Two-photon exