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Recent measurements of nucleon electro-magnetic and spin structure at MIT-Bates, MAMI, and JLab

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Abstract. Recent measurements of nucleon (elastic) electro-magnetic form-factors, of nucleon resonance electro-excitation amplitudes, generalized polarizabilities from real and virtual Compton scattering, of parity-violating contributions to electron scattering, and of neutron spin structure functions are described. The main emphasis is on the results from the OOPS Collaboration at MIT-Bates, the A1 Collaboration at MAMI (Mainz), and the Hall A Collaboration at Jefferson Lab.

1 Nucleon electro-magnetic form-factors

The experimental effort on the elastic form-factor front has recently been mostly focused on the electric form-factor of the neutron (G_E^n) and the ratio of the electric and magnetic form-factors of the proton (G_E^p/G_M^p). With respect to existing data, the measurements of G_E^n in Hall A at Jefferson Lab [1] have been extended to significantly larger values of Q^2 where no usable older data exist (see Fig. 1). The new data were taken in early 2006.

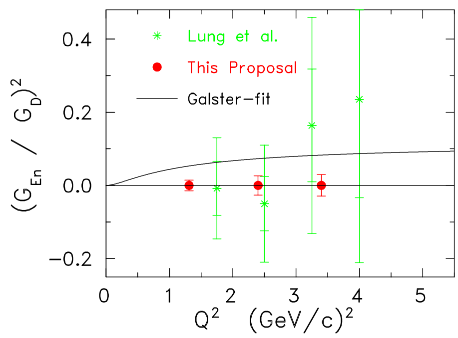

Fig. 1. Expected uncertainties of the high-Q^2 measurement of G_E^n in Hall A at Jefferson Lab (symbols on the axis). The existing experimental points below $Q^2 = 1\,(\text{GeV}/c)^2$ are not shown. The continuous line shows the traditional Galster parameterization.

The proton form-factor ratio case has stirred a lively discussion due to the rather surprising result of the double-polarized measurement [2] which exhibited a rapid Q^2-fall-off of the G_E^p/G_M^p ratio. Accuracy of older Rosenbluth-type measurements has been questioned, but a recent precise Rosenbluth-separation determination of the form-factors [3] indicates that both experimental approaches are correct and that two-photon corrections to the polarized result, previously considered to be negligible, may be responsible for the majority, if not all of the discrepancy. This is an ongoing investigation.

A high-precision unpolarized (Rosenbluth) measurement of G_E^p and G_M^p at low Q^2 is presently also being pursued at MAMI, while extensions of the double-polarization to momentum transfers beyond $Q^2 \sim 6\,(\mathrm{GeV/c})^2$ are planned for the 12-GeV upgrade of CEBAF. The high-Q^2 experiment will require the construction of a new focal-plane polarimeter and is likely to be performed in Hall C.

2 Nucleon resonances

Conventionally, the EMR and CMR ratios

$$\mathrm{EMR} = \mathrm{Re}\left(E_{1+}^{(3/2)}/M_{1+}^{(3/2)}\right), \qquad \mathrm{CMR} = \mathrm{Re}\left(S_{1+}^{(3/2)}/M_{1+}^{(3/2)}\right)$$

are used to quantify what strength the electric and Coulomb quadrupole amplitudes E_{1+} (or E2) and S_{1+} (or C2) contribute to the $N \to \Delta$ transition in the isospin-3/2 channel with respect to the dominant spin-isospin-flip transition amplitude M_{1+} (or M1). The E2 and EMR are more difficult to isolate in pion electroproduction than C2 and CMR because the transverse parts of the cross-section are dominated by the $|M_{1+}|^2$ term which is absent in the longitudinal parts.

New precise data from the process $\mathrm{H}(e, e'p)\pi^0$ in the region of the $\Delta(1232)$ resonance have been published by the OOPS Collaboration at the MIT-Bates facility [4]. The measurements were performed at $Q^2 = 0.127\,(\mathrm{GeV/c})^2$. The measurements at MIT-Bates were particularly sensitive to the E2 amplitude through the partial cross-section

$$\begin{aligned}\sigma_{E2}(\theta) = {} & 2\,\mathrm{Re}\left[E_{0+}^*(3E_{1+} + M_{1+} - M_{1-})\right](1 - \cos\theta) \\ & -12\,\mathrm{Re}\left[E_{1+}^*(M_{1+} - M_{1-})\right]\sin^2\theta\,.\end{aligned}$$

The advantage of this approach is that the $E_{1+}^* M_{1+}$ interference term in σ_{E2} is amplified by a factor of 12 (which can be fully exploited at $\theta = 90°$), while the σ_0 and σ_{TT} parts of the cross-section are dominated by $|M_{1+}|^2$ (see Fig. 2).

An experiment at the same value of Q^2 was performed by the A1 Collaboration at the MAMI facility at Mainz. With measurements at three values of the pion center-of-mass azimuthal angle ϕ at a fixed polar angle θ, and using polarized electron beam, the cross-sections σ_0, σ_{TT}, σ_{LT}, and σ'_{LT} were extracted from the azimuthal and the beam-helicity dependence of the cross-section. The preliminary result [5] for the magnetic dipole amplitude at $W = 1232\,\mathrm{MeV}$ is

$$M_{1+}^{(3/2)} = (40.33 \pm 0.63_{\mathrm{stat+syst}} \pm 0.61_{\mathrm{model}}) \cdot 10^{-3}/m_{\pi^+}\,,$$

while the EMR and CMR ratios are

$$\begin{aligned}\mathrm{EMR} &= (-2.28 \pm 0.29_{\mathrm{stat+syst}} \pm 0.20_{\mathrm{model}})\,\%\,, \\ \mathrm{CMR} &= (-4.81 \pm 0.27_{\mathrm{stat+syst}} \pm 0.26_{\mathrm{model}})\,\%\,.\end{aligned}$$

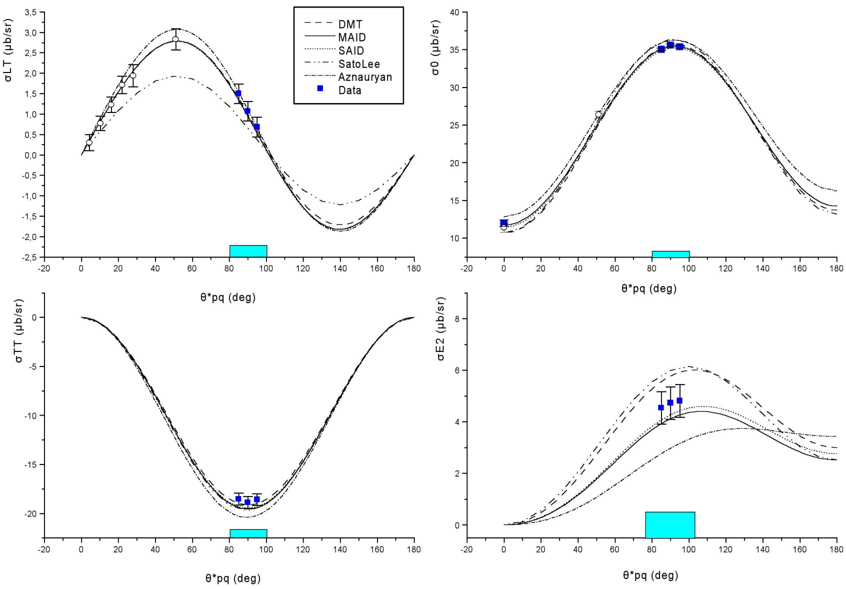

Fig. 2. Partial cross-sections in the MIT-Bates measurement of the $N \to \Delta$ transition in neutral-pion electro-production at $Q^2 = 0.127\,(\mathrm{GeV/c})^2$. The σ_{E2} partial cross-section is particularly sensitive to the E2 multipole transition strength.

Looking at the experimental efforts at higher Q^2, the Hall A measurement at $Q^2 = 1\,(\mathrm{GeV/c})$ [6] still stands as a benchmark experiment of unprecedented physics insight and unparalleled accuracy. This double-polarization experiment utilized the technique of focal-plane polarimetry to determine the polarization of protons recoiled from the $H(\mathbf{e}, e'\mathbf{p})\pi^0$ reaction. Thanks to the extended coverage in azimuthal and polar angles at the single Q^2-point, a nearly model-independent multipole analysis could be performed. We obtained very precise values of

$$\mathrm{EMR} = (-2.91 \pm 0.19)\,\%\,,$$
$$\mathrm{CMR} = (-6.84 \pm 0.15)\,\%$$

that are distinctly different from those from the traditional Legendre analyses based upon the dominance of the M_{1+} amplitude and the truncation of the partial-wave series at $l \leq 1$.

