The OLYMPUS Experiment at DESY

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Introduction

It has been about 100 years since Ernst Rutherford named the hydrogen nucleus the proton; later discovered to be a fundamental component in all nuclei. Yet many fundamental parameters of the proton are still not completely understood and still excite both theoretical and experimental research. The proton radius [1], the proton spin [2], and how the proton mass arises from the energy of the constituent and current quarks in lattice QCD [3] are all still topical subjects in nuclear physics. The OLYMPUS experiment addressed yet another “proton puzzle” concerning the ratio of the charge and magnetic form factors.

Electron scattering has long been a standard technique for studying nucleons and nuclei. The electromagnetic interaction is well understood and the point-like nature of electrons make them ideal for probing electric and magnetic charge distributions. Historically, unpolarised electron-proton scattering has been analysed in terms of one-photon exchange (Born approximation) to determine the electric, G_E^p, and magnetic, G_M^p, form factors for the proton. But recent experiments with polarized electrons, polarized targets, and measurements of the polarization transferred to the proton are in striking disagreement with the unpolarised results (see Figure 1). The unpolarised results, obtained using the Rosenbluth technique, are known to be insensitive to the electric form factor, G_E^p, at high momentum transfer while the polarization measurements make a direct measurement of the form factor ratio, $\mu_p\, G_E^p/G_M^p$, by measuring the ratio of transverse to longitudinal nuclear polarization (see [4] for references). But how to reconcile the discrepancy between the two techniques?

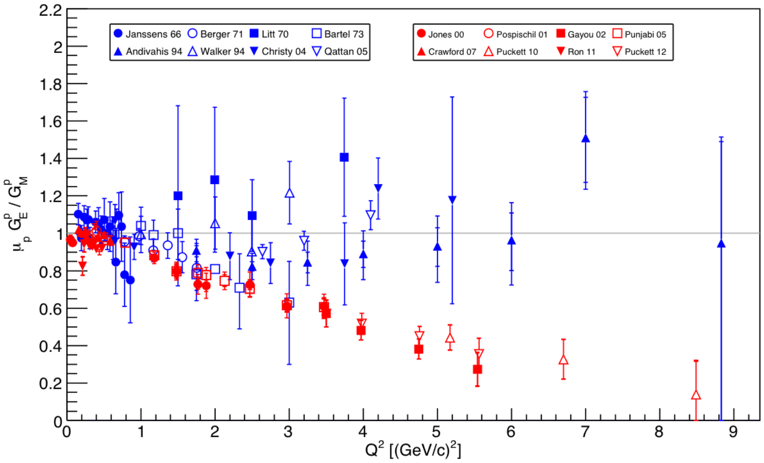

Figure 1Proton form factor ratio, $\mu_p G_E^p/G_M^p$, from unpolarised measurements shown in blue and polarized measurements shown in red.

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Radiative corrections must be applied to the measured cross sections to extract the equivalent one-photon exchange value so results from different experiments and theoretical calculations can be compared. These radiative corrections can be significant and are complicated by details of the experimental acceptance, efficiency, and resolution. But radiative corrections might be the key to resolve the observed discrepancy. A more complete handling of two-photon exchange contributions has been suggested as a possible explanation (see Figure 2). Two-photon exchange is generally included in the standard radiative corrections but only in the "soft" limit where one of the photons imparts negligible energy to the proton. Such calculations are generally independent of models for the proton structure. "Hard" two-photon exchange is more difficult to calculate because details of the proton ground state and nucleon resonances for the intermediate state must also be considered.

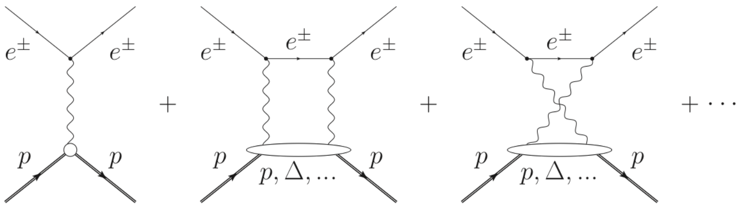

Figure 2 Feynman diagrams for one and two-photon exchange contributions to lepton-proton scattering. Other radiative corrections (not shown) arising from bremsstrahlung, vertex corrections, self-energy, and vacuum polarization diagrams must also be included in calculations.

To determine the contribution of "hard" two-photon exchange the OLYMPUS experiment proposed to measure the ratio of positron-proton to electron-proton elastic scattering. If two-photon exchange is a significant factor in lepton-proton scattering the ratio will deviate from unity because the interference between one- and two-photon exchange changes sign between electron and positron scattering. Naively, one would expect a small effect of order $\alpha \approx 1/137$ but that wouldn't explain the striking discrepancy observed in the proton form factor ratio.

