Form factor measurements in the presence of two-photon exchange

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Form Factors

- Elastic scattering (Born approx.)

\[ \langle N(P')| J_{\text{EM}}^\mu(0) | N(P) \rangle = \]
\[ \bar{u}(P') \left[ \gamma^\mu F_1^N(Q^2) + i \sigma^{\mu\nu} \frac{q_\nu}{2M} F_2^N(Q^2) \right] u(P) \]

- Electric and magnetic form factors \( G_E \) and \( G_M \)
  - Fourier transforms of resp. distributions

\[ G_E = F_1 - \tau F_2; \quad G_M = F_1 + F_2, \quad \tau = \frac{Q^2}{4M^2} \]
Classical Approach

- Assume single photon exchange – Born approximation
  - Measure cross section (Rosenbluth)
    \[ \left( \frac{d\sigma}{d\Omega} \right)_{\text{Rosenbluth}} = \left[ \frac{|G_E|^2 + \tau|G_M|^2}{1 + \tau} + 2\tau|G_M|^2 \tan^2 \frac{\theta}{2} \right] \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \]
  - Extract \( G_E \) and \( G_M \)

\[ \sigma_{\text{red}} = \frac{\left( \frac{d\sigma}{d\Omega} \right)_{\text{Rosenbluth}}}{\left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}}} \epsilon \left( 1 + \tau \right) \]

\[ = \epsilon |G_E|^2 + \tau |G_M|^2 \]

- with \( \tau = \frac{Q^2}{4M_p^2} \)

\[ \epsilon = \left[ 1 + 2(1 + \tau) \tan^2 \frac{\theta}{2} \right]^{-1} \]
Multi-Photon Contributions?

- Long standing beliefs:
  - $G_E \sim G_M$
  - Multi-photon contribution 1-2% only
- Experimental arguments
  - Linearity of Rosenbluth plot
  - $e^+/e^- (and \mu^+/\mu^-)$ ratio found to be 1
    - as required in Born approximation
Recent Puzzle in $G_E/G_M$

Rosenbluth separation

Double polarisation measurements

Additional JLab results here
How to address the issue

- Measure cross section ratio $e^+/e^-$ versus epsilon
  - exactly unity in Born approximation
  - two-photon effects at low epsilon
  - several percent effect at $Q^2 \sim 2 \text{ GeV}^2$
  - 3 experiments: OLYMPUS, CLAS, VEPP3

\[ \epsilon = \left[ 1 + 2(1 + \tau) \tan^2 \frac{\theta}{2} \right]^{-1} \]

![Graph showing saturation at $Q^2 \sim 2-3 \text{ (GeV/c)}^2$](image1.png)

![Graph showing $R_{e^+e^-}$ ratio](image2.png)


J. Guttmann, et al., arXiv: 1012.0564
Measurement Concept

- Electron and positron beams
- Proton target
- OLYMPUS features
  - $E \sim 2$ GeV
  - Frequent switch between $e^+$ and $e^-$
  - Lepton-proton coincidence measurement
  - Windowless, pure proton target
  - Large theta coverage, i.e. epsilon range
  - Minimal systematic uncertainties
    - symmetric arrangement
    - reversible magn. field
  - Precise luminosity measurement
    - ratio $e^+$ to $e^-$ with precision <1%
  - Redundancy
Where to go

DORIS at DESY, Hamburg

- $e^+$ and $e^-$ beams
  - frequent switch
- $E = 2.0 \ (4.5) \text{GeV}$
  - $Q^2 = 0.6-2.4(4.1) \ (\text{GeV/c})^2$

- ARGUS location

Inti Lehmann
2-Photon, IOP Glasgow, 6/4/2011
Experimental Set-Up

- Use BLAST detector from MIT-Bates
  - refurbished
  - add-ons
- Symmetric spectrometer
- Luminosity monitors
  - precise + redundant
- Toroidal field
  - frequent reversal
Experimental Set-Up
Expected Performance

- Theoretical predictions
  - large variations

\[ \epsilon = \left[ 1 + 2(1 + \tau) \tan^2 \frac{\theta}{2} \right]^{-1} \]
Expected Performance

- Theoretical predictions
  - large variations
- Existing data
  - not conclusive
Expected Performance

- Beam $E = 2$ GeV
  - $Q^2 = 0.6 - 2.2$ (GeV/c)$^2$
  - $\varepsilon = 0.37 - 0.9$
  - sys. uncert. 1%

\[
e = \left[ 1 + 2(1 + \tau) \tan^2 \frac{\theta}{2} \right]^{-1}
\]
Other Experiments

- Projected resolutions
  - scaled to fit scales
- CLAS/PR04-116
  - secondary $e^+/e^-$ beam
  - syst. challenging
- Novosibirsk/VEPP-3
  - storage ring/intern. target
  - low statistics

