Parity violating electron scattering at MAMI

Sebastian Baunack
Institut für Kernphysik, Universität Mainz, J. J. Becherweg 45, 55099 Mainz, Germany
E-mail: baunack@kph.uni-mainz.de

Abstract. The investigation of the structure of the nucleon can help to understand the non-pertubative regime of the QCD. In the viewpoint of QCD, the nucleon is made up of constituent quarks, sea quarks and gluons. The nucleon structure can be described by the electromagnetic form factors. Parity violating electron scattering offers a tool to investigate the strange quark contribution to the nucleon form factors. Such measurements are carried out at the electron accelerator facility MAMI at Mainz. Recent results are presented here.

1. Strange form factors
The proton is in the viewpoint of QCD a highly relativistic strong interacting system, where, beside the constituent quarks, also sea quarks and gluons contribute to its properties. Strange quark contributions are of a specific interest since this is a pure sea quark effect. Various matrix elements may be used for an investigation of strange quark effects [1]. The vector element $< p | \bar{s} \gamma^\mu s | p >$ provides access to the contribution of strange quarks to the vector current of the nucleon expressed by the vector form factors [2, 3]. In order to determine the contribution of individual quark flavors to the nucleon form factors, a flavor decomposition is done omitting the heavier quarks $c, b$ and $t$:

$$G_{E,M}^{p/n} = \sum_{f=u,d,s} q_f G_{E,M}^{f,p/n} = \frac{2}{3} G_{E,M}^{p,u} - \frac{1}{3} G_{E,M}^{p,d} - \frac{1}{3} G_{E,M}^{p,s}$$

(1)

$$G_{E,M}^{n} = \sum_{f=u,d,s} q_f G_{E,M}^{f,n} = \frac{2}{3} G_{E,M}^{n,u} - \frac{1}{3} G_{E,M}^{n,d} - \frac{1}{3} G_{E,M}^{n,s}$$

(2)

$G_{E,M}^{p/n, x}$ denotes the contribution of the quark flavor $x$ to the electric or magnetic form factor of the proton or the neutron. The factors $2/3$ and $-1/3$ reflect the electric charges of the corresponding quarks. Isospin symmetry reduces the number of unknown flavor form factors from 12 to 6. The weak interaction provides additional information:

$$\tilde{G}_{E,M}^{p} = (\frac{1}{4} - \frac{2}{3} \sin^2 \theta_W) G_{E,M}^{u} - (\frac{1}{4} - \frac{1}{3} \sin^2 \theta_W) G_{E,M}^{d} - (\frac{1}{4} - \frac{1}{3} \sin^2 \theta_W) G_{E,M}^{s}$$

$$\tilde{G}_{E,M}^{n} = (\frac{1}{4} - \frac{2}{3} \sin^2 \theta_W) G_{E,M}^{u} - (\frac{1}{4} - \frac{1}{3} \sin^2 \theta_W) G_{E,M}^{d} - (\frac{1}{4} - \frac{1}{3} \sin^2 \theta_W) G_{E,M}^{s}$$

(3)

$\tilde{G}_{E,M}^{p/n}$ denote the weak form factors of proton and neutron and the factors in front of the flavor form factors represent the weak charges of the corresponding quarks. The interference between tree level electromagnetic and weak amplitudes leads to a parity violating asymmetry in the elastic scattering cross section of right- and left-handed electrons $\sigma^+, \sigma^-$. $A_{PV} = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-)$. This asymmetry can be expressed by the known electromagnetic form...
factors of proton and neutron, by the weak axial form factor of the proton $G^p_A$ and the unknown strange form factors $G^s_E$ and $G^s_M$ as a sum of three terms, $A_{PV} = A_V + A_S + A_A$: $A_V$ represents the vector coupling on the proton vertex where the strangeness contribution has been taken out, $A_S$ contains the strange quark vector contribution, and $A_A$ represents the axial coupling on the proton vertex [2]:

\[ A_{PV} = -a\rho'_{eq} \left( 1 - 4\kappa'_{eq}\tilde{s}^2 \right) - \frac{\epsilon G^p_E G^p_M + \tau G^p_M G^s_M}{\epsilon (G^p_E)^2 + \tau (G^p_M)^2} \]  

