Measurement of the two-photon exchange contribution in elastic $e^\pm p$ scattering at the VEPP–3 storage ring


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Workshop “Scattering and annihilation electromagnetic processes”
The EM form factors are essential ingredients of our knowledge of the nucleon structure and this justifies the efforts devoted to their experimental determination.

In the one-photon (Born) approximation:

\[ \Gamma^\mu(q) = \gamma^\mu F_1(q^2) + i\sigma^{\mu\nu}q_\nu F_2(q^2) \]

- \( F_1(q^2) \) – non-spin-flip Dirac form factor
- \( F_2(q^2) \) – spin-flip Pauli form factor

Nucleon current operator \( \Gamma^\mu(q) \)

In non-relativistic limit \( G_E \) and \( G_M \) describe charge and magnetization distribution in nucleon.

Sachs form factors

- Electric form factor
  \[ G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{4M} F_2(Q^2) \]
- Magnetic form factor
  \[ G_M(Q^2) = F_1(Q^2) + F_2(Q^2) \]

\[ G_E \approx G_M/\mu_p \approx G_D \equiv (1 + Q^2/0.71)^{-2} \]
Measurements of the proton form factors

- Study with elastic $ep$ scattering
- The Rosenbluth separation method at constant $Q^2$

**Rosenbluth Formula**

\[
\frac{d\sigma}{d\Omega} = \frac{1}{\varepsilon(1 + \tau)} \left[ \varepsilon G_E^2 + \tau G_M^2 \right] \frac{d\sigma_{\text{Mott}}}{d\Omega},
\]

where $\tau = Q^2/4M^2$ and $\varepsilon = \left[ 1 + 2(1 + \tau) \tan^2(\theta/2) \right]^{-1}$

- Polarized beams and targets and recoil polarimeters

**Form factor ratio from polarization transfer**

\[
\frac{G_E}{G_M} = \frac{P_T}{P_L} \times K,
\]

where $P_T$ and $P_L$ - transverse and longitudinal polarization components of proton,

\[
K = -\sqrt{\tau(1 + \varepsilon)}/2\varepsilon - \text{kinematic factor}
\]
Clear discrepancy between the two experimental data sets is observed.
Inconsistency?

Rosenbluth separation:
- Walker (1994), global analysis
- Qattan (2005)

Polarization transfer:
- Gayou (2002), Puckett (2012)
- Puckett (2010)

\(-q^2, \text{GeV}^2\)

\(\mu_p G_E/G_M\)

Clear discrepancy between the two experimental data sets is observed.

Radiative corrections, in particular, a hard Two-Photon Exchange (TPE) is a likely origin of the discrepancy.
Example of calculation of the TPE contribution


If this model is correct, the contradiction in the measurements of $G_E^p/G_M^p$ will be eliminated!
Radiative corrections to elastic $ep$ scattering

“Elastic” scattering ($e^{\pm}p \rightarrow e^{\pm}p$):

$\mathcal{M}_{\text{Born}}$

$\mathcal{M}_{2\gamma}$

$\mathcal{M}_{\text{vac}}$

$\mathcal{M}_{\ell \text{ vert}}$

$\mathcal{M}_{p \text{ vert}}$

Bremsstrahlung ($e^{\pm}p \rightarrow e^{\pm}p\gamma$):

$\mathcal{M}_{\ell \text{ brems}}$

$\mathcal{M}_{p \text{ brems}}$

$\sigma(e^{\pm}p) = |\mathcal{M}_{\text{Born}}|^2 \pm 2 \text{Re} \left( \mathcal{M}_{\text{Born}}^{\dagger} \mathcal{M}_{2\gamma} \right) +$

$+ 2 \text{Re} \left( \mathcal{M}_{\text{Born}}^{\dagger} \mathcal{M}_{\text{vac}} \right) + 2 \text{Re} \left( \mathcal{M}_{\text{Born}}^{\dagger} \mathcal{M}_{\ell \text{ vert}} \right) + 2 \text{Re} \left( \mathcal{M}_{\text{Born}}^{\dagger} \mathcal{M}_{p \text{ vert}} \right) +$

$+ |\mathcal{M}_{\ell \text{ brems}}|^2 + |\mathcal{M}_{p \text{ brems}}|^2 \pm 2 \text{Re} \left( \mathcal{M}_{\ell \text{ brems}}^{\dagger} \mathcal{M}_{p \text{ brems}} \right)$

✓ Cancellation of infrared divergences (corresponding terms are marked in color)

✓ Some of the terms are of different signs ("\pm") for $e^+p$ and $e^-p$ scattering
Direct measurement of TPE