3 Real and virtual Compton scattering

Polarization transfer in real-photon Compton scattering (RCS) off the proton at high momentum transfer was measured by the Hall A Collaboration at Jefferson Lab (experiment E99-114, [7]). The measurements were performed at $s = 6.9\,\mathrm{GeV}^2$ and $t = -4.0\,\mathrm{GeV}^2$ via polarization transfer from circularly polarized incident photons. The longitudinal and sideways polarization transfer parameters

$$K_{LL} = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow) + d\sigma(\uparrow\downarrow)} , \qquad K_{LS} = \frac{d\sigma(\uparrow\leftarrow) - d\sigma(\uparrow\rightarrow)}{d\sigma(\uparrow\leftarrow) + d\sigma(\uparrow\rightarrow)}$$

were extracted from the measurement of the proton recoil polarization. The results are in disagreement with the prediction of perturbative QCD based on a two-gluon exchange mechanism, indicating that the perturbative regime has not been reached yet in the kinematics of this experiment. On the other hand, the results agree well with the prediction based on a reaction mechanism in which the photon interacts with a single quark carrying the spin of the proton (the handbag reaction mechanism). For details, see [7].

Experiments in virtual Compton scattering (VCS) off the proton are a prime example of how the leading electron-scattering laboratories exploit the complementarity of their experimental equipment in order to achieve a common goal. The Jefferson Lab Hall A Collaboration has recently completed an extensive VCS program at $Q^2 = 0.92\,(\mathrm{GeV}/c)^2$ [8], complemented by the work of the A1 Collaboration at MAMI at $Q^2 = 0.33\,(\mathrm{GeV}/c)^2$ [9]. The results of the measurements by the OOPS Collaboration at MIT-Bates at very small $Q^2 = 0.06\,(\mathrm{GeV}/c)^2$ are at a preliminary stage and are being published shortly [10]. The purpose of this joint effort is to determine the Q^2-evolution of the electric and magnetic polarizabilities of the proton α_p and β_p. The measurements at low Q^2 from MIT-Bates are of particular relevance since both α and β appear to have strong Q^2-dependencies. In particular, the prediction of chiral perturbation theory that $\beta(Q^2)$ has a positive slope at origin (indicating a negative magnetic polarizability mean-square radius) will be tested. Taken together, the experiments will also shed light on the theory that the proton possesses a distinct paramagnetic core and a diamagnetic tail [11].

Most recently, the A1 Collaboration has initiated a study of the single-spin and double-polarization asymmetries in the VCS process [12]. In these time-consuming and experimentally demanding experiments, an attempt is being made to extract six generalized polarizabilities of the proton: P_{LL} (corresponding to electric polarizability α in RCS), P_{LT} (magnetic polarizability β in RCS), P_{TT} (spin polarizability γ in polarized RCS), as well as three new ones, P^z_{LT}, P'^z_{LT}, and $P'^{\perp}_{LT}$. This experimental effort (close to 2000 hours beam-time) is ongoing, and data acquisition is nearing completion. Figure 3 shows the anticipated error budget for three different linear combinations of generalized polarizabilities contained in the Ψ_0, $\Delta\Psi_{x0}$, and $\Delta\Psi_{z0}$ structure functions.

4 Parity violation

Parity-violating (PV) experiments exploit the interference of neutral weak (Z^0 exchange) and electro-magnetic (photon exchange) currents in scattering of polarized electrons off light nuclei, with typical PV asymmetries on the order of 10^{-4} to 10^{-7}. Most experiments to-date have been performed at momentum transfers below $\sim 1\,(\mathrm{GeV}/c)^2$. The SAMPLE Collaboration at MIT-Bates, the A4 Collaboration at MAMI, and the HAPPEX Collaboration at Jefferson Lab are involved

