

Hard two-photon contribution to elastic lepton-proton scattering determined by the OLYMPUS experiment

D K Hasell for the OLYMPUS Collaboration

Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139 USA

E-mail: hasell@mit.edu

Abstract. The OLYMPUS collaboration has recently made a precise measurement of the positron-proton to electron-proton elastic scattering cross section ratio, $R_{2\gamma}$, over a wide range of the virtual photon polarization, $0.456 < \epsilon < 0.978$. This provides a direct measure of hard two-photon exchange in elastic lepton-proton scattering widely thought to explain the discrepancy observed between unpolarized and polarized measurements of the proton form factor ratio, $\mu_p G_E^p/G_M^p$. The OLYMPUS results are small, $< 1\%$, over the range of momentum transfers measured and significantly lower than theoretical calculations that can explain part of the observed discrepancy in terms of two-photon exchange at higher momentum transfers. However, the results are in reasonable agreement with predictions based on phenomenological fits to the available form factor data.

The motivation for measuring $R_{2\gamma}$ will be presented followed by a description of the OLYMPUS experiment. The importance of radiative corrections in the analysis will be shown also. Then we will present the OLYMPUS results and compare with results from two similar experiments and theoretical calculations.

1. 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” [4, 5] 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, unpolarized 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 unpolarized results for the proton form factor ratio, $\mu_p G_E^p/G_M^p$ (see Fig. 1). The unpolarized results [6–13] obtained using the Rosenbluth technique, are known to be insensitive to the electric form factor, G_E^p , at high

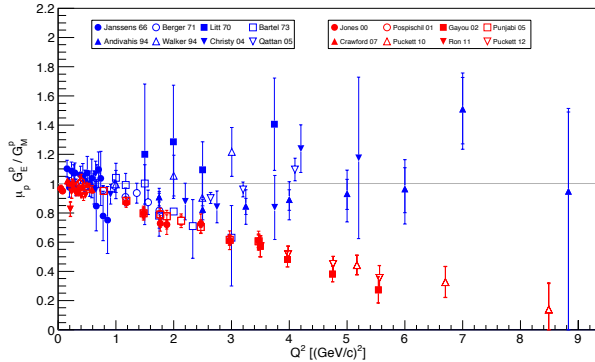


Figure 1. Ratio of proton form factors measured using the unpolarized Rosenbluth technique and using polarization transfer.

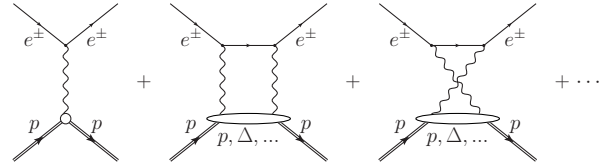


Figure 2. Some of the Feynman diagrams for lepton-proton scattering showing one- and two-photon exchange. Diagrams for self-energy, vertex corrections, vacuum polarization, and bremsstrahlung (not shown) must also be included in any calculation.

momentum transfer while the polarization measurements [14–21] make a direct measurement of the form factor ratio, by measuring the ratio of transverse to longitudinal nuclear polarization.

It has been suggested that two-photon exchange (see Fig. 2) might be able to explain the observed discrepancy in the measured form factor ratio. 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. 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. These calculations were independent of models for the proton structure. A more complete handling of two-photon exchange contributions might be able to resolve the discrepancy. A proper calculation of “hard” two-photon exchange is more difficult because details of the proton ground state and nucleon resonances for the intermediate state must also be considered.

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.

2. OLYMPUS Experiment

The OLYMPUS experiment [22] ran on the DORIS storage ring at the DESY Laboratory in Hamburg, Germany. 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. This capability was crucial for the OLYMPUS experiment, which switched daily between beams of electrons and positrons. 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.

A hydrogen gas target [23] was installed internal to the storage ring. 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/cm². Additionally, the target region required collimators to shield against synchrotron radiation and specially designed transition pieces to minimize wakefield effects.

In 2010, the former BLAST detector [24] from MIT-Bates was disassembled and shipped to DESY where it was reassembled. The detector, shown schematically in Fig. 3, consisted of an eight-sector toroidal magnetic spectrometer with the two horizontal sectors instrumented with large acceptance drift chambers covering polar angles $20^\circ \leq \theta \leq 80^\circ$ and azimuthal angles $-15^\circ \leq \phi \leq 15^\circ$ for 3D particle tracking and 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.

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 $\theta = \pm 12^\circ$ relative to the beam axis.

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.

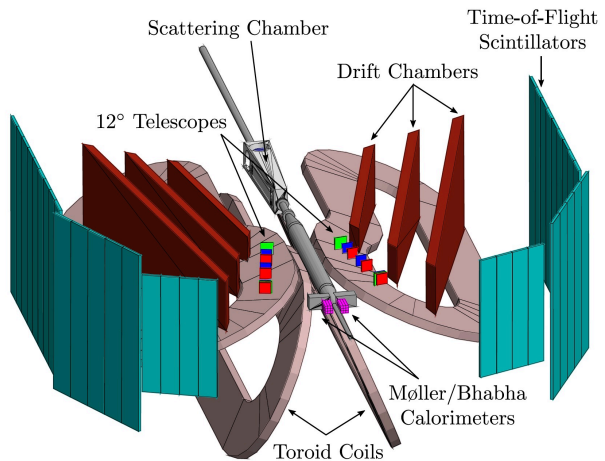


Figure 3. Schematic of OLYMPUS detector. The top four toroid coils are not shown to reveal the horizontal sectors. The drift chambers are shown as three separate chambers in each sector but are actually combined into a single gas volume.