Method of direct measurement of TPE:

Measure the ratio of positron-proton to electron-proton elastic scattering cross-section ⇒ interference term is extracted:

\[ R = \frac{\sigma(e^+p)}{\sigma(e^-p)} \approx 1 + 4 \frac{\Re \left( M^\dagger_{\text{Born}} M_{2\gamma} \right)}{|M_{\text{Born}}|^2} \]

- Experimental data – from 1960-th
- Many theoretical/phenomenological approaches, producing clearly different results
- New precise data, especially for \( \varepsilon \leq 0.5 \) are required to verify the models
Three experiments aimed at measuring the ratio $R$

- Novosibirsk experiment ($E_{\text{beam}} = 1.6, 1.0$ and $0.6$ GeV)
- CLAS @ JLab experiment ($E_{\text{beam}} = 0.5 ÷ 4$ GeV)
- OLYMPUS @ DESY experiment ($E_{\text{beam}} = 2$ GeV)
OLYMPUS experiment at DESY

- First month-long run in Feb 2012
- Another run: Oct – Dec 2012
TPE experiment at CLAS (JLab Hall B)

Data taking completed in Feb-2011
Very preliminary results reported

- **Primary electron beam:** 5.5 GeV and 100 nA
- **Radiator:** 0.9% of primary electrons radiate high energy photons
- **Tagger magnet:** Transport electrons tagger dump
- **Converter:** 9% of photons are converted to electron/positron pairs
- **Chicane:** separate the lepton beams
  - Remaining photons are stopped at the photon blocker
  - $e^+$ and $e^-$ beams are then recombined and continue to the target
- **Target:** liquid hydrogen: length = 18cm (30 cm) & diameter = 6cm (6 cm)
- **Detector:** CLAS (DC, TOF)
### Comparison of three TPE experiments

<table>
<thead>
<tr>
<th></th>
<th>VEPP-3 Novosibirsk</th>
<th>OLYMPUS DESY</th>
<th>EG5 CLAS JLab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>3 fixed</td>
<td>1 fixed</td>
<td>wide spectrum</td>
</tr>
<tr>
<td>equality of $e^\pm$ beam energy</td>
<td>measured precisely</td>
<td>assumed (measured?)</td>
<td>reconstructed</td>
</tr>
<tr>
<td>$e^+/e^-$ swapping frequency</td>
<td>half-hour</td>
<td>8 hours</td>
<td>simultaneously</td>
</tr>
<tr>
<td>$e^+/e^-$ lumi monitor</td>
<td>elastic low-$Q^2$</td>
<td>elastic low-$Q^2$, Möller/Bhabha</td>
<td>from simulation</td>
</tr>
<tr>
<td>energy of scattered $e^\pm$</td>
<td>EM-calorimeter</td>
<td>mag. analysis</td>
<td>mag. analysis</td>
</tr>
<tr>
<td>proton PID</td>
<td>$\Delta E/E$, TOF</td>
<td>mag. analysis, TOF</td>
<td>mag. analysis, TOF</td>
</tr>
<tr>
<td>$e^+/e^-$ detector acceptance</td>
<td>identical</td>
<td>big difference</td>
<td>big difference</td>
</tr>
<tr>
<td>luminosity</td>
<td>$1.0 \times 10^{32}$</td>
<td>$2.0 \times 10^{33}$</td>
<td>$2.5 \times 10^{32}$</td>
</tr>
<tr>
<td>systematic error</td>
<td>$&lt; 0.3%$</td>
<td>1%</td>
<td>1%</td>
</tr>
</tbody>
</table>

- Novosibirsk experiment is inferior to the other two in experimental luminosity and in quality of particle ID;

- However, the detector performance is sufficient for reliable identification of elastic scattering events;

- Non-magnetic detector, measurement of beams energy, frequent swapping of $e^+/e^-$ beams allow lowest systematic error;

- Novosibirsk is the first to provide results on precise measurement of $R(e^\pm p)$ ratio.
Milestones of the Novosibirsk experiment

- The proposal was published (Aug 2004): nucl-ex/0408020

### Data taking:

<table>
<thead>
<tr>
<th>Run</th>
<th>Duration</th>
<th>$E_{\text{beam}}$, GeV</th>
<th>Number of $e^+e^-$ cycles</th>
<th>$\int$ luminosity, pb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering run</td>
<td>May–Jul 2007</td>
<td>1.6</td>
<td>90</td>
<td>12</td>
</tr>
<tr>
<td>Run I</td>
<td>Sep–Dec 2009</td>
<td>1.6</td>
<td>1100</td>
<td>324</td>
</tr>
<tr>
<td>Run II</td>
<td>Sep 2011 – Mar 2012</td>
<td>1.0</td>
<td>2350</td>
<td>600</td>
</tr>
<tr>
<td>Run III</td>
<td>Apr 2012</td>
<td>0.6</td>
<td>220</td>
<td>18</td>
</tr>
</tbody>
</table>

