributions to the resonant and non-resonant multipoles can not be ignored in the interpretation of these data for the extraction of R_{SM}. A further indication of this fact is the factor-of-2 difference in our measured A_{LT} below and on the resonance, as well as the apparent sign change between $W = 1172$ MeV and $W = 1292$ MeV.

Using a focal plane polarimeter [22], we made a separate measurement of the polarization of the recoiling proton at $W = 1232$ MeV. With an unpolarized electron beam and target, the final state proton polarization in parallel kinematics has only one component (P_n) normal to the scattering plane, which

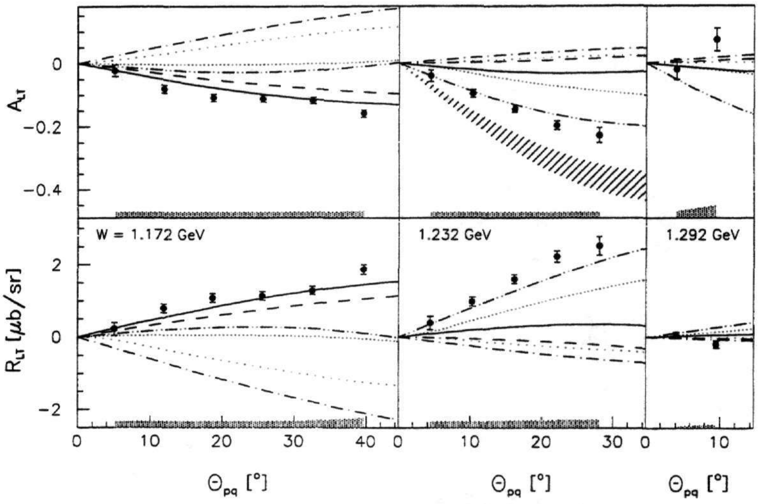

Fig. 2. The longitudinal-transverse asymmetry and response, as a function of the CM proton polar angle [20]. The dense dotted and dotted curves are the "deformed" and "non-deformed" cases of Ref. [8]. The notation of the other curves is explained in Fig. 1. The hatched band is the projection of the result of Ref. [13], as explained in the text. The shaded bands show the values of the systematic error.

is $P_n = v_{LT} R^n_{LT}/d\sigma_{||}$. The response function R^n_{LT} is similar to R'_{LT}, in that to leading order it is proportional to the term $\mathrm{Im}\, m(S^*_{1+} M_{1+})$ which would be zero in the case of a pure resonance. The large measured value [23] of $P_n = -0.397 \pm 0.055 \pm 0.009$ provides another indication of strong "background" contributions in the Δ electro-excitation. The P_n result is in good agreement with that of Drechsel *et al.* [10], but about a factor of 2 larger than the prediction of the model of Sato and Lee [9,23].

3.2 Out-of-plane Measurements of A_{LT}, A'_{LT}

In the first out-of-plane measurements of the $\Delta \to p\pi^0$ channel, two OOPS spectrometers were positioned at $\phi_{pq} = 45, 135$ deg. (Table 1), while a third OOPS was used as a luminosity monitor. Beams of 820 MeV energy and 1% duty factor were incident on a liquid H_2 target. In all but one measurement, longitudinal polarization of $\approx 37\%$ was delivered, produced by circularly polarized laser light hitting a GaAs crystal. The beam polarization was measured intermittently during the experiments using a Moller polarimeter [24].

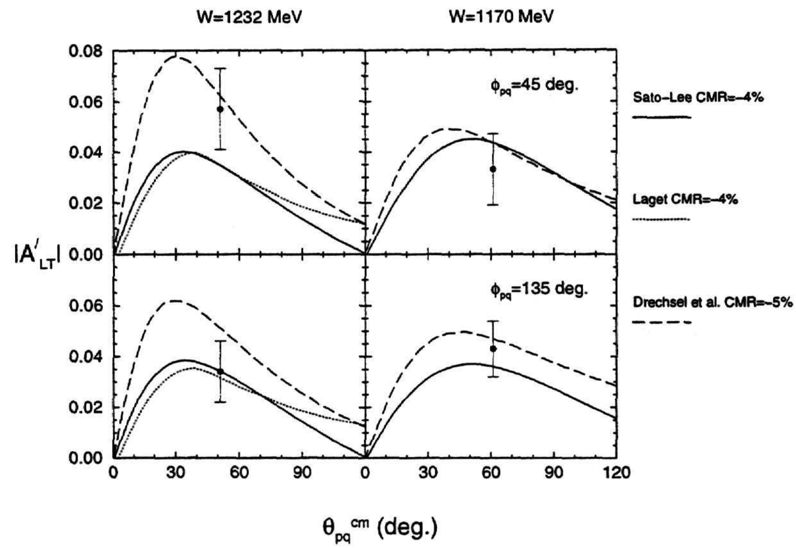

Fig. 3. Preliminary result of the imaginary part of the longitudinal-transverse asymmetry, as a function of the CM proton polar angle. The curves are theoretical calculations due to Refs. [8–10].