DORIS Storage Ring

The OLYMPUS experiment [4] ran on the DORIS storage ring at the DESY Laboratory in Hamburg, Germany. DORIS began operation in 1974 as an electron-positron collider for particle physics experiments. In 1981, it was also developed as a synchrotron light source for the HASYLAB facility, which became the sole function for DORIS after 1993 until October, 2012. But DORIS retained the ability to store both electrons and positrons. This capability was crucial for the OLYMPUS experiment, which switched daily between beams of electrons and positrons.

DESY undertook significant modifications to the DORIS storage ring to accommodate the OLYMPUS experiment. RF cavities and quadrupoles had to be relocated from the straight section of the storage ring where OLYMPUS was to be located. Services for cooling water and power for the OLYMPUS toroidal magnet had to be installed and the shielding walls extended to make room for the detector. The power supplies for the DORIS ring were also modified so their polarity could be changed quickly when switching between positron and electron running. A large transport frame was also produced to support the OLYMPUS detector on rails. This allowed the detector to be assembled outside the ring and then rolled into the ring for the experiment. At the end of

2012 DORIS ran in “top-up” mode to deliver a steady, high intensity current to achieve the luminosity OLYMPUS needed.

The OLYMPUS experiment installed a hydrogen gas target internal [5] to the storage ring (see Figure 3). The target consisted of a thin-walled, elliptical tube 600 mm long without entrance or exit windows. Hydrogen gas was injected into the centre of the tube and allowed to diffuse to either end where series of vacuum pumps were used to maintain the high vacuum required by the storage ring. The nominal target areal density was approximately 3×10^{15} atoms / cm^2. Additionally, the target region required collimators to shield against synchrotron radiation and specially designed transition pieces to minimize wakefield effects.

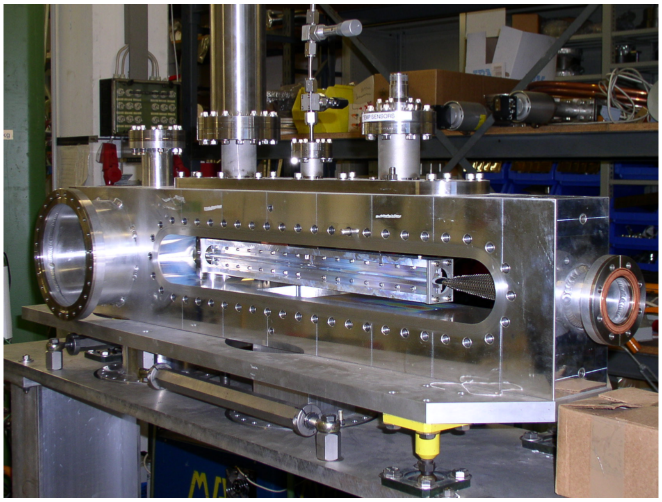

Figure 3 OLYMPUS target cell in the scattering chamber. The target cell is elliptical to accommodate the beam halo profile. Also shown are the wakefield transtition pieces.

OLYMPUS Experiment

In 2010, the former BLAST detector [6] from MIT-Bates was disassembled and shipped to DESY where it was reassembled. The detector (see Figure 4) consisted of an eight-sector toroidal magnetic spectrometer with the two horizontal sectors instrumented with drift chambers covering polar, $20^\circ \leq \theta \leq 80^\circ$, and azimuthal, $-15^\circ \leq \phi \leq 15^\circ$, angles for 3D particle tracking together with walls of time-of-flight scintillator bars for triggering and particle identification. The detector was left-right symmetric and this was used as a cross-check during the analysis.

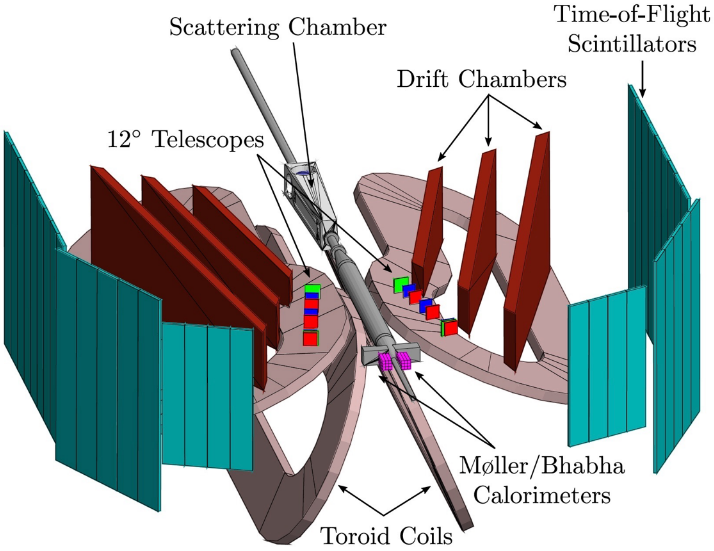

Figure 4 Schematic of the OLYMPUS detector with the top magnet coils removed to show the horizontal sector holding the detectors. The drift chambers are shown as three separate chambers in each sector but are actually combined to form a single gas volume.