- Some preliminary results were published (Dec 2011): arXiv:1112.5369

Measurement of the two-photon exchange contribution in elastic $ep$ scattering at VEPP-3,


To appear in the proceedings of Conference: C11-09-19


- Final results of the data analysis are expected in 2013
Novosibirsk experiment at the VEPP-3 storage ring

A precision measurement of the ratio \( R = \sigma(e^+p)/\sigma(e^-p) \) at the VEPP-3 storage ring at the energy of electron/positron beams of 1.6 GeV (run I), 1.0 GeV (run II) and 0.6 GeV (run III).

Kinematic parameters of three runs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Run I</th>
<th>Run II</th>
<th>Run III</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\text{beam}}, \text{GeV} )</td>
<td>1.6</td>
<td>1.0</td>
<td>0.6</td>
</tr>
<tr>
<td>( \int l_{\text{beam}} dt, \text{kC} )</td>
<td>54</td>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>( \theta_\ell, ^\circ )</td>
<td>55÷75</td>
<td>15÷25</td>
<td>8÷15</td>
</tr>
<tr>
<td>( Q^2, \text{GeV}^2 )</td>
<td>1.26÷1.68</td>
<td>0.16÷0.41</td>
<td>0.05÷0.16</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>0.37÷0.58</td>
<td>0.90÷0.97</td>
<td>0.97÷0.99</td>
</tr>
<tr>
<td>( \Delta R/R, \text{stat.} )</td>
<td>1.1%</td>
<td>0.1%</td>
<td>—</td>
</tr>
</tbody>
</table>

The smallest angle regions were used for luminosity monitoring only.
VEPP–3 is a booster for the VEPP–4M electron-positron collider.

**VEPP–3 parameters for $e^-$ beam:**

- **Electron energy** $E_0$ 2 GeV
- **Mean beam current** $I_0$ 150 mA
- **Energy spread** $\Delta E/E$ 0.05%
- **RF HV magnitude** $U_{72}$ 0.8 MV
- **Revolution period** $T$ 248.14 ns
- **Bunch length** $\sigma_L$ 15 cm
- **Vertical beam size** $\sigma_z$ 0.5 mm
- **Horizontal beam size** $\sigma_x$ 2.0 mm
- **Vert. $\beta$-function** $\beta_z$ 2 m
- **Horiz. $\beta$-function** $\beta_x$ 6 m
- **Injection beam energy** $E_{\text{inj}}$ 350 MeV
- **Injection rate** $\dot{I}_{\text{inj}}$ $1.5\cdot10^9$ s$^{-1}$

*parameters in the center of 2nd straight section (in Internal Target Area)*

Largest $e^+$ current: 60 mA
target thickness \(= \frac{1}{2} \cdot 10^{15} \text{ at/cm}^2\)
Detector package for the run I

- Plastic scintillators
- Drift chambers
- Proportional chambers
- e^+/e^- beam $E = 1.6$ GeV
- Storage cell (H$_2$ target)
- Aperture counters
- Sandwiches at small angle

**Distance:**
- 8.3 $X_0$
- 10.6 $X_0$
- 0.5 m
Detector package for the runs II, III

- NaI
- CsI
- Drift chambers
- Proportional chambers
- $\pi^+$ beam
- $E = 1$ GeV
- Storage cell (hydrogen target)
- Scintillators (polystyrene)

0.5 m
Detector and target at VEPP–3
Selection of the elastic scattering events

- Correlations characteristic for two-body final state:
  - Correlation between polar angles ($\theta_{e\pm}$ vs. $\theta_p$)
  - Correlation between azimuthal angles ($\phi_{e\pm}$ vs. $\phi_p$)
  - Correlation between lepton scattering angle and proton energy ($\theta_{e\pm}$ vs. $E_p$)
  - Correlation between lepton scattering angle and electron energy ($\theta_{e\pm}$ vs. $E_{e\pm}$)

- Particle ID:
  - Time-Of-Flight analysis for low-energy protons
  - $\Delta E - E$ analysis for middle-energy protons
  - Energy deposition in EM-calorimeter for electrons/positrons
MC simulation of the standard radiative corrections

- Standard prescription with soft-photon/peaking approximation is not applicable. Detailed Monte Carlo simulation with a dedicated event generator is mandatory.
- New event generator ESEPP is applied to the Monte-Carlo detector simulation using the Geant4 software package.

