Bled Workshops in Physics
Vol. 8, No. 1
p. 70

Proceedings of the Mini-Workshop
Hadron Structure and Lattice QCD
Bled, Slovenia, July 9-16, 2007

Exclusive processes on the nucleon at MAMI and Jefferson Lab

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Abstract. The MAMI accelerator (Mainz, Germany) and the CEBAF at Jefferson Laboratory (Newport News, USA) are the world leading electron-scattering facilities in the several 100 MeV to several 1 GeV energy range. A large fraction of the experimental program in these laboratories has recently been focused on the electroweak properties of the nucleon, its spin structure, and on nucleon resonance excitation. Latest results from MAMI (A1 Collaboration) and Jefferson Lab (mostly Hall A) are described.

1 Electroweak properties of nucleons

The elastic form factors of the nucleon remain of prime interest. New measurements of the proton electric-to-magnetic form-factor ratio have been performed or are being planned in order to resolve the persistent discrepancy between the double-polarization measurement [1] versus a precise Rosenbluth-separation determination [2], which exhibit different Q^2-dependencies. Presently the main reason for the disagreement is believed to be the two-photon correction to the elastic scattering process, which contributes differently in both cases. One should also mention the recent precise results at the other end of the spectrum, at very low Q^2 where pion-cloud effects play the dominant role. These were obtained by the BLAST Collaboration at MIT-Bates [3].

An extension of the double-polarized measurement to about $9\,(\mathrm{GeV/c})^2$ is in progress at Jefferson Lab (Hall C), while a high-precision unpolarized (Rosenbluth) measurement of G_E^p and G_M^p at low Q^2 is being pursued at MAMI. Measurements of G_E^p to as high as $15\,(\mathrm{GeV/c})^2$ and G_M^p to $18\,(\mathrm{GeV/c})^2$ are planned with the 12 GeV-upgrade of CEBAF. There are also efforts in JLab Hall B which are concentrated around the measurement of cross-section differences for electrons versus positrons, which are an independent means of distinguishing the role of the two-photon contributions.

An exciting development in the form-factor arena is the recent high-Q^2 measurement of the neutron charge form-factor G_E^n in Hall A. These measurements are relevant both to explore the transition to pQCD (two-gluon exchanges) and to test the importance of the handbag diagrams (from the perspective of generalized parton distributions (GPDs)), as well as for nucleon spin (sum rules) and lattice QCD. Preliminary results at intermediate Q^2 have been reported at various conferences this Fall and indicate values of G_E^n which lie above the conventional (Platchkov) parameterization.

The HAPPEX Collaboration at Jefferson Lab is dedicated to the determination of the strange-quark contributions to the distributions of charge (G_E^s) and magnetization (G_M^s) within the proton. The parity-violating 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. Both targets have been used at HAPPEX in different kinematical conditions. Most recent results have now been published [5], and the results of this experiment *only* (i.e. without averaging over other experiments) are

$$G_E^s = 0.002 \pm 0.014 \pm 0.007 \,,$$
$$G_E^s + 0.09\, G_M^s = 0.007 \pm 0.011 \pm 0.006 \,.$$

Real-photon Compton scattering (RCS) and its virtual counterpart (VCS) are being utilized to access further information on the electromagnetic structure of the proton. The E99-114 experiment at Hall A has measured polarization transfer in RCS off the proton at high momentum transfer [6]. Polarization transfer parameters K_{LL} and K_{LS} were extracted and were shown to be in disagreement with the prediction of perturbative QCD based on a two-gluon exchange mechanism. Specifically, the nonzero value of the ratio

$$\frac{K_{LS}}{K_{LL}} \propto \frac{R_T}{R_V} = 0.21 \pm 0.11 \pm 0.03$$

implies that the proton helicity is flipped in the RCS process (which is forbidden in leading-twist pQCD). The RCS studies have been forwarded another step by examining the scaling

$$\frac{d\sigma}{dt} \propto \frac{f(\theta)}{s^n}$$

of the RCS cross-section (at a fixed angle), where pQCD predicts $n = 6$ based on constituent scaling rules. In contrast to this expectation, a relatively precise value of $n = 8.0 \pm 0.2$ has been found [7]. The scaling result also disagrees with the predictions based on the handbag reaction mechanism.

The OOPS Collaboration at MIT-Bates has finished analyzing the data from experiments in virtual Compton scattering (VCS) off the proton at low Q^2 [8]. The mean-square electric polarizability of the proton

$$\langle r_\alpha^2 \rangle = 2.16 \pm 0.31\,\mathrm{fm}^2$$

(basically the slope of the Q^2-dependent electric polarizability $\alpha(Q^2)$ at low Q^2) has been determined for the first time in a VCS process. The magnetic polarizability $\beta(Q^2)$, on the other hand, could not be determined well due to poor statistics, although the data is consistent with β having a positive slope at origin, corresponding to a negative magnetic polarizability mean-square radius and characteristic of a diamagnetic contribution from the pion cloud. Unfortunately, the statistics and systematics of the data gathered over the years at MIT-Bates, MAMI and JLab, are still insufficient to allow for a reliable determination of the Q^2-dependence of the polarizabilities.