Two new detector systems were built to monitor the luminosity. These were symmetric Møller/Bhabha calorimeters at $\theta = \pm 1.29^\circ$ and two telescopes of three triple GEM (gas electron multiplier) detectors interleaved with three multi-wire proportional chambers mounted at $\theta = \pm 12^\circ$ in the horizontal plane.

The timeline for the OLYMPUS experiment was very tight. OLYMPUS received approval and funding in December, 2009 and faced a fixed deadline of December 2012 when DORIS was scheduled to be shut down. The detector rolled into the DORIS ring in July, 2011. After a few commissioning tests, it ran for one month in February, 2012, and then for two months at the end of 2012, alternating daily between electrons and positrons at 2.01 GeV with a typical current around 65 mA. In total OLYMPUS collected approximately 4.5 fb^{-1} of data, 25% more than the original proposal.

Analysis Results and Discussion

The analysis of the OLYMPUS experiment [7] was complicated by an inhomogeneous magnetic field and drift chamber inefficiencies due to the high rate of Møller and Bhabha electrons that were bent into the innermost drift chambers. Originally it was planned to change the toroid magnet polarity each day to reduce tracking systematics but the background with negative polarity prevented operation at high currents so the OLYMPUS data currently analysed is with positive polarity only. To properly analyse the OLYMPUS data a detailed Monte Carlo simulation was written using GEANT4. This allowed the Monte Carlo simulation to account for the differences between electrons and positrons with respect to radiative effects, changing beam position and energy, the spectrometer acceptance, track reconstruction efficiency, luminosity, and elastic event selection. The resulting ratio for the positron-proton to electron-proton cross sections was then determined by calculating:

$$R_{2\gamma} = \frac{\sigma_{e^+p}}{\sigma_{e^-p}} = \frac{N_{exp}(e^+)}{N_{exp}(e^-)} \Big/ \frac{N_{MC}(e^+)}{N_{MC}(e^-)}$$

where the N_i are luminosity normalized experimental and Monte Carlo yields.

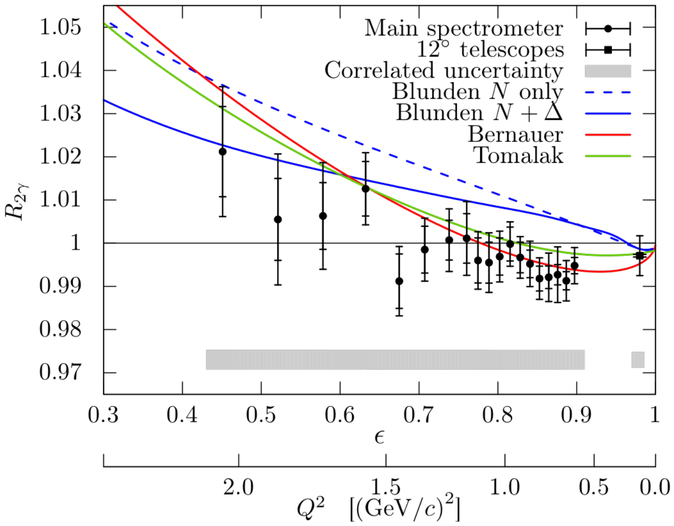

Figure 5 OLYMPUS results compared to calculations from Blunden, Bernauer, and Tomalak. The inner error bars correspond to statistical uncertainty while the outer bars include uncorrelated systematic uncertainties added in quadrature. The grey band indicates correlated systematic uncertainties.

The OLYMPUS results are shown in Figure 5 together with various calculations [8-10]. The results are below unity at low Q^2 (high ϵ) but tend to rise with increasing Q^2 (decreasing ϵ). The dispersive calculations of Blunden, which can account for part of the discrepancy observed in the form factor ratio at higher Q^2, are systematically above the OLYMPUS results in this energy regime. The phenomenological prediction from Bernauer and the subtractive dispersion calculation from Tomalak (that also uses Bernauer's fit to the form factor data) are in reasonable agreement with the OLYMPUS results.

Two other recent experiments, VEPP-3 [11] and CLAS [12], also measured the ratio of positron-proton to electron-proton scattering to determine the contribution of two-photon exchange to elastic lepton scattering. However, it is difficult to compare these results directly with OLYMPUS since their measurements were performed at different energies with results at different points in the (ϵ, Q^2) plane. To partially account for this, we can compare all the two-photon exchange results by taking the difference with respect to a theoretical calculation (in this case Blunden's $N + \Delta$ calculation) evaluated at the correct (ϵ, Q^2) for each data point. This is shown in Figure 6 plotted versus ϵ. In this view, the results for $R_{2\gamma}$ from the three experiments are seen to be in reasonable agreement with each other over the range in ϵ but are systematically below the theoretical calculation. This supports the previous assertion that the theoretical calculation over estimates the results in this energy regime. However, the ϵ dependence of both the results and calculations appears to be in agreement.

