Results from the OLYMPUS Experiment on the Contribution of Hard Two-Photon Exchange to Elastic Electron-Proton Scattering

Brian S. Henderson

XVII International Conference on Hadron Spectroscopy and Structure

Massachusetts Institute of Technology

September 25, 2017
The elastic $ep$ cross section and form factors

$$\frac{d\sigma}{d\Omega} = \frac{1}{\varepsilon \left(1 + \frac{Q^2}{4m_p^2}\right)} \left(\frac{\alpha^2 E' \cos^2(\theta/2)}{4E^3 \sin^4(\theta/2)}\right) \left(\varepsilon G_E^2(Q^2) + \frac{Q^2}{4m_p^2} G_M^2(Q^2)\right)$$

$\theta =$ Lab frame scattering angle of the lepton

$Q^2 =$ $-q_\mu q^{\mu}$ = Squared four-momentum transfer

$$\varepsilon = \left(1 + 2 \left(1 + \frac{Q^2}{4m_p^2}\right) \tan^2 \left(\frac{\theta}{2}\right)\right)^{-1}$$
Rosenbluth separation

Form of cross section suggests a straightforward way to measure the form factors: fix $Q^2$ and vary $\varepsilon$ (i.e., $\theta$) using a small-acceptance spectrometer

$$G_E^2(Q^2) \propto \text{slope}, \quad G_M^2(Q^2) \propto \text{cross-section at } \theta = 0$$
The form factors from Rosenbluth separation

\[ G_D = \left( 1 + \frac{Q^2}{0.71 \text{ GeV}^2} \right)^{-2} \]
Availability of highly polarized $e^-$ beams and targets starting in the mid-to-late 1990s provided a new way to measure $G_E/G_M$.

Scatter longitudinally-polarized $e^-$ from unpolarized protons, and measure the cross-sections for the different polarizations of the outgoing lepton.

\[
\frac{d\sigma^{(L)}}{d\Omega} = h\sigma_{Mott} \frac{E + E'}{m_p} \sqrt{\frac{1}{1 + \frac{4m_p^2}{Q^2}}} \tan^2 \left( \frac{\theta}{2} \right) G_M^2
\]

\[
\frac{d\sigma^{(T)}}{d\Omega} = 2h\sigma_{Mott} \sqrt{\frac{1}{1 + \frac{4m_p^2}{Q^2}}} \tan \left( \frac{\theta}{2} \right) G_E G_M
\]
The $G_E/G_M$ ratio discrepancy

The Rosenbluth and polarization form factor ratios show a large discrepancy!

<table>
<thead>
<tr>
<th>Rosenbluth</th>
<th>Polarization</th>
<th>Fits Bernauer '13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Litt '70</td>
<td>Gayou '01</td>
<td>Fit Rosenbluth</td>
</tr>
<tr>
<td>Bartel '73</td>
<td>Punjabi '05</td>
<td>Fit all + phen. TPE</td>
</tr>
<tr>
<td>Andivahis '94</td>
<td>Jones '06</td>
<td></td>
</tr>
<tr>
<td>Walker '94</td>
<td>Puckett '10</td>
<td></td>
</tr>
<tr>
<td>Christy '04</td>
<td>Paolone '10</td>
<td></td>
</tr>
<tr>
<td>Qattan '05</td>
<td>Puckett '12</td>
<td></td>
</tr>
</tbody>
</table>

- $Q^2$ [($GeV/c$)$^2$]
- $\mu G_E/G_M$
Questioning the Born approximation

Results from both methods (especially Rosenbluth separation), depend heavily on radiative corrections

Most of these are calculable, but the two photon exchange (TPE) box and crossed-box contributions had always been “assumed to be negligible” due to the challenges of the off-shell proton propagator.
Measuring TPE directly with $\sigma_{e^+p}/\sigma_{e^-p}$

A TPE correction could bring the data into agreement, but calculation of the diagrams is highly model-dependent.