Angular correlations:

**Θ-angles correlation**

![Theta-angle correlation graph](image)

**Φ-angles correlation**

![Phi-angle correlation graph](image)
MC simulation of background processes

- **GEANT4** detector model
- **MAID2007** and **2-PION-MAID** based event generator for single- and double-pion electro-production
- **ESEPP** event generator for elastic \( ep \) scattering with bremsstrahlung

Spectrum of missed mass, reconstructed from energy and direction of electron (for \( E_{e^\pm} = 1 \text{ GeV} \)), after cuts on \((\Delta \phi, \Delta \theta)\) applied:

![Graph showing data and MC simulation for different processes](image)

- \( e p \rightarrow e' p (\gamma) \)
- \( e p \rightarrow e' n \pi^+ \)
- \( e p \rightarrow e' p \pi^0 \)
- \( \gamma^* p \rightarrow n \pi^+ \)
- \( \gamma^* p \rightarrow p \pi^- \pi^+ \)
- MC Total

DATA and ESEPP+MAID2007+GEANT4 when all cuts applied:

- \( \Delta \phi, \Delta \theta < 6.0^\circ \)
MC simulation of background processes

- **GEANT4** detector model
- **MAID2007** and **2-PION-MAID** based event generator for single- and double-pion electro-production
- **ESEPP** event generator for elastic \( ep \) scattering with bremsstrahlung

Spectrum of missed mass, reconstructed from energy and direction of electron (for \( E_{e^\pm} = 1 \text{ GeV} \)), after cuts on \((\Delta \phi, \Delta \theta)\) applied:

\[
\begin{array}{c}
\text{DATA and ESEPP+MAID2007+GEANT4} \\
\end{array}
\]

\[
\begin{array}{c}
\Delta \phi, \Delta \theta < 3.0^\circ \\
\end{array}
\]

- \( e^+ p \rightarrow e^+ p (\gamma) \)
- \( e^+ p \rightarrow e^+ n \pi^+ \)
- \( e^+ p \rightarrow e^+ p \pi^0 \)
- \( \gamma^* p \rightarrow n \pi^+ \)
- \( \gamma^* p \rightarrow p \pi^- \pi^+ \)
- **MC Total**

\[
\begin{array}{c}
\text{DATA} \\
\end{array}
\]

**when all cuts applied:** \( N_{\text{background}} / N_{\text{elastic}} < 1.5\% \)
Suppression of the systematics: alternation of $e^-$ and $e^+$

- Data collection with $e^-$ and $e^+$ beams was alternated regularly. This allows us to suppress effects of slow drift in time of the target thickness, detection efficiency and some other parameters.
- One cycle ($e^-$ and $e^+$ beams) per 1 hour approximately.
- Starting and ending values of beam currents and beam lifetime for $e^-$ and $e^+$ beams in each cycle were kept as close as possible.

Contribution to the systematic error: $< 0.2\%$
Suppression of the systematics: beam position

- Using the VEPP–3 beam orbit stabilization system.
- Continuous measurement of the beam position at the entrance and exit of the experimental section by pick-up electrodes.
- Periodical “absolute” beam position measurements using movable shutters.
- Determination of beam position in the target from data analysis.

Measurement of beam position by the 2P3 pick-up electrode:

Contribution to the systematic error: < 0.2%

Alexander Gramolin
Suppression of the systematics: beam energy

- Reconstruction of beam energy from the energy spectrum of laser photons backscattered on beam particles.

\[ E_{\text{beam}} = 0.5 \cdot \omega_{\text{max}} \cdot \left( 1 + \sqrt{1 + \frac{m_e^2}{\omega_0 \omega_{\text{max}}}} \right) \]

- This allows us to tune the VEPP–3 operation regimes and to monitor the beams energy during the experiment.

VEPP–3 energy measurement

Contribution to the systematic error: < 0.1%
Suppression of the systematics: beam energy

- Reconstruction of beam energy from the energy spectrum of laser photons backscattered on beam particles.

\[ E_{\text{beam}} = 0.5 \cdot \omega_{\text{max}} \cdot \left( 1 + \sqrt{1 + \frac{m_e^2}{\omega_0 \omega_{\text{max}}}} \right) \]

- This allows us to tune the VEPP–3 operation regimes and to monitor the beams energy during the experiment.