3. Analysis and Results

The analysis of the OLYMPUS experiment 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 complete 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:

$$R_{2\gamma} = \frac{\sigma_{e^+p}}{\sigma_{e^-p}} = \frac{N_{e^+p}^{Data}}{N_{e^-p}^{Data}} \times \frac{N_{e^+p}^{MC}}{N_{e^-p}^{MC}} \times \frac{\mathcal{L}_{e^+p}}{\mathcal{L}_{e^-p}}$$

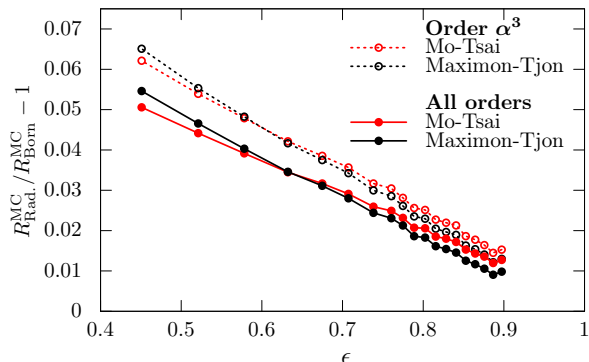


Figure 4. Magnitude of radiative corrections as a function of ϵ for two common “soft” photon prescriptions with exponentiation (all orders) or just to α^3 .

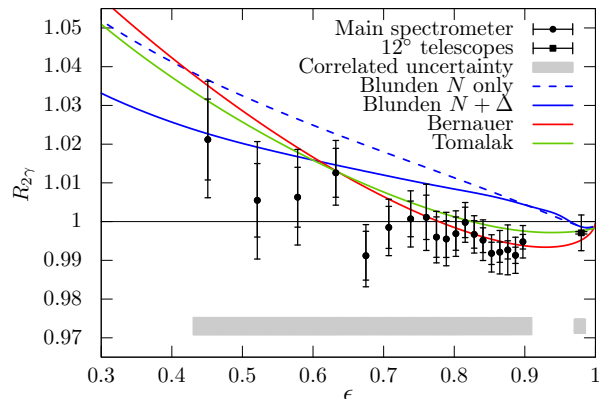


Figure 5. OLYMPUS results for $R_{2\gamma}$ as a function of ϵ . Inner error bars are statistical while the outer error bars include uncorrelated systematic uncertainties added in quadrature. The gray band is correlated systematic uncertainty.

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

The OLYMPUS Monte Carlo event generator included a full treatment of radiative corrections. To remove contributions from “soft” two-photon exchange two standard prescriptions: Mo-Tsai [25] and Maximon-Tjon [26] were used calculated to order α^3 or to all orders through exponentiation. The effect of these radiative corrections is shown in Fig. 4 relative to the Born approximation.

The OLYMPUS results are shown in Fig. 5 together with various calculations. The results are below unity at high ϵ but tend to rise with decreasing ϵ . The dispersive calculations of Blunden [27], 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 [28] and the subtractive dispersion calculation from Tomalak [29] (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 [30] and CLAS [31], also measured the ratio of positron-proton to electron-proton scattering to determine the contribution of two-photon exchange to elastic lepton=proton scattering. However, it is difficult to compare these results directly with OLYMPUS since their measurements were performed at different energies yielding 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 Fig. 6 plotted versus ϵ . In this view, the results 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 does not reproduce the results in this energy regime. However, the ϵ dependence of both the results and calculations appears to be in agreement.

4. 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 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 $N+\Delta$ need to be considered.

The discrepancy in the form factor ratio measured using unpolarized and polarized techniques and the possible role played by two-photon exchange continues to be topical within the nuclear physics community. A parallel session at the NSTAR 2017 Workshop [32] will be devoted to two-photon exchange. Also, the need for future experiments at higher energy have stimulated discussions at JLab [33] as well as other laboratories. Hopefully, more theoretical and experimental work will bring a better understanding of the proton's structure in the near future.

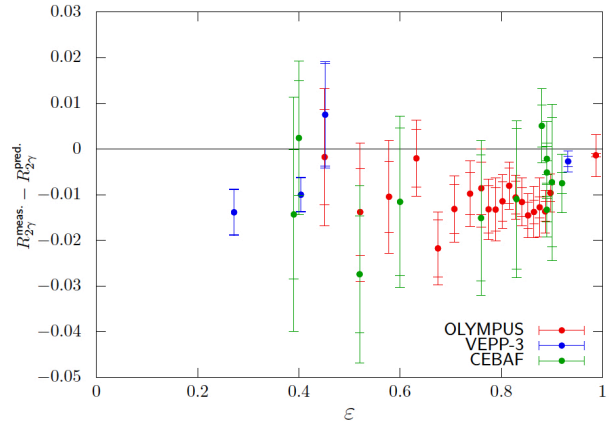


Figure 6. Difference between experimental measurements and the $N+\Delta$ calculation by Blunden.

Acknowledgments

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