The VCS program on nucleon targets has recently evolved into a much broader effort by including polarization degrees of freedom. Single-spin (beam) asymmetries at low energies have been measured at MAMI/A1 on the proton [9], as well as in the deep-inelastic regime (so-called deeply virtual Compton scattering, DVCS) at JLab Hall A on both the proton and the neutron. The analysis of the Mainz experiment, the goal of which is to determine three different linear combinations of generalized polarizabilities contained in the Ψ_0, $\Delta\Psi_{x0}$, and $\Delta\Psi_{z0}$ structure functions is underway while the proton DVCS results from Hall A appeared recently [10]. This is a first DVCS experiment in the valence-quark region (large Bjorken x). Real and imaginary parts of twist-2 and twist-3 coefficients of the angular expansion of the cross-section have been measured with great accuracy. One of the conclusions was that perturbative scaling applies in DVCS, indicating that the GPDs are in principle accessible already at modest values of Q^2 in this process.

2 Nucleon spin structure

The neutron DVCS experiment E03-106 utilizes the same (single-spin) technique as the proton DVCS to constrain $\mathcal{E}$, the least-known GPD, and as such complements nicely the proton case which predominantly depends on $\mathcal{H}$ and $\widetilde{\mathcal{H}}$. In addition, the neutron channel is particularly important because the of the nucleon total angular momentum sum rule $J = J_q + J_g = \frac{1}{2}$ (quarks plus gluons), where

$$J_q = \frac{1}{2}\Delta\Sigma + L_q = \frac{1}{2}\int dx\, x \left[H(x,\xi,0) - E(x,\xi,0) \right] .$$

While the spin part $\Delta\Sigma$ can be determined in DIS experiments (and L_g in experiments like COMPASS), the nDVCS at high values of Bjorken x has a unique opportunity to help determine the orbital contribution L_q. The analysis of the neutron DVCS experiment is underway.

3 Nucleon resonances

The multipole character of the $N \to \Delta(1232)$ transition is being probed with ever increasing accuracy and at varying kinematical conditions (in particular, at several values of Q^2 accessible at different laboratories). In fact, the experimental methods have been improved to a degree that allows for a rather clear determination of the individual transition amplitudes, such that the model dependence usually dominates the final uncertainties.

Sadly, professor Jim Kelly, the spokesperson and the spiritus agens of the landmark $N \to \Delta(1232)$ experiment in Hall A at Jefferson Lab, has passed away this year. It is in respect and admiration that we look at the extensive paper on that experiment [11] which he managed to bring to completion in the very last weeks of his illness.

The A1 Collaboration at MAMI has reported on new precise $p(\mathbf{e}, e'p)\pi^0$ measurements at the peak of the $\Delta(1232)$ resonance at $Q^2 = 0.20\,(\mathrm{GeV}/c)^2$ [12]. The new data are sensitive to both the electric (E2) and the Coulomb (C2) quadrupole amplitudes of the $N \to \Delta$ transition. New precise values for the quadrupole to dipole amplitude ratios

$$\mathrm{CMR} = (-5.09 \pm 0.28\,(\mathrm{stat} + \mathrm{sys}) \pm 0.30\,(\mathrm{model}))\% \,,$$
$$\mathrm{EMR} = (-1.96 \pm 0.68\,(\mathrm{stat} + \mathrm{sys}) \pm 0.41\,(\mathrm{model}))\%$$

have been obtained, with a value for the dominant magnetic dipole amplitude

$$M_{1+} = (39.57 \pm 0.75\,(\mathrm{stat} + \mathrm{sys}) \pm 0.40\,(\mathrm{model})) \cdot 10^{-3}/m_{\pi}^{+} \,.$$

The results are in disagreement with the predictions of the Constituent Quark Model and in qualitative agreement with models that account for mesonic contributions, including recent Lattice QCD calculations. They thus support the conjecture of deformation in hadronic systems with its origin in the dominance of mesonic effects.

