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EM Form Factors and OLYMPUS

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Abstract. The elastic form factors of the nucleon characterize the distributions of charge and magnetization in momentum space and are important input for calculations of strong interaction phenomena and nuclear structure. The dramatic discrepancy in the observed ratio of elastic proton form factors between the Rosenbluth separation and polarization transfer methods has invoked numerous theoretical and experimental investigations. The previously neglected effect from two-photon exchange has become the favored explanation for the discrepancy. While the effect can not be calculated from first principles, it can be verified experimentally in several ways, most stringently by comparing the positron-proton and electron-proton elastic cross sections. The OLYMPUS experiment at DESY has been carried out to quantify the effect of two-photon exchange using intense stored positron and electron beams along with an internal unpolarized hydrogen target and a large acceptance detector to measure the ratio of the positron-proton and electron-proton elastic scattering cross sections. The status of proton form factor measurements and of the experimental efforts to verify the effect of two-photon exchange is presented, with some emphasis on the OLYMPUS experiment.

1 Introduction

Elastic electromagnetic form factors of the proton and neutron are fundamental quantities characterizing the distributions of charge and magnetization of the nucleon. Significant advances in experiment and theory have been made over the last decade. In particular, the use of spin degrees of freedom has led to unprecedented experimental precision in determinations of the nucleon form factors.

The pioneering measurements of elastic form factors were done more than 50 years ago at SLAC [1]. It was discovered that the finite size of the nucleon plays an important role in the description of the proton and deuteron form factors. In the one-photon exchange approximation, the elastic form factors of the nucleon G_E (electric) and G_M (magnetic) are experimentally determined by the elastic electron-nucleon scattering cross section $d\sigma/d\Omega = (d\sigma/d\Omega)_{Mott}\, f_{rec}^{-1}\, \sigma_{red}/[\varepsilon(1+\tau)]$ with the reduced cross section

$$\sigma_{red} = \varepsilon(1+\tau)\left[\frac{\left(G_E^2(Q^2) + \tau G_M^2(Q^2)\right)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}\right] = \varepsilon G_E^2 + \tau G_M^2\,, \tag{1}$$

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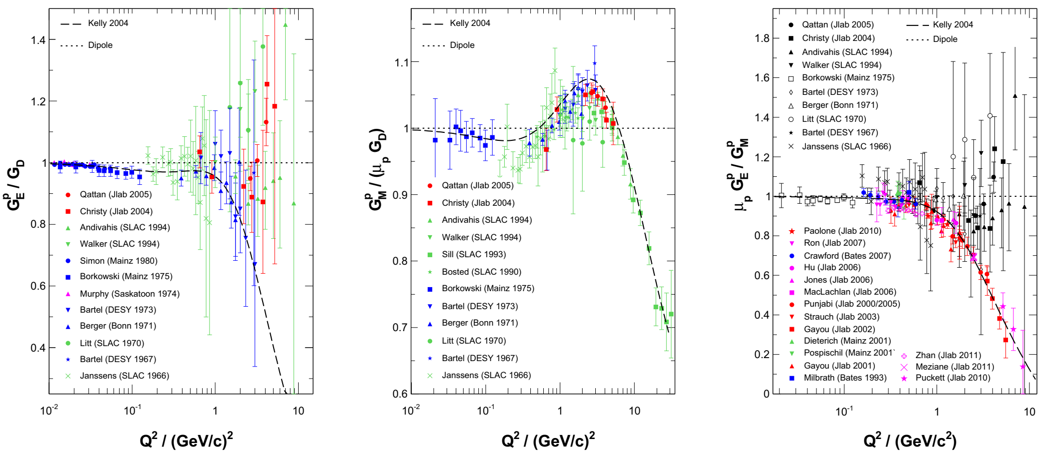

Figure 1. Left: Proton electric form factor G_E^p from Rosenbluth separation and forward-angle measurements [2, 3] normalized to the dipole form factor $G_D = (1 + Q^2/0.71)^{-2}$. Middle: Proton magnetic form factor G_M^p from Rosenbluth separation, backward-angle, and high-Q^2 cross section measurements [2, 4]. Right: Proton electric to magnetic form factor ratio from Rosenbluth-separated cross sections (black symbols) [2] and from double polarization experiments (colored symbols) [6, 7]. The Mainz Rosenbluth data [8, 9] are not shown.