\[ A_S = a\rho'_{eq} \frac{\epsilon G^p_E G^s_E + \tau G^p_M G^s_M}{\epsilon (G^p_E)^2 + \tau (G^p_M)^2} \]  

\[ A_A = a \frac{(1 - 4\tilde{s}^2) \sqrt{1 - \tau^2} \sqrt{\tau(1 + \tau)G^p_M G^p_A}}{\epsilon (G^p_E)^2 + \tau (G^p_M)^2} \]

with $a = \frac{G_\mu Q^2}{4\pi\alpha\sqrt{2}}$, $G_\mu$ the Fermi coupling constant, $\alpha$ the fine structure constant, $\tau = \frac{Q^2}{4M_p^2}$, $Q^2$ the negative squared momentum transfer and $M_p$ the proton mass, $\epsilon = [1 + 2(1 + \tau)\tan^2\frac{\epsilon M_p}{2}]^{-1}$, $\Theta$ the scattering angle in the laboratory frame, $\tilde{s}^2(M_Z) = 0.23116(13)[4]$. $\rho'_{eq}$ and $\kappa'_{eq}$ include the electro-weak radiative corrections evaluated in the $\overline{MS}$ scheme. One measurement of the parity violating asymmetry $A_{PV}$ yields one linear combination of strange electric and magnetic form factor $G^s_E + \alpha G^s_M$, where $\alpha$ depends on the kinematics. Two independent measurements at the same momentum transfer $Q^2$ but with different kinematics allow to disentangle $G^s_E$ and $G^s_M$ when $G^p_A$ is used as an input parameter. There are numerous theoretical approaches to the strange quark contribution to the vector current of the proton, covering the wide range from nonrelativistic constituent quark models [6] until quenched lattice calculations [7, 8].

2. Measurement of strange form factors

A measurement at forward angles with a proton target yields a linear combination of $G^s_E$ and $G^s_M$, a measurement at backward angles on a helium target gives a measurement of $G^s_E$ alone, a measurement at backward angles measurements on a proton and a deuterium target yield two different linear combinations of $G^s_M$ and $G^p_A$. Table 1 summarizes the experiments that made such measurements. At the negative squared momentum transfer $Q^2 = 0.1$ GeV$^2$ there are four collaborations that have published results: the SAMPLE collaboration at MIT MIT-Bates [9], the A4 collaboration at Mainz [10], the $G^0$ collaboration at TJNAF [11] and the HAPPEX collaboration at TJNAF [12]. A global analysis yields the values of $G^s_E = -0.005 \pm 0.019$ and $G^s_M = 0.18 \pm 0.27$ [12] favoring calculations that predict only small strangeness contributions.

At $Q^2 = 0.23$ GeV$^2$ there are results for forward and backward angle measurements published by the collaborations A4 [10, 13] and $G^0$ [11, 16], also excluding large strangeness contributions. The experimental setup of the A4 collaboration and new results will be presented in the following chapters.

3. The A4 experimental setup

The measurement of small parity violating asymmetries of the order $10^{-6}$ requires high statistics on the one hand since the statistical uncertainty in the measured asymmetry scales with $1/\sqrt{N}$ where $N$ is the number of registered elastically scattered electrons, and control of systematic effects on the other hand.

The concept of the A4 experiment [17] at MAMI is a single arm calorimetric measurement. The electron beam has an intensity of 20 $\mu$A and an average polarization of about 80%. The electrons are accelerated up to $E = 1.5$ GeV. Two polarimeters are in the beamline of the A4 experiment, a
Table 1. Experiments that measure parity violating asymmetries, and their kinematical conditions and targets. A wide range of momentum transfers and scattering angles is already covered. The A4 data point shown in italic is scheduled for the measurement in 2012.