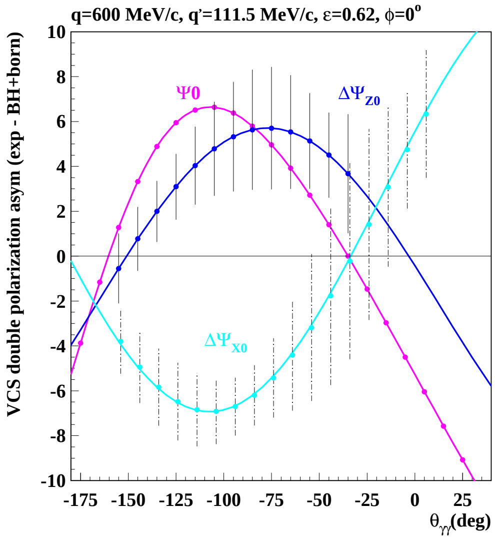

Fig. 3. Anticipated uncertainties in three different linear combinations of generalized polarizabilities contained in the Ψ_0, $\Delta\Psi_{x0}$, and $\Delta\Psi_{z0}$ structure functions, for the double-polarized VCS measurement at Mainz.

in a comprehensive program to determine the strange-quark contributions to the distributions of charge (G_E^s) and magnetization (G_M^s) within the proton. The PV asymmetry on hydrogen is proportional to a linear combination of G_E^s and G_M^s, while it is proportional to G_E^s only in the case of the spin-less ^{4}He nucleus. It is therefore important that both targets are used in experiments under different kinematical conditions in order to achieve a good lever-arm for an intercept in the G_E^s-G_M^s plane.

Most recent results, taken in 2006, come from the HAPPEX II Collaboration who measured elastic scattering of 3 GeV electrons off hydrogen and ^{4}He targets, and provide the most precise data so far on the PV asymmetries. Strange electric and magnetic form-factors

$$G_E^s = 0.002 \pm 0.014 \pm 0.007 \qquad \text{at } Q^2 = 0.077\,(\mathrm{GeV/c})^2\,,$$
$$G_E^s + 0.09 G_M^s = 0.007 \pm 0.011 \pm 0.006 \qquad \text{at } Q^2 = 0.109\,(\mathrm{GeV/c})^2$$

were extracted, providing new limits on the role of strange quarks in the nucleon charge and magnetization distributions [13].

5 Neutron spin structure

Most exciting new results on the neutron spin structure functions g_1^n (or the corresponding asymmetry A_1^n) and g_2^n come from experiments with the high-pressure polarized ^{3}He target in Hall A at Jefferson Lab. The measurements of these structure functions are motivated by several open questions.

Relativistic constituent quark models (RCQM) incorporating orbital angular momentum (OAM) of the quarks and leading-order perturbative QCD (pQCD) predictions assuming hadron helicity conservation (no OAM) make dramatically different predictions polarized quark distributions in the valence region. The A_1^n asymmetry and the corresponding polarized spin structure function g_1^n are sensitive tools to improve upon our knowledge of the neutron spin structure.

The naive quark-parton model predicts $g_2^n = 0$, while non-zero values occur in more realistic models of the nucleon which include quark-gluon correlations, finite quark masses, or quark orbital angular momentum. If the electron is considered to scatter from a non-interacting quark, the g_2^n structure function can also be obtained from NLO fits of g_1^n to world data. Deviations from this connection provide an opportunity to examine the dynamics of QCD in nucleon structure.

A precision measurement of A_1^n and a spin-flavour decomposition in the valence-quark region has been performed in Hall A at Jefferson Lab [14]. The results show a zero-crossing of A_1^n at $x \sim 0.47$, and A_1^n becoming significantly positive at $x \sim 0.60$. In general, the results agree with RCQM and pQCD analyses based on earlier data. However, they deviate from pQCD predictions based on hadron helicity conservation. Within the 12-GeV upgrade of CEBAF, there is an ambitious program to continue the A_1^n to Bjorken $x \sim 0.7$ at $W > 2\,\text{GeV}$ or even beyond $x \sim 0.9$ at $W > 1.2\,\text{GeV}$.

The first measurement of the Q^2-dependence of g_2^n has also been performed at Hall A [15]. The kinematics spanned five points in the range of $0.57 \leq Q^2 \leq 1.34\,(\text{GeV}/c)^2$ at Bjorken $x = 0.2$. The results indicate a departure from the g_2^n-g_1^n connection at lower Q^2, indicating that contributions such as quark-gluon interactions may be important.

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