![OLYMPUS Q^2=2GeV](image1)

![CLAS](image2)

![VEPP3](image3)
Conclusions

- Form factors
  - old but still hold surprises
- Discrepancy in $G_E/G_M$
  - unpredicted, 2-photon exch. not sufficient
  - no experimentally verified explanation
- Experimental approach
  - measure $e^+/e^-$ ratio over large $\varepsilon$ range
  - systematic uncertainties $\sim 1\%$
- The OLYMPUS experiment
  - symmetric toroidal spectrometer at DESY
  - preparation progressing well and in time
  - measurements in 2012
- Decisive information
  - nature of discrepancy
  - sensitivity to nucleon EM structure
- Further future: time-like form factors (PANDA)
Olympus Collaboration

- Arizona State University
- DESY Hamburg
- Hampton University
- INFN Bari
- INFN Ferrara
- INFN Rome
- Massachusetts Institute of Technology
- Petersburg Nuclear Physics Institute
- Universität Bonn
- University of Colorado
- University of Glasgow
- University of Kentucky
- Universität Mainz
- University of New Hampshire
- Yerevan Physics Institute
BLAST at MIT-Bates

- **BLAST Detector Set-Up**
  - Fulfils most criteria
- **MIT-Bates South Hall Ring**
  - Too low $Q^2$ to study the observed effect

C.B. Crawford et al., PRL 98 (2007) 052301
Normalisation

- 2 symmetric luminosity monitors
  - 12deg telescopes: GEMs + MWPCs (coincident)
  - Moller/Bhabha calorimeters
- Regular change of both
  - particle type: $i = e^+$ or $e^-$
  - magnet polarity: $j = \text{pos or neg}$
- Combination
  - efficiency and acceptance effects cancel to first order

\[ N_{ij} = \tilde{L}_{ij} \sigma_i \kappa^p_{ij} \kappa^l_{ij} \]

\[ \sigma_{e^+} \sigma_{e^-} = \left[ \left( \frac{N_{e^+} + N_{e^-}}{N_{e^-} + N_{e^-}} / \frac{A_{e^+} + A_{e^-}}{A_{e^-} + A_{e^-}} \right) \right]^{1/2} \]
Recent Puzzle in $G_E/G_M$

- Nobody predicted this effect
- Polarization measurements
  - measure asymmetry ratio
    \[
    \frac{P_\perp}{P_\parallel} = \frac{A_\perp}{A_\parallel} \propto \frac{G_E}{G_M}
    \]
  
    \[\quad - \sigma_0 \vec{P}_p \cdot \vec{A} = \sqrt{2\tau\epsilon(1-\epsilon)} G_E G_M \sin \theta^* \cos \phi^* \]
    \[\quad + \tau \sqrt{1-\epsilon^2} G_M^2 \cos \theta^*\]

- Rosenluth separation at high $Q^2$
  - $G_E$ difficult to extract
  - $2\gamma$ corrections large
Recent Puzzle in $G_E/G_M$

- Observed effect
  - mostly explicable by 2-photon exchange
  - experimental proof missing

Rosenbluth data with two-photon exchange correction


Aside: Time Like Form Factors

- PANDA (FAIR)
  - \( R = \mu_p G_E/G_M \) with unprecedented precision
  - Absolute value of \( |G_M| \) up to \( 30(\text{GeV/c})^2 \)

Existing data extracted assuming \( |G_E| = |G_M| \)

• Lowest epsilon $\sim 0.4$ only for $E < 2.3$ GeV
• At epsilon = 0.4, require $E > 2$ GeV to maintain $Q^2 > 2 \text{ (GeV}/c)^2$
Unofficial Novosibirsk information

$e^+p/e^-p$ cross section ratio

$Q^2$: 1.4-1.76  
$\varepsilon$: 0.32 to 0.51

P.G. Blunden et al.,  
Rosenbluth separation for $e^+p$

PT results

<table>
<thead>
<tr>
<th>$R_{L-T}$ [Bosted fit]</th>
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<tbody>
<tr>
<td>$R_{Pol}$</td>
</tr>
<tr>
<td>$R_{Pol}$ + TPE ($e^-$)</td>
</tr>
<tr>
<td>$R_{Pol}$ + TPE ($e^+$)</td>
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</tbody>
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$\mu_p G_E/G_M$ vs $Q^2 \ [GeV^2]$
Two-Photon Exchange

- Secondary beams
  - low luminosity
- data taken
  - at high $Q^2$
  - OR large $\theta$
- Unobserved correction?
  - at large $\theta$ (small $\epsilon$)
Further Model Predictions


\[ \frac{\sigma_{e^+}}{\sigma_{e^-}} \]

\[ \epsilon \]

\[ \text{FIG. 3: Predictions for the ratio} \]

\[ \text{FIG. 4: The ratio} \]

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