|       | p target forward angle | p target backward angle | $^4$He target forward angle | d target backward angle |
|-------|------------------------|-------------------------|-----------------------------|-------------------------|
| SAMPLE |                        | 0.10 GeV$^2$            |                             | 0.04 GeV$^2$            |
| Happex | 0.10 GeV$^2$           | 0.10 GeV$^2$            |                             | 0.11 GeV$^2$            |
|        | 0.48 GeV$^2$           |                         |                             | 0.23 GeV$^2$            |
|        | 0.62 GeV$^2$           |                         |                             | 0.23 GeV$^2$            |
| A4     |                        |                         | 0.11 GeV$^2$                | 0.11 GeV$^2$            |
|        | 0.23 GeV$^2$           |                         | 0.23 GeV$^2$                | 0.23 GeV$^2$            |
|        | 0.62 GeV$^2$           |                         |                             | 0.62 GeV$^2$            |
| $G^0$  | (0.12...1) GeV$^2$     |                         | 0.23 GeV$^2$                | 0.23 GeV$^2$            |
|        |                        |                         | 0.62 GeV$^2$                | 0.62 GeV$^2$            |

Compton Backscatter polarimeter [18] and a Transmission Compton polarimeter [19]. Additional polarization measurements were made by the Moeller polarimeter of the A1 collaboration and by a Mott polarimeter situated close to the electron source. Altogether a 4% uncertainty in the knowledge of the beam polarization is achieved.

The helicity of the electrons is changed every 20 ms. In order to suppress helicity correlated false asymmetries due to different beam position, angle, intensity or energy for different helicity states, several feedback stabilization systems are installed along the way of the electrons from the accelerator to the target. The high power liquid hydrogen target [20] is 10 cm long for the forward angle measurements and 23.4 cm long for the backward angle measurement. The luminosity is $L \approx 0.5 \cdot 10^{38}$ cm$^{-2}$s$^{-1}$ or $L \approx 1.2 \cdot 10^{38}$ cm$^{-2}$s$^{-1}$ respectively.

The scattered electrons are detected in a homogenous electromagnetic calorimeter that consists of 1022 lead fluoride crystals [14] (see fig. 1). The calorimeter can cope with event rates of 100 MHz, the energy resolution is about $\Delta E/E = 3.9%/\sqrt{E[GeV]}$. The covered angles are $2\pi$ in the azimuthal range and $30^\circ \leq \theta \leq 40^\circ$ (forward angle configuration) or $140^\circ \leq \theta \leq 150^\circ$ (backward angle configuration) in the polar range. The covered solid angle is $\Delta \Omega = 0.62$ sr. 72 plastic scintillators are installed in front of the PbF$_2$ crystals for a separation of neutral from charged particles. This is necessary at backward angles because photons from $\pi^0$ decay cannot be distinguished by the PbF$_2$ calorimeter itself because the photons produce in the crystals electromagnetic showers very similar to those coming from electrons.

4. Recent results from the A4 experiment

The preliminary results of the two most recent measurements are presented here: A backward angle measurement with a deuterium target at a low beam energy and a forward angle measurement with a proton target at a high beam energy.

In order to obtain the strange form factors $G_E^s$ and $G_M^s$, the axial form factor $G_A^p$ of the proton must also be known. At backward angles, a measurement with a proton target is mainly sensitive to a linear combination of $G_M^s$ and $G_A^p$. A measurement with a deuterium target at the same momentum transfer yields a different linear combination of these two form factors and allows a determination of $G_A^p$. About 1100 h of data were taken with a deuterium target at the momentum transfer of $Q^2 = 0.23$ GeV$^2$ which matches to the previous measurement with a hydrogen target [13]. Compared to the analysis of the hydrogen data the analysis is more challenging: The peak of the quasielastic scattered electrons is broader due to the...
Figure 1. Drawing of the A4 lead fluoride calorimeter and the scattering chamber [13]. The calorimeter is mounted on a rotatable platform so that one can easily change between forward and backward angle configuration. The backward angle configuration is shown here. The lead fluoride crystals cover the $2\pi$ azimuthal range and polar angles between $30^\circ$ and $40^\circ$ in forward angle configuration and between $140^\circ$ and $150^\circ$ in backward angle configuration. Plastic scintillators are installed between the crystals and the scattering chambers for a separation of neutral and charged particles.