Total systematic error is < 0.3%

Contribution to the systematic error: < 0.1%
Beam integral collection during run I and run II

Beam integral per shift, C

Beam integral collection, run I

Day of year-2009
24/09 01/10 08/10 15/10 22/10 29/10 05/11 12/11 19/11 26/11 03/12 10/12 17/12 24/12 31/12
Beam integral collection, run I day night
Total beam integral, kC
0
54.27 kC

Beam integral per shift, C

Beam integral collection, run II

Day of year-2011/2012
24/09 08/10 22/10 05/11 19/11 03/12 17/12 31/12 14/01 28/01 11/02 25/02 10/03
Beam integral collection, run II day night
Total beam integral, kC
0
99.90 kC
Raw ratio $R$ during the run I and run II

For $E_\text{e} = 1.6$ GeV:
- $\chi^2$/ndf = 8.94
- P1: $1.062 \pm 0.1138 \times 10^{-1}$

For $E_\text{e} = 1$ GeV:
- $\chi^2$/ndf = 30.27
- P1: $1.046 \pm 0.3237 \times 10^{-2}$

Graphs showing the variation of $R^{\pm}_{\text{raw}}$ with $N_{\text{cycle}}$.
The experimentally measured ratio $R$ before (left figure) and after (right figure) taking into account the radiative corrections (FF model). Red markers correspond to the cut $\Delta \theta = \Delta \phi = 3^\circ$ on the angular correlations, blue markers correspond to the cut $\Delta \theta = \Delta \phi = 6^\circ$ (data for LA range of the Run II).
Preliminary results of the Novosibirsk TPE experiment

Run I (2009):
\[ E_{\text{beam}} = 1.6 \text{ GeV} \]

Run II (2011–2012):
\[ E_{\text{beam}} = 1 \text{ GeV} \]


- Only statistical errors are shown.
- The radiative corrections are taken into account.
- Some minor corrections have not yet been made.
Conclusion

- The first precision measurement of the ratio $R = \sigma(e^+ p)/\sigma(e^- p)$ has been performed. Data taking has been completed, analysis is in progress.
- Systematic errors in VEPP-3 experiment is expected to be lower than those at OLYMPUS and CLAS TPE experiments.
- It is very important to carefully consider the standard radiative corrections. Procedure of account for RC has been developed (ESEPP event generator + Geant4 detector simulation).
- Preliminary results are presented. They are pretty consistent with the theoretical predictions by Blunden et al.
- Final results of the experiment will be published this year.

Support

This work was supported by Ministry of Education and Science of the Russian Federation; RFBR grants: 08-02-00624-a, 08-02-01155-a, 12-02-33140; Russian Federal Agency for Education, State Contract P522; Russian Federal Agency for Science and Innovation, Contracts: 02.740.11.0245.1, 14.B37.21.1181; US DOE grant: DE-AC02-06CH11357; US NSF grant: PHY-03-54871
Thank you for your attention!
Backup slides

Uses modified Rosenbluth separation technique, detecting proton: *black points*
Asymmetry $A$ and ratio $R$ for the cross sections

\[ A = \frac{\sigma(e^+p) - \sigma(e^-p)}{\sigma(e^+p) + \sigma(e^-p)} \quad R = \frac{\sigma(e^+p)}{\sigma(e^-p)} \]

How are they related?

\[ A = \frac{R - 1}{R + 1} \approx \frac{R - 1}{2} \quad R = \frac{1 + A}{1 - A} \approx 1 + 2A \]

After taking into account the radiative corrections:

\[ A \approx 2 \frac{\Re \left( \mathcal{M}_{\text{Born}}^\dagger \mathcal{M}_{2\gamma} \right)}{|\mathcal{M}_{\text{Born}}|^2} \quad R \approx 1 + 4 \frac{\Re \left( \mathcal{M}_{\text{Born}}^\dagger \mathcal{M}_{2\gamma} \right)}{|\mathcal{M}_{\text{Born}}|^2} \]

How to take into account the radiative corrections?

\[ A = A_{\text{exp}} - A_{\text{MC}} \quad (\text{exp} = \text{experimental}, \quad \text{MC} = \text{Monte Carlo}) \]

\[ R = \frac{R_{\text{exp}}R_{\text{MC}} + 3R_{\text{exp}} - R_{\text{MC}} + 1}{R_{\text{exp}}R_{\text{MC}} - R_{\text{exp}} + 3R_{\text{MC}} + 1} \approx R_{\text{exp}} - R_{\text{MC}} + 1 \]

The asymmetry is more natural, but the ratio is used more often.