TPEX@DESY - A Two-Photon Exchange Experiment at DESY Test Beam

on behalf of the TPEX collaboration

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QED theory is perturbative!  \[ \text{Born (One Photon) Approximation!} \]

Electrons (positrons) are an ideal probe for studying the structure of the proton:

- point-like,
- spin 1/2,
- purely electromagnetic interaction,
- well described to high precision by QED.

Differential Cross Section is proportional to the scattering amplitude squared:

\[
\frac{d\sigma^{\text{Born}}}{d\Omega} = \left( \frac{\alpha}{4 m_p Q^2 E} \right) |M_\gamma|^2 = \frac{d\sigma^{\text{Mott}}}{d\Omega} \frac{\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)}{\epsilon (1 + \tau)}
\]
The Proton Form Factor Puzzle

Large Discrepancy at high $Q^2$

Unpolarized Measurements
- Janssens 66
- Berger 71
- Litt 70
- Bartel 73
- Andivahis 94
- Walker 94
- Christy 04
- Qattan 05

Polarization Measurements
- Jones 00
- Pospischil 01
- Gayou 02
- Punjabi 05
- Crawford 07
- Puckett 10
- Ron 11
- Puckett 12

$\mu_p G_E^p / G_M^p$

$Q^2$ [(GeV/c)$^2$]
Beyond Born Approximation (L and NL order)

\[ \frac{d\sigma}{d\Omega} = \left( \frac{\alpha}{4m_p E} \right)^2 \left| M_{\text{Born}} + \sum_{NL} M_{NL} \right|^2 = \left( \frac{\alpha}{4m_p E} \right)^2 |M_{\text{Born}}|^2 \left| 1 + \frac{\sum_{NL} M_{NL}}{M_{\text{Born}}} \right|^2 \]

\[ \frac{d\sigma}{d\Omega} = \frac{d\sigma^{\text{Born}}}{d\Omega} \left| 1 + \sum_{NL} \delta_{NL} \right|^2 \]
Two Photon Exchange (TPE) is the next-to-leading order correction that depends on nucleon structure:

- "soft" TPE correction is included in calculations: removes the divergence term from bremsstrahlung correction.
- "hard" TPE is difficult to calculate: intermediate state \((p, \Delta, \ldots)\) model dependent!

Need to measure "hard" TPE
The differential cross section of elastic lepton-proton scattering is proportional to the square of the matrix element:

$$\frac{d\sigma}{d\Omega} \propto |M|^2 = |M_{\text{Born}} + M_{\text{brems}}^l + M_{\text{brems}}^p + M_{\text{virtual}} + M_{2\gamma}|^2$$

Considering only terms up to 4th order:

$$\frac{d\sigma}{d\Omega} \propto [M_{\text{Born}}]^2 + [M_{\text{brems}}^l]^2 + 2\Re \left( (M_{\text{brems}}^l)^\dagger M_{\text{brems}}^p \right) + [M_{\text{brems}}^p]^2 +$$
$$+ 2\Re \left( M_{\text{Born}}^\dagger M_{\text{virtual}} \right) + 2\Re \left( M_{\text{Born}}^\dagger M_{2\gamma} \right) + O(\alpha^4)$$

**Cross Section Ratio:**

$$R = \frac{\sigma(l^+p)}{\sigma(l^-p)} = \frac{1 + \delta_{\text{even}} - \delta_{2\gamma} - \delta_{\text{brems}}}{1 + \delta_{\text{even}} + \delta_{2\gamma} + \delta_{\text{brems}}} \approx 1 - 2 \cdot \frac{\delta_{2\gamma} + \delta_{\text{brems}}}{1 + \delta_{\text{even}}}$$

The sign of a QED vertex \((-iQ|e|\gamma^\mu\rangle\) depends on the change of the lepton that scatters off the proton.
Recent Experimental Results Overview

Recent Experiments $Q^2 < 2.1$ (GeV/c)$^2$:

- VEPP – 3 (Novosibirsk, Russia, 2009);
- CLAS TPE experiment (Jefferson Lab’s Hall B, USA, 2015);
- OLYMPUS (DESY, Germany, 2016);

$$R_{2\gamma} = \frac{\sigma_{e^+p}}{\sigma_{e^-p}}$$

Difference with respect to Blunden ND vs $Q^2$
OLYMPUS Results

- Region $Q^2 < 1 \text{ GeV}^2$ not understood in terms of QED theory
- Further theoretical effort needed. Experiments at higher energy required.

[Drawing of a graph showing $R_{2\gamma}$ vs. $Q^2$ with different lines and data points.]

The Two-Photon Exchange eXperiment @ DESY

- 0.5–6.3 GeV beam
- Beam intensity: electrons (60 nA) or positrons (30 nA)
- 12.5 Hz

DESY the only facility with intense electron and positron beams!
The Proton Form Factor Puzzle and TPEX

Recent TPEX Experiments:
- \( Q^2 < 2.1 \text{ (GeV/c)}^2 \)
- \( Q^2 < 2.7 \text{ (GeV/c)}^2 \)
- \( Q^2 < 4.6 \text{ (GeV/c)}^2 \)

Future of TPEX:
- TPEX(2 GeV):
  \[ R_{2\gamma} = \frac{\sigma_{e^+p}}{\sigma_{e^-p}} \]
- TPEX(3 GeV):

VEPP – 3 (Novosibirsk, Russia, 2009);
CLAS TPE experiment (Jefferson Lab’s Hall B, USA, 2015);
OLYMPUS (DESY, Germany, 2016);
• Commission @ 2 GeV beam (2 weeks): $Q^2 \leq 2.7 \text{ (GeV/c)}^2$.
• Run @ 3.0 GeV beam (6 weeks): $Q^2 \leq 4.57 \text{ (GeV/c)}^2$. 
• Scattering: 5x5 arrays Calorimeter at 30°, 50°, 70°, 90°, and 110°.
• Beam Luminosity: Luminosity Monitor (Quartz Cherenkov Counter)
TPEX Apparatus: 5x5 Calorimeter (MIT)

TPEX Test Calorimeter 5×5 version:

- 10 detectors of 5 × 5 calorimeters (PbWO4).
- Density: ρ=8.3g/cm³
  ⇒ 2×2×20 cm³ crystal=0.664kg.
- Energy loss dE/dx = 10.2 MeV/cm.
- Moliere radius = 1.959 cm.
TPEX Apparatus: Luminosity Monitor (GWU)

TPEX luminosity systematics:

- Magnetic Field → not relevant
- Beam position: $\sim 1/\sin\theta$
  
  $(0.21 \pm 0.01 \%/\text{mm})$
- Monitor position: $\sim 1/\sin\theta$
  
  $(0.0235 \pm 0.0004 \%/\text{mm})$
1. CH110-LT cryocooler (25 W at 20 K)
2. hydrogen supply and exhaust lines
3. condenser with a cooling loop
4. target cell

Total heat load (Radiation + Beam) < 4 W
1. top block with liquid hydrogen level sensor;
2. target cell with long channel on top to help the release of bubbles from LH$_2$;
3. bottom block with temperature sensor and heater

Q$^2 \leq 4.57$ (GeV/c)$^2$ requires LH$_2$ target:
- max beam current:
  - 60 nA (e$^-$), 30 nA (e$^+$)
- 20-cm long LH2 target:
  \[ L_{\text{avg}} = 2.1 \times 10^{-4} \text{ fb-1 s}^{-1} \] (~200 x OLYMPUS)

all components are made of aluminum!
Further TPEX Design Upgrade: GEMs (Hampton)

- 2x GEM planes in front of calorimeter.
- Provide tracking between target vertex and point of incidence on calorimeter.
- Could help to almost double acceptance and suppress backgrounds.

[credit to Patrick Moran (MIT) & Michael Kohl (Hampton)]
TPEX Expectations/ Uncertainties

![Graphs showing TPEX Expectations/ Uncertainties for 2 GeV and 3 GeV beams.](image)

- **2 GeV Beam**
  - Data points and error bars for various models (Bernauer, Kuraev, Schmidt, Afanasev, Blunden, OLYMPUS).
  - Models are represented by different colors: red, orange, green, blue, and gray.

- **3 GeV Beam**
  - Data points and error bars for the projected TPEX.
  - Models are represented similarly to the 2 GeV beam.

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**References**

- Bernauer, Kuraev, Schmidt, Afanasev, Blunden.

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**Institutional Logos**

- University of Michigan
- DESY
TPEX Collaboration - 15 Institutions, 40 Collaborators (13 OLYMPUS)

- Arizona State University, Tempe, AZ, USA
- Catholic University of America, Washington, DC, USA
- Charles University, Prague, Czech Republic
- Deutsches Elektronen-Synchrotron, Hamburg, Germany
- Friedrich Wilhelms Universitat, Bonn, Germany
- George Washington University, Washington, DC, USA
- Hampton University, Hampton, VA, USA
- Johannes Gutenberg Universitat, Mainz, Germany
- Massachusetts Institute of Technology, Cambridge, MA, USA
- Riken BNL Research Center, Upton, NY, USA
- Stony Brook University, Stony Brook, NY, USA
- University of Glasgow, Glasgow, Scotland
- University of Michigan, Ann Arbor, MI, USA
- University of Zagreb, Zagreb, Croatia
- University of Manitoba, Winnipeg, Canada

Thank you!