Fermi motion of the nucleons within the nucleus and the signal to background ratio is worse because the rate of charged particles increases by a factor of 1.5, while the rate of decay photons increases by a factor of 2. This requires a careful study of the background subtraction procedure. We obtain a preliminary value for the asymmetry in quasielastic $ed$ scattering of $A_d = (-20.02 \pm 0.84_{\text{stat}} \pm 1.25_{\text{syst.}}) \times 10^{-6}$. Adding these uncertainty in quadrature, we get for the form factors a linear combination of $\tilde{G}_A^p + 0.61 \cdot G_M^p = -0.55 \pm 0.35$. For $\tilde{G}_A^p$ alone, we obtain the preliminary value of $\tilde{G}_A^p = -0.47 \pm 0.31$ which is smaller than the value taken from the calculation [15], but in good agreement with the result from the G0 collaboration at the same momentum transfer [16].

In the year 2009, a measurement with a proton target at high momentum transfer was carried out at the MAMI-C beam energy of 1508 MeV. The resulting momentum transfer is $Q^2 = 0.62$ GeV$^2$. In this momentum transfer region the results of the G0 forward angle measurements suggested nonvanishing strange quark contributions to the vector form factors of the proton [11]. 600 h of data were taken for this measurement. The average beam polarization was 85%. Fig. 2 shows the preliminary results with respect to the sign of the electron beam polarization (halfwave plate at the source in or out). We obtain a preliminary result for the linear combination of the strange form factors of $G_E^s + 0.628 \cdot G_M^s = 0.067 \pm 0.030$, where all errors have been added in quadrature.
Figure 2. Preliminary result from the forward angle measurement at $Q^2 = 0.62$ GeV$^2$. The asymmetries that are shown are corrected for false asymmetries and the beam polarization. “Out” and “In” denote subsets of the measurement with either a positive or a negative electron beam polarization (halfwave plate at the source out or in). The sign change in the measured asymmetries can be easily observed.

5. Conclusions and outlook
Parity violating electron scattering can be used to determine the strange quark contributions to the vector form factors of the proton. After some years of operation, the A4 experiment at MAMI measures routinely such asymmetries of the order of $10^{-6}$. Our recent measurements are in good agreement with results from other collaboration and confirm that the strangeness contribution to the vector form factors of the protons are small. With the existing techniques it will be difficult to measure non-zero strange form factors significantly. However, strange quark contributions are a source of hadronic uncertainty in precision measurements of the weak charge of the proton like the Qweak experiment at Jefferson Lab is carried out right now [21] or the new planned project P2 at MAMI. Therefore it is necessary to determine the strange form factors as precise as possible especially at low momentum transfer. Currently, the A4 collaboration is performing backward angle measurements with a proton and a deuterium target at $Q^2 = 0.1$ GeV$^2$. The projected measurement times are 1000 h for each target. The aim is to reduce the existing uncertainties by factor of 2.

References
[1] B Kaplan and A Manohar 1988 Nucl. Phys. B 310 527
[2] M J Musolf et al. 1994 Phys. Rep. 239 1
[3] D H Beck and B R Holstein 2001 Int. J. Mod. Phys. E 10 1-41
[4] K Nakamura et al. (Particle Data Group) 2010 J. Phys. G 37 075021
[5] D O Riska 2007 Eur. Phys. J. A 32 389
[6] A Kiswandhi et al. 2011 Phys. Lett. B704 373-377
[7] D B Leinweber et al. 2006 Phys. Rev. Lett. 97 022001
[8] P Wang et al. 2009 Phys.Rev. C 79 065202
[9] D T Spayde et al. 2004 Phys. Lett. B583 79
[10] F E Maas et al. 2004 Phys. Rev. Lett. 93 022002
[11] D Armstrong et al. 25 Phys. Rev. Lett. 95 092001
[12] A Acha et al. 2007 Phys. Rev. Lett. 98 032301
[13] S Baunack et al. 2009 Phys. Rev. Lett. 102 151803
[14] S Baunack et al 2011 Nucl. Inst. Meth. A 640 58-68
[15] S L Zhu et al. 2000 Phys. Rev. D 62 033008
[16] D Androic et al. 2010 Phys. Rev. Lett. 104 012001
[17] F E Maas et al. 2003 Eur. Phys. J. A 17 339
[18] J Diefenbach et al. 2007 Eur. Phys. J. A 32 555-559
[19] C Weinrich et al. Eur. Phys. J. A 24S2 129-130
[20] I Altarev et al. 2006 Nucl. Instr. Meth. A 564 13
[21] R D Carlini 2010 AIP Conf. Proc. 1261 172-178