Abstract.

The study of the $\gamma^* N \to \Delta$ reaction presents the best quantitative method to explore the deviation of hadron shapes from spherical symmetry (nonspherical amplitudes). Significant non-spherical electric (E2) and Coulomb quadrupole (C2) amplitudes have been observed with good precision as a function of $Q^2$ from photon point up to $\approx 7 (\text{GeV}/c)^2$. Quark model calculations for these quadrupole amplitudes are at least an order of magnitude too small and even have the wrong sign. Lattice QCD, chiral effective field theory, and dynamic model calculations which include the effects of the pion-cloud are in approximate agreement with experiment.

Keywords: EMR, CMR

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INTRODUCTION

The complex quark-gluon and meson cloud dynamics of hadrons give rise to non-spherical components in their wavefunction which in a classical limit and at large wavelengths will correspond to a "deformation". The spectroscopic quadrupole moment provides the most reliable and interpretable measurement of these components. For the proton, the only stable hadron, it vanishes identically because of its spin 1/2 nature. Instead, the signature of the non-spherical components of the proton is sought in the presence of resonant quadrupole amplitudes $(E^{3/2}_{1+}, S^{3/2}_{1+})$ in the predominantly magnetic dipole $(M^{3/2}_{1+})$ $\gamma^* N \to \Delta$ transition. Nonvanishing resonant quadrupole amplitudes will signify that either the proton or the $\Delta^+$ (1232) or more likely both are deformed. The ratios $\text{CMR} = Re(S^{3/2}_{1+}/M^{3/2}_{1+})$ and $\text{EMR} = Re(E^{3/2}_{1+}/M^{3/2}_{1+})$ are routinely used to present the relative magnitude of the amplitudes of interest.

In the quark model, the non-spherical amplitudes in the nucleon and $\Delta$ are caused by the non-central, tensor interaction between quarks \cite{1}. However, the magnitudes of this effect for the predicted E2 and C2 amplitudes \cite{2} are at least an order of magnitude too small to explain the experimental results and even the dominant M1 matrix element is $\approx 30\%$ low. A likely cause of these dynamical shortcomings is that the quark model does not respect chiral symmetry, whose spontaneous breaking leads to strong emission of virtual pions (Nambu-Goldstone Bosons)\cite{3}. These couple to nucleons as $\vec{\sigma} \cdot \vec{p}$ where $\vec{\sigma}$ is the nucleon spin, and $\vec{p}$ is the pion momentum. The coupling is strong in the p wave and mixes in non-zero angular momentum components. Based on this, it is physically reasonable to expect that the pionic contributions increase the M1 and dominate the E2 and C2 transition matrix elements in the low $Q^2$ (large distance) domain. This was first
indicated by adding pionic effects to quark models\cite{4,5,6}, subsequently in pion cloud model calculations\cite{7,8}, and recently demonstrated in effective field theory (chiral) calculations \cite{9}.

**EXPERIMENTAL AND THEORETICAL LANDSCAPE**

In recent years an extensive experimental and theoretical effort has been focused on identifying and understanding the origin of possible non-spherical components in the nucleon wavefunction \cite{10} through the study of the $\gamma^* N \to \Delta$ transition. The exploration of the two pion excitation channels has allowed the measurement of the E2 and C2 amplitudes up to $Q^2 \approx 7 (GeV/c)^2$ \cite{13,14,15,16,17,18,19,20,21} with JLab dominating the intermediate and high momentum transfer region and with MAMI and Bates focusing at the low momentum transfers, a region where the pionic contributions are expected to dominate. Both quadrupole amplitudes have been precisely measured to be non zero, with EMR exhibiting a relatively constant behavior as a function of the momentum transfer while CMR is following a fall off as a function of $Q^2$.

With the existence of non-spherical components in the nucleon wavefunction well established, recent investigations have focused on understanding the various mechanisms that could generate it. The experimental results \cite{13,14,15,16,17,18,19,20,21} are in reasonable agreement with predictions of models invoking the presence of non-spherical amplitudes and in strong disagreement with all nucleon models that assume sphericity for the proton and the $\Delta$. A wide range of theoretical approaches has been developed to interpret the experimental data such as the phenomenological model MAID 2007 \cite{11,12}, the dynamical calculations of Sato-Lee \cite{7} and of DMT \cite{8} and the ChEFT calculation of Pascalutsa and Vanderhaegen \cite{9}. The MAID model which offers a flexible phenomenology provides an overall consistent agreement with the experimental results. The DMT and Sato-Lee are dynamical reaction models which include pion cloud effects and both calculate the resonant channels from dynamical equations. DMT uses the background amplitudes of MAID with some small modifications while Sato-Lee calculate all amplitudes consistently within the same framework with only three free parameters. DMT exhibits a reasonable agreement with the data while the Sato-Lee model on the other hand exhibits a clear disagreement with the $\pi^+$ data which is a bit surprising if we consider the reasonable agreement of the Sato-Lee calculation with the $\pi^\circ$ channel experimental results \cite{16}. The chiral effective field theory (ChEFT) calculation of Pascalutsa and Vanderhaegen is a systematic expansion based on QCD\cite{9}. The results of this expansion up to next to leading order exhibit an overestimation of the $\pi^+$ channel results which indicates that the next order calculation is required. It is worth pointing out that this calculation is in reasonable agreement with the experimental results for the $\pi^\circ$ channel \cite{22,19}.

**FUTURE PROSPECTS**

Although the Electric quadrupole amplitude has been sufficiently mapped as a function of momentum transfer the Coulomb quadrupole still needs to be further explored at the
low $Q^2$ regime. Jefferson Lab Hall A experiment E08-010 [23] will extend the Coulomb quadrupole measurements lower in momentum transfer down to $Q^2 = 0.04 \text{ (GeV}/c)^2$ and it will map the low $Q^2$ region with measurements of unprecedented precision. Data taking of the E08-010 experiment was completed in 2011 and the results are expected in early 2013.

Another valuable prospect will be offered by the exploration of the VCS excitation channel at the $\Delta$ region. A MAMI experiment [24] will offer the first precise exploration of the weak $H(e,e'p)\gamma$ channel at the $\Delta$ at $Q^2 = 0.20 \text{ (GeV}/c)^2$. The experiment will offer the first results for the quadrupole amplitudes through the photon channel; the different nature of this reaction channel, being purely electromagnetic, and the fact that it will be measured simultaneously with the dominant $\pi^0$ channel [22], will allow important tests of the reaction framework and of the systematic uncertainties of the extracted resonant amplitudes. The experiment will also offer a simultaneous measurement of the protons electric generalized polarizability exploring further its non trivial behavior at low momentum transfers. The experiment will acquire data at the end of 2012.

The upcoming results from JLab and MAMI along with the expected progress on the theoretical front will provide a definitive measurement of the non-spherical components in the nucleon wave function, the identification of the dynamics that give rise to it, and will have a profound impact on our understanding of hadrons and QCD in the confinement regime.

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