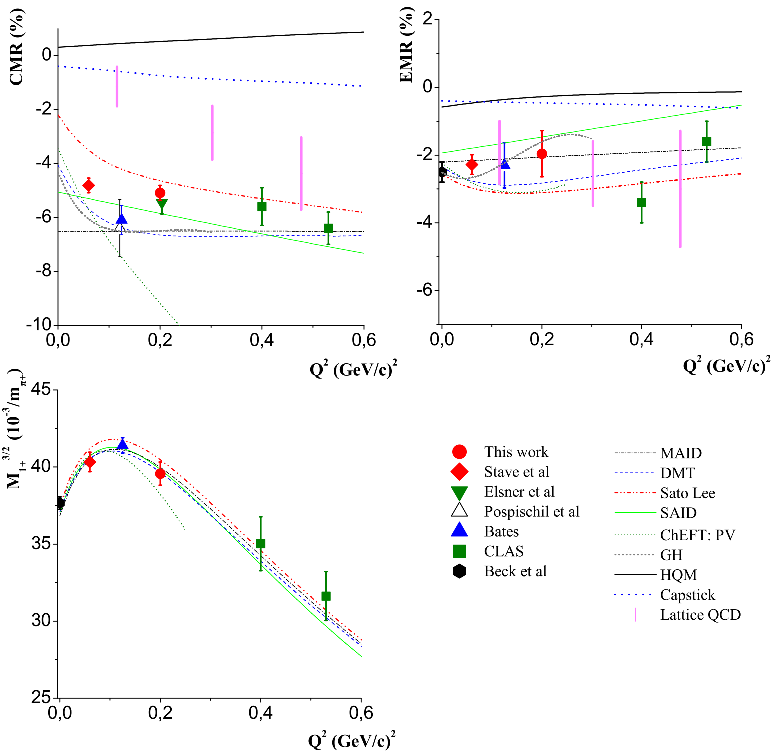

Fig. 1. The extracted values for CMR, EMR and M_{1+} as a function of Q^2 from recent low-Q^2 experiments. The theoretical predictions of models MAID, DMT, SAID, Sato-Lee, Capstick, HQM, the linearly extrapolated Lattice-QCD calculation, ChEFT of Pascalutsa-Vanderhaegen and Gail-Hemmert are also shown.

Similar goals have been set by another experiment at MAMI [13], but at a lower value of $Q^2 = 0.060\,(\mathrm{GeV}/c)^2$. Here, the reported ratios are even more precise,

$$\mathrm{CMR} = (-4.81 \pm 0.27\,(\mathrm{stat} + \mathrm{sys}) \pm 0.26\,(\mathrm{model}))\% ,$$
$$\mathrm{EMR} = (-2.28 \pm 0.29\,(\mathrm{stat} + \mathrm{sys}) \pm 0.20\,(\mathrm{model}))\%$$

while the magnetic dipole amplitude is

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

with similar conclusions. A summary of the results from recent experiments at low Q^2, where pion cloud physics (long-range effects) is believed to play a most prominent role, is given in Figure 1.

Polarization degrees of freedom have also been exploited in the measurement of $p(\mathbf{e}, e'p)\pi^0$ at $Q^2 = 0.35\,(\mathrm{GeV}/c)^2$ in the resonance region [14]. The results (unpolarized and polarized structure functions) have been compared to calculations based on dispersion relations for VCS and to the phenomenological pion electroproduction model MAID. There is an overall good agreement between experiment and theoretical calculations. The remaining discrepancies have been mostly attributed to imperfect parameterizations of non-resonant (background) multipoles, to which the measured beam-helicity asymmetry is particularly sensitive.

In another polarized experiment, both beam polarization and proton polarimetry have been utilized in an experiment inaugurating the MAMI-C accelerator with its new, 1.5 GeV CW beam [15]. The beam-recoil polarization transfer coefficients P_x' and P_z' as well as the (induced) recoil polarization P_y were measured for the first time in the $p(\mathbf{e}, e'p)\eta$ reaction at $Q^2 = 0.1\,(\mathrm{GeV}/c)^2$, with a center of mass production angle of 120° and spanning a center of mass energy range of $1500\,\mathrm{MeV} < W < 1550\,\mathrm{MeV}$, thus covering the region of the S11(1535) and D13(1520) resonances. The values obtained are

$$P_x' = (-67.6 \pm 3.2\,(\mathrm{stat}) \pm 2.6\,(\mathrm{sys}))\% ,$$
$$P_y = (16.1 \pm 3.2\,(\mathrm{stat}) \pm 2.3\,(\mathrm{sys}))\% ,$$
$$P_z' = (-29.3 \pm 2.6\,(\mathrm{stat}) \pm 2.6\,(\mathrm{sys}))\% .$$

The P_x' and P_z' are in good agreement with the phenomenological isobar model (Eta-MAID), while P_y shows a significant deviation, consistent with existing photoproduction data on the polarized-target asymmetry from Bonn. However, if a strong phase change between E_{0+} and $(E_{2-} + M_{2-})$ multipoles is applied, which gives a good description of the Bonn polarized target data, the electroproduction data point is also in good agreement with the model. Such a strong phase change is incompatible with a standard Breit-Wigner behavior of the S11(1535) resonance. Indeed this appears to be yet another of the peculiarities of this resonance, the most notable one being the remarkably slow Q^2-falloff of the helicity amplitude corresponding to η electroproduction seen in Hall B.

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