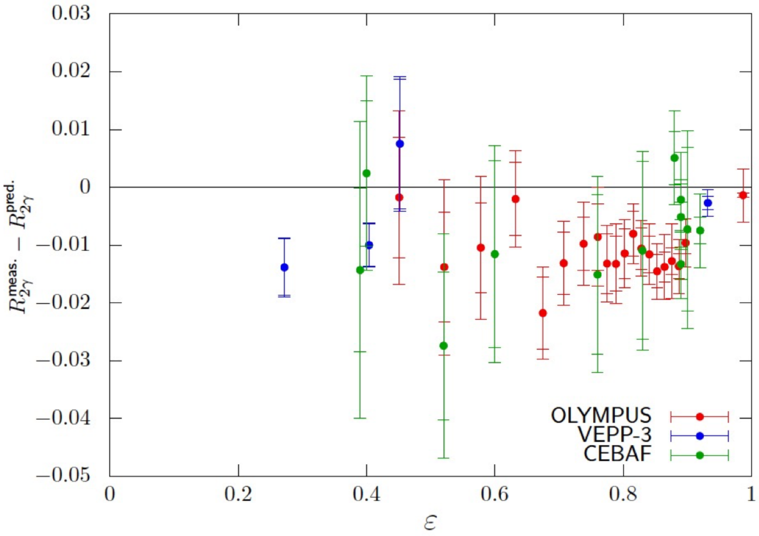

Figure 6 Difference between the three recent two-photon exchange experimental results and the theoretical $N + \Delta$ calculation from Blunden.

Conclusions

At the momentum transferred range measured by OLYMPUS the effect of "hard" two-photon exchange is small, on the order of 1%. This is good news for historical electron scattering measurements made at low energies but does not explain the observed discrepancy in the form factor ratio at higher energies. The rising trend in the ratio $R_{2\gamma}$ with increasing Q^2 (decreasing ϵ) may indicate that two-photon exchange is present and may become significant at higher energies. However, to prove this will require measurements at higher energies that will be difficult due to the rapid decrease in the cross section.

Current theoretical calculations that explain part of the observed discrepancy at higher energies overestimate the effect at the energies measured by the three recent experiments. Possibly higher order radiative corrections are required or nucleon states beyond the $N + \Delta$ need to be considered.

The discrepancy in the form factor ratio measured using unpolarised and polarized techniques and the possible role played by two-photon exchange continues to be topical within the nuclear physics community [13]. A parallel session at the NSTAR 2017 Workshop [14] will be devoted to two-photon exchange. Also, the need for future experiments at higher energy have stimulated discussions at JLab [15] as well as other laboratories. A review of two-photon exchange in elastic electron-proton scattering will also be published soon [16]. Hopefully, more theoretical and experimental work will bring a better understanding of the proton's structure in the near future.

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Bibliography

[1] R. Pohl *et al*. *Annu. Rev. Nucl. Part. Sci.* 63 (2013) 175-204.
[2] C. A. Aidala *et al. Rev. Mod. Phys.* 85 (2013) 655-691.
[3] S. Dürr *et al. Science* 322 (2008) 1224-1227.
[4] R. Milner *et al. Nucl. Instrum. Methods,* A741 (2014) 1-17.
[5] J. C. Bernauer *et al. Nucl. Instrum. Methods*, A755 (2014) 20-27.
[6] D. Hasell *et al. Nucl. Instrum. Methods,* A603 (2009) 247-262.
[7] B. Henderson *et al. Phys. Rev. Lett.* 118 (2017) 092501-092505.
[8] P. Blunden and W. Melnitchouk, *arXiv 1703.06181 (nucl-th),* 2017.
[9] J. Bernauer *et al. Phys. Rev.* C90 (2014) 01520.
[10] O. Tomalak and M. Vanderhaeghen, *Eur. Phys. J.* A51 (2015) 24.
[11] I. Rachek *et al. Phys. Rev. Lett.* 114 (2015) 062005.
[12] D. Adikram *et al. Phys. Rev. Lett.* 114 (2015) 062003.
[13] S. K. Blau, *Physics Today,* 70 (2017) 14.
[14] *11th International Workshop on the Physics of Excited Nucleons,* Columbia, SC, 2017.
[15] *International Workshop on Physics with Positrons at Jefferson Lab,* Newport News, VA, 2017.

[16] A. Afanasev *et al. Prog. Part. Nucl. Phys.* 95 (2017) 245-278.