Interference of the tree-level and TPE diagrams changes sign with the charge of the lepton $\rightarrow$ comparing $e^+$ and $e^-$ scattering gives you a direct link to the TPE contribution

$$R_{2\gamma}(\epsilon, Q^2) = \frac{\sigma_{e^+}}{\sigma_{e^-}} \sim 1 + 4\alpha \frac{M_{\gamma\gamma}}{M_\gamma}$$
OLYMPUS seeks to provide a measurement of the $e^+p/e^-p$ elastic cross section ratio with better than 1% uncertainty over a range of $0.15 \text{ GeV}^2 < Q^2 < 2.2 \text{ GeV}^2$ to test the TPE hypothesis.

Experiment requirements:

- Strong statistics over a large $\theta$ range
- Precise monitoring of the relative $e^+/e^-$ luminosity collected
- Complete understanding of any systematic difference between $e^+$ and $e^-$ running
  - Acceptance effects
  - Beam conditions
  - Associated background/noise
  - ...
- Careful radiative corrections (especially $\alpha^3$ soft effects)
OLYMPUS basics

- Located at the DORIS storage ring, DESY, Hamburg, Germany
- 2.01 GeV $e^+$ and $e^-$ on a fixed internal gaseous hydrogen target
- Main tracking detectors and toroidal magnet from BLAST (MIT Bates)
- New detectors for precision luminosity monitoring
- Two other experiments: CLAS and VEPP-3
• Exclusively reconstruct elastic $e^\pm p$ events from $\theta \approx 20^\circ - 70^\circ$

• Switch beam species approximately daily to control long-period systematics

• Construct an extremely detailed Monte Carlo simulation including detector efficiencies and acceptance, radiative corrections, and experiment conditions (beam current, target density, beam position, etc.)

$$R_{2\gamma} = \frac{\sigma_{e^+ p}(\theta)}{\sigma_{e^- p}(\theta)} = \frac{N_{e^+, \text{data}}(\theta)}{N_{e^-, \text{data}}(\theta)} \cdot \frac{N_{e^-, \text{MC}}(\theta, L_{e^-})}{N_{e^+, \text{MC}}(\theta, L_{e^+})}$$
Projected reach and previous data

![Graph showing e+/e− ratio vs. ε with data points and error bars for various authors and experiments: Yount+Pine 1962, Browman 1965, Mar 1968, Bouquet 1968, Olympus projected, Yang phen., Guttmann phen., Bernauer phen., Afanasev, Blunden (g.s.), Blunden (g.s. + ∆), Borisyuk (g.s.), Tomasi-Gustafsson.](graph.png)
Reach of the modern TPE experiments

\[ Q^2 \text{[GeV/c]}^2 \]

\[ \epsilon \]

- CLAS
- OLYMPUS
- VEPP-3 Run I
- VEPP-3 Run II

Brian S. Henderson (MIT)

Measurement of TPE at OLYMPUS

September 25, 2017
The OLYMPUS detector
The OLYMPUS detector

Brian S. Henderson (MIT)

Measurement of TPE at OLYMPUS

September 25, 2017
The OLYMPUS detector

Measurement of TPE at OLYMPUS

September 25, 2017
The OLYMPUS detector

e^+ / e^−
The OLYMPUS detector

e^+/e^−
The OLYMPUS detector

Brian S. Henderson (MIT)

Measurement of TPE at OLYMPUS

September 25, 2017

14 / 21
The OLYMPUS detector
Luminosity determination

Three independent monitors of the $e^+/e^-$ relative luminosity:

Beam current + molecular flow modeling of target density
$\sim 5\%$ absolute, $\sim 1\%$ species-relative uncertainty
Luminosity determination

Three independent monitors of the $e^+/e^-$ relative luminosity:

12 Degree Elastic Scattering ($R_{2\gamma} \approx 1$ at high $\varepsilon$)

$\sim 2\%$ absolute, $\sim 0.4\%$ species-relative uncertainty
Luminosity determination

Three independent monitors of the $e^+/e^-$ relative luminosity:

Multi-Interaction Events in Forward Calorimeter

$\sim 10\%$ absolute, $\sim 0.35\%$ species-relative uncertainty

A. Schmidt et al., arXiv:1708.04616 (physics.ins-det)
Main analysis

Specific to each analysis

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

Common to all analyses
$R_{2\gamma}$, Mo-Tsai radiative correction model

Comparison to Blunden $N + \Delta$ model

$R_{exp}^{2\gamma} - R_{Blunden}^{2\gamma}$ vs $\epsilon$

VEPP-3
CLAS
OLYMPUS

Brian S. Henderson (MIT)
Measurement of TPE at OLYMPUS
September 25, 2017

19 / 21
Conclusions

- OLYMPUS achieved measurement of $\sigma_{e^+p}/\sigma_{e^-p}$ for $0.15 \text{ GeV}^2 < Q^2 < 2.2 \text{ GeV}^2$, with $\lesssim 1\%$ uncertainty.

- In general, the three modern TPE experiments agree; the effect is small at low $Q^2$, consistent with the slope of theoretical models, and roughly consistent with the magnitude of some phenomenological models.

- The definitive answer may be at higher $Q^2$, plans are forming to explore this region experimentally.
The OLYMPUS collaboration

- Arizona State University
- DESY
- INFN Bari
- INFN Ferrara
- INFN Rome
- Hampton University
- Massachusetts Institute of Technology

- Petersburg Nuclear Physics Institute
- University of Bonn
- University of Glasgow
- University of Mainz
- University of New Hampshire
- A. Alikhanyan National Laboratory (Yerevan Physics Institute)
$R_{2\gamma}$, Mo-Tsai Radiative Correction Model

![Graph showing the comparison of Mo-Tsai and Maximon-Tjon estimations with different orders of $\alpha^3$. The graph plots $R_{MC\text{Rad.}} / R_{MC\text{Born}} - 1$ against $\epsilon$. The graph includes lines for Mo-Tsai and Maximon-Tjon estimations at different orders: $\alpha^3$, all orders. The data points are shown for different values of $\epsilon$.]

Brian S. Henderson (MIT)  
Measurement of TPE at OLYMPUS  
September 25, 2017  
22 / 21
Comparison to Bernauer phen. model

\[ R_{\text{meas.}} - R_{\text{pred.}} \]

\[ Q^2 \text{ [(GeV}/c)^2] \]

OLYMPSUS
VEPP-3
CEBAF

$Q^2 = 1.525 (\text{GeV}^2/c^2)$, Integral = 21113, Background = 2671.8239, Fraction = 0.1918
Background Fraction for Lepton Left

![Graph showing Background Fraction for Lepton Left]

- Data
- MC

Brian S. Henderson (MIT)

Measurement of TPE at OLYMPUS

September 25, 2017
Lepton left/right yields

![Graph showing lepton left/right yields](image-url)
Slow control luminosity normalization, blinded common slope
Other TPE experiments

Two other experiments have also completed data-taking for $e^+ p / e^- p$ ratio measurements; different systematics and kinematic coverages

CLAS, Jefferson Lab, USA
- Unique tertiary beam
- Sensitive to lower $Q^2$
- Very large acceptance
- Statistics limited
- Results published, long paper pending

VEPP-3, Novosibirsk, Russia
- Sensitive to lower $Q^2$
- Calorimetry-based detector
- Smaller acceptance
- Relatively advanced results already out

The three experiments are quite complimentary; should provide a definitive answer
CLAS and VEPP-3 results

\[ \langle Q^2 \rangle = 0.85 \text{ GeV}^2 \]

- Zhou & Yang (N only)
- Zhou & Yang (N+Δ)
- Blunden et al. (N only)
- Point-like proton

\[ \langle Q^2 \rangle = 1.45 \text{ GeV}^2 \]

\[ \langle e \rangle = 0.45 \]

\[ \langle e \rangle = 0.88 \]
VEPP-3 TPE experiment

Plastic scintillators
Drift chambers
Proportional chambers
$e^+/e^-$ beam $E = 1.6$ GeV
Storage cell ($H_2$ target)

0.5 m

Sandwich scintillators
Aperture counters

Brian S. Henderson (MIT)
Measurement of TPE at OLYMPUS
September 25, 2017
• Broad theory consensus that $R_{2\gamma} \approx 1$ at high $\varepsilon$
• High resolution $12^\circ$ tracking telescopes with dedicated trigger provide high statistics measurement
  • 3 GEMs + 3 MWPCs per detector side
  • Exclusive $e^{\pm}p$ reconstruction
  • $\sim 1\%$/hour statistical uncertainty from each telescope
  • Additional $R_{2\gamma}$ point with SYMB luminosity
12° results