For this out-of-plane case, the LT response and asymmetry are related by

$$A_{LT} = \frac{d\sigma(\phi = \pi/4) - d\sigma(\phi = 3\pi/4)}{d\sigma(\phi = \pi/4) + d\sigma(\phi = 3\pi/4)} = \frac{v_{LT}R_{LT}}{v_L R_L + v_T R_T}. \tag{2}$$

The measurements were made at angles considerably larger than in the in-plane case. This gives a lever arm in the θ_{pq} angle which can prove very useful in the eventual multipole decomposition of the resonant quadrupole from the "background" amplitudes. While analysis for the LT observables is under way [25], the projected statistical error in A_{LT} is less than 1%.

The first measurement of A'_{LT} in the $p\pi^0$ channel is shown in Fig. 3. The statistics-dominated errors will be reduced by combining the measurements at $\phi_{pq} = 45$ deg. and 135 deg. for each W-point, once the absolute cross section has been extracted from the data [25]. The preliminary results are several standard deviations away from zero, thus providing yet another indication of non-zero "background". However, unlike the case of P_n, here the available calculations [8–10] are in fair agreement with the data. Although the leading term in the multipole expansion of both A'_{LT} and P_n is the same ($\mathrm{Im}\, m(S^*_{1+}M_{1+})$), the next-to-leading-order terms are not. This points to the complexity of describing all resonant and "background" multipoles in the framework of a nucleon model.

A second generation of measurements will soon be possible at Bates due to the availability of high quality continuous-wave beams and to the full 4-spectrometer OOPS apparatus. For the first time, the simultaneous measurement of five responses at identical kinematics will be possible over a large range of kinematics and with superior control of the systematic uncertainties. New measurements will extend to cover larger regions of W, Q^2 and θ_{pq} angle. Also the R_{TT} response and asymmetry will be accessed, opening the study of the Q^2 evolution of R_{EM}, on which little is known. Finally, the availability of beams with polarization higher than 60% will greatly reduce the statistical error of A'_{LT}, which is much larger than the systematic.

4 The $\Delta \rightarrow n\pi^+$ Channel

The motivation to study the $\Delta \rightarrow n\pi^+$ channel [16] is to add isospin discrimination to the determination of resonant and "background" amplitudes. If only proton targets are utilized, then two of the three independent isospin amplitudes can be determined, the resonant $I = 3/2$ amplitude ($A_{1+}^{3/2}$) and the non-resonant $I = 1/2$ amplitude ($A_{1+}^{1/2}$) which is the sum of isoscalar and isovector terms. Measurements for the $p\pi^0$ and $n\pi^+$ channels give a different weighting of the resonance and "background" amplitudes [26].

$$A_{1+}^{3/2} = \sqrt{\frac{1}{3}}\, A_{1+}\,(\gamma p \rightarrow \pi^+ n) + \sqrt{\frac{2}{3}}\, A_{1+}\,(\gamma p \rightarrow \pi^0 p) \tag{1}$$

$$A_{1+}^{1/2} = \sqrt{\frac{2}{3}}\, A_{1+}\,(\gamma p \rightarrow \pi^+ n) - \sqrt{\frac{1}{3}}\, A_{1+}\,(\gamma p \rightarrow \pi^0 p) \tag{2}$$

The Bates measurements program for the $H(\vec{e}, e'\pi^+)n$ reaction parallels the one of the $p\pi^0$ channel. So far, one experiment has been completed at the kinematics shown in Table 1. The LT and LT' responses and asymmetries were measured on the resonance, at the same momentum transfer as in the previously described experiments on the $p\pi^0$ channel. A preliminary data analysis [25] indicates that A'_{LT} is much larger than in the π^0 case.

5 The $\Delta \rightarrow p\gamma$ Channel

The motivation to study the $H(\vec{e}, e'p)\gamma$ reaction [17] is to complete the information on all decay channels of the $\Delta^+(1232)$. This process - also called Virtual Compton Scattering (VCS) - can be used to enlarge the $\gamma^* N \rightarrow \Delta$ data base with different resonance-background interference observables, due to its purely electromagnetic nature. Two calculations for this reaction exist to date [27,28]. The one by Vanderhaeghen [28] predicts the helicity asymmetry to have an oscillation pattern, as a result of the resonance interfering with the Bethe-Heitler background. This distinct signal is of general interest in the study of other known resonances and potentially in the search for missing ones.

Although this measurement was first proposed a decade ago [15], this remains a virgin field mainly due to the technical difficulties associated with the low cross section of this leptonic channel. This experiment will take place in the near future at Bates using high duty factor beam, which is absolutely necessary in order to suppress the background of accidental coincidences. It will be possible to measure the $p\gamma$ channel simultaneously with the $p\pi^0$ channel - due to the large momentum acceptance of the OOPS spectrometers - and to separate the two by reconstructing the missing mass spectrum.

6 Conclusions

A program for high precision electro-production studies of the $\Delta^+(1232)$ resonance has been underway at Bates Laboratory. The technique of out-of-plane detection has been implemented in the construction of the OOPS spectrometer facility, which permits the isolation of five response functions. First data on polarization obervables and the invariant mass dependence give indications for strong "background" contributions in the reaction mechanism. Furthermore, they reveal significant disagreements with the available models of the nucleon. Future measurements will extend the present range in the dynamic variables for all three $\Delta^+(1232)$ decay channels, and will also include the TT response function. Such a complete data set and improved theoretical input are absolutely necessary in order for conclusions on the issue of nucleon deformation to be drawn.

Acknowledgements

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