where $\left(\frac{d\sigma}{d\Omega}\right)_{Mott} f_{rec}^{-1} = \left(\frac{\alpha}{2E}\right)^2 \left(\frac{\cos^2(\theta/2)}{\sin^4(\theta/2)}\right) \frac{E'}{E}$ denotes the Mott cross section with recoil factor. A variation of the scattering angle θ, or likewise of the virtual photon polarization $\varepsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}$ at constant value of Q^2 allows to separate G_E^2 and G_M^2 (Rosenbluth separation). The factor $\tau = Q^2/(4m_N^2)$ (with m_N the nucleon mass) increases with Q^2 and eventually makes a separation of the two terms more and more difficult. Figure 1 left and middle plots show the existing data on electric and magnetic proton form factors from unpolarized measurements using the Rosenbluth method [2], G_E^p from forward-angle [3], and G_M^p from large-angle or high-Q^2 cross sections [4], along with a recent form factor parameterization [5]. Up to $Q^2 \approx 10$ (GeV/c)^2 both form factors are reasonably well described by the dipole parameterization $G_D = (1 + Q^2/0.71)^{-2}$, which corresponds to an exponential shape of the proton. The unpolarized data indicated a scaling law of $\mu_p G_E^p / G_M^p = 1$.

The development of polarized beams, targets and recoil polarimeters in the 1990's enabled access to the nucleon form factor ratio G_E/G_M through a spin correlation in double polarization experiments. The interference of G_E and G_M causes an asymmetry

$$-\sigma_0 P_e \vec{P_N} \cdot \vec{A} = P_e P_N \left[\sqrt{2\tau\varepsilon(1-\varepsilon)} G_E G_M \sin\theta^* \cos\phi^* + \tau\sqrt{1-\varepsilon^2} G_M^2 \cos\theta^* \right], \tag{2}$$

where the scalar product of $\vec{P_N}$ and $\vec{A}$ can be interpreted as that of target polarization and (vector) asymmetry, or as that of recoil polarization and analyzing power. In both cases, a longitudinally polarized electron beam (P_e) is required. The angles θ^* and ϕ^* denote the spin orientation of the recoil or target nucleon relative to the momentum transfer direction, and $\sigma_0 = \sigma_{red}/[\varepsilon(1+\tau)]$ is the unpolarized elastic cross section in units of the Mott cross section $(d\sigma/d\Omega)_{Mott} f_{rec}^{-1}$.

The world data of the proton form factor ratio $\mu_p G_E^p / G_M^p$ from double polarization experiments [6, 7] are shown in Fig. 1 (r.h.s.) along with those obtained from Rosenbluth-separated form factors [2]. For $Q^2 > 1$ (GeV/c)^2 the polarization data are monotonically decreasing, dramatically different from the unpolarized data which followed the scaling law. The data in the left and middle plot of Fig. 1

are displayed together with a form factor parameterization [5]. Figure 1 does not show the recent Mainz Rosenbluth data [8, 9], which would add about 1400 data points at low Q^2. Additional low-Q^2 data taken with polarized target at Jefferson Lab are under analysis [11]. A future recoil polarization experiment at Jefferson Lab will extend the Q^2 range up to 15 $(\mathrm{GeV/c})^2$ after the 12 GeV upgrade [10].

The form factor discrepancy at high Q^2 has been explained as the effect of hard two-photon exchange beyond the usual one-photon exchange approximation in the calculation of the elastic electron-proton scattering cross section [12–18]. The results from both methods are mostly based on the single photon exchange assumption including standard radiative corrections [19], which account for two-photon exchange only to the extent that one of the photons is soft. Most of our understanding of the structure of the nucleon and of nuclei is based upon lepton scattering analyzed in terms of the single photon approximation, hence it is essential to precisely quantify the effect from the exchange of two and more photons. Contrary to standard radiative corrections of the lepton arm, which are calculable based on pure QED principles, calculations of the two-photon exchange amplitude are necessarily model-dependent in order to describe the intermediate off-shell hadronic state between the two photon vertices. Such calculations have been carried out e.g. in hadronic [15, 16], or partonic frameworks of generalized parton distributions and perturbative QCD [17, 18]. Also the importance of higher-order radiative effects, not necessarily through two or more photons, has been emphasized [20]. Most calculations tend to remove the discrepancy in the form factor data, however different model assumptions generally do not lead to a consistent determination of the individual amplitudes. For a satisfactory solution for the concurrent interpretation issue of lepton scattering experiments, it is essential to definitively verify the contribution of multiple photon exchange. The general structure of two-photon exchange introduces three new complex amplitudes [12]. While the imaginary parts give rise to small single-spin asymmetries, which can be measured with transversely polarized electron beam [21], transversely polarized target, or induced transverse recoil polarization, only the real parts of the two-photon exchange amplitude are relevant for proton form factor extractions. The real parts of the two-photon exchange amplitudes can affect the linearity of the ε-dependence of the Rosenbluth cross sections [22], introduce a ε- (or angular) dependence of the form factor ratio [23], or generate an e^+p/e^-p cross section asymmetry [24–26].

The only stringent observable that directly probes the size of the two-photon exchange amplitude is the difference of unpolarized elastic electron-proton and positron-proton cross sections. Experimentally, it is more advantageous to measure the ratio of such cross sections. To leading order, the interference of the single and two-photon amplitudes yield a contribution $\propto \alpha^3$ $(\alpha = 1/137)$ to the cross section. This interference effect is odd in the number of lepton vertices and therefore changes its sign when switching between electron and positron probes. In the presence of two-photon exchange, the e^+/e^- cross section ratio will deviate from unity. This effect is expected to be angular dependent, to increase with the scattering angle, likewise to decrease with the virtual photon polarization ε, and to increase with Q^2, in order to explain the form factor discrepancy. The effect disappears for $\varepsilon \to 1$. Previous measurements of the ratio were carried out in the 1960's without showing significant evidence for an effect [27], as displayed in Fig. 2. Most of these data were however measured either at low Q^2 or at large ε, where the effect is also expected to be small.

2 The OLYMPUS Experiment

The OLYMPUS experiment [26, 28–30] aims to precisely measure the ratio of elastic e^+p and e^-p scattering cross sections to better than 1% total error for a beam energy of 2 GeV and a wide range of scattering angles. In the kinematic region covered by OLYMPUS the cross section ratio is expected to deviate from unity by as much as 5-10%, if the form factor discrepancy between Rosenbluth and recoil polarization measurements is caused by two-photon exchange.

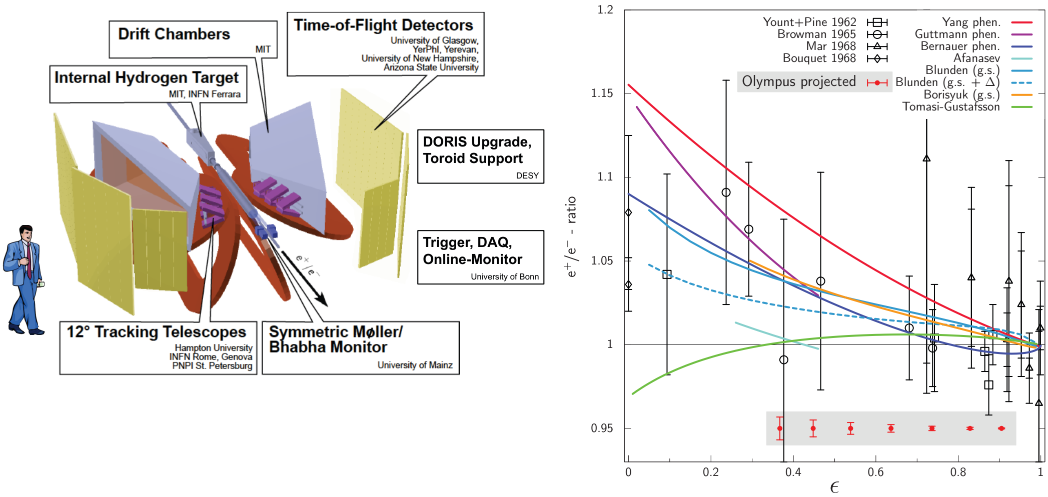

Figure 2. *Left:* Schematic layout of the OLYMPUS experiment with components labeled in the figure. *Right:* Projected precision of OLYMPUS for the e^+p to e^-p cross section ratio versus ε along with previous data [27] and various theoretical predictions [12–18], which have been evaluated for a constant beam energy of E = 2 GeV.

The OLYMPUS experiment has been run at the DORIS storage ring at DESY, Hamburg, Germany, which provided both electron and positron beams in excess of 100 mA at 2 GeV. Both the lepton and recoiling proton were detected in coincidence. The internal, unpolarized, isotopically pure hydrogen gas target was designed to deliver $3 \cdot 10^{15}$ atoms/s, corresponding to a luminosity of $2 \cdot 10^{33}/(\text{cm}^2\text{s})$. The OLYMPUS detector has largely been based on the previous BLAST apparatus from the MIT-Bates Linear Accelerator Center [31–34], a toroidal spectrometer with excellent tracking capability over a wide range of scattering angles of $\approx 20^\circ - 80^\circ$ and $\pm 15^\circ$ out of plane. Several upgrades were implemented for OLYMPUS, in particular two redundant systems were added to measure the relative luminosity of electron and positron beams using forward-angle elastic lepton-proton and symmetric Møller/Bhabha scattering, respectively.

Preparations of the OLYMPUS experiment have begun upon approval in 2010 after securing the required funding from the US agencies DOE and NSF, DESY and the German agency DFG. The BLAST detector was transferred from MIT and reassembled at DESY in a park position. In summer 2011 it was brought into final position in the DORIS storage ring. The new internal hydrogen gas target has been designed and constructed at MIT with a 60 cm long target cell made by INFN Ferrara. The experiment was commissioned in 2011 in parallel with the regular DORIS synchrotron operation, with several dedicated beamtests before the first production data taking took place at the beginning of 2012. OLYMPUS has successfully taken data during two running periods in February 2012 and from October 2012 until January 2013. The integrated luminosity goal was exceeded with the data acquired. After the production running, detailed surveys of the target and detector geometry and of the magnetic field map were undertaken. Calibrations, data analysis and detailed simulations are now in full swing, using an integrated analysis framework. A total integrated luminosity of 3.6 fb^{-1} at a beam energy of 2.0 GeV is required to provide the statistical accuracy of $< 1\%$ up to $Q^2 \leq 2.2$ $(\text{GeV/c})^2$. The four-momentum transfer region near $Q^2 = 2.5$ $(\text{GeV/c})^2$ is of particular interest, where the most complete experimental data set of cross sections and polarization observables exists [14, 23]. The schematic layout of OLYMPUS is shown on the l.h.s. of Fig 2. Of the original BLAST setup [31], the toroidal magnet, the wire chambers (WC) and the time-of-flight scintillators (TOF) have been used. Forward-angle elastic scattering luminosity monitoring systems have been constructed at Hampton University (GEM detector telescopes) and Petersburg Nuclear Physics Institute (multi-wire proportional chambers, MWPC). In addition, a symmetric Møller/Bhabha monitoring system has been developed at Mainz University. The trigger and data acquisition systems were provided by Bonn University. Figure 2 (r.h.s.) shows the projected statistical uncertainties for the e^+p to e^-p cross section ratio at a beam energy of 2.0 GeV as a function of virtual photon polarization along with previous data [27] and various theoretical expectations [13–18]. The systematic uncertainties of the ratio are expected to be less than 1%.

To summarize, the OLYMPUS experiment at the lepton storage ring DORIS at DESY will provide a definitive determination of the two-photon exchange effect by precisely measuring the e^+p / e^-p unpolarized cross section ratio up to $Q^2 = 2.2$ (GeV/c)^2 and virtual photon polarization down to $\varepsilon = 0.37$.

Acknowledgements

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