Left+Right Arm MWPC–Only, Lepton + WC Proton Passing Cuts

e−: \( \mu = 1.0447, \sigma = 0.014 \)
e+ : \( \mu = 1.0478, \sigma = 0.012 \)

Brian S. Henderson (MIT)
Measurement of TPE at OLYMPUS
September 25, 2017 34 / 21
Measurement of $R_{2\gamma}$ at $\theta \approx 12^\circ$

$$R_{2\gamma} \left( \epsilon = 0.98, Q^2 = 0.165 \text{ GeV}^2 \right) = 0.9975 \pm 0.0010 \text{ (stat.)} \pm 0.0053 \text{ (syst.)}$$
Left Arm MWPC–Only, Lepton + WC Proton Passing Cuts

e^−: µ = 1.0525, σ = 0.019

e^+: µ = 1.0538, σ = 0.016
12° right results

Right Arm MWPC−Only, Lepton + WC Proton Passing Cuts

\[ e^-: \mu = 1.0374, \sigma = 0.019 \]
\[ e^+: \mu = 1.0418, \sigma = 0.016 \]
### Uncertainty Source

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>Relative (%)</th>
<th>Absolute (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ToF trigger efficiency ($\delta_{\epsilon_{\text{ToF}}}$)</td>
<td>±0.19</td>
<td>±0.25</td>
</tr>
<tr>
<td>SiPM trigger efficiency ($\delta_{\epsilon_{\text{SiPM}}}$)</td>
<td>±0.01</td>
<td>±0.10</td>
</tr>
<tr>
<td>MWPC plane efficiency ($\delta_{\epsilon_{\text{MWPC}}}$)</td>
<td>±0.01</td>
<td>±0.05</td>
</tr>
<tr>
<td>Magnetic field ($\delta_{B}$)</td>
<td>±0.15</td>
<td>±0.35</td>
</tr>
<tr>
<td>Lepton tracking efficiency ($\delta_{\epsilon_{e,\text{track}}}$)</td>
<td>±0.18</td>
<td>±0.86</td>
</tr>
<tr>
<td>Proton tracking efficiency ($\delta_{\epsilon_{p,\text{track}}}$)</td>
<td>±0.10</td>
<td>±0.80</td>
</tr>
<tr>
<td>Beam position/slope ($\delta_{\text{BPM}}$)</td>
<td>±0.01</td>
<td>±0.01</td>
</tr>
<tr>
<td>Beam energy ($\delta_{E_{\text{beam}}}$)</td>
<td>±0.02</td>
<td>±0.02</td>
</tr>
<tr>
<td>Detector position ($\delta_{\text{det}}$)</td>
<td>±0.02</td>
<td>±0.20</td>
</tr>
<tr>
<td>Fiducial cuts ($\delta_{\text{fid}}$)</td>
<td>±0.12</td>
<td>±0.22</td>
</tr>
<tr>
<td>Elastic cuts ($\delta_{\text{elas}}$)</td>
<td>±0.27</td>
<td>±1.63</td>
</tr>
<tr>
<td>Radiative corrections ($\delta_{\text{rad}}$)</td>
<td>±0.08</td>
<td>±0.45</td>
</tr>
<tr>
<td>Form factors ($\delta_{\text{ff}}$)</td>
<td>±0.14</td>
<td>±1.20</td>
</tr>
<tr>
<td>TPE at $\theta = 12^\circ$ ($\delta_{\text{TPE}}$)</td>
<td>±0.10</td>
<td>±0.10</td>
</tr>
<tr>
<td>Total including TPE uncertainty ($\delta_{12^\circ,\text{TPE}}$)</td>
<td>±0.47%</td>
<td>±2.44%</td>
</tr>
<tr>
<td>Total without TPE uncertainty ($\delta_{12^\circ}$)</td>
<td>±0.46%</td>
<td>±2.44%</td>
</tr>
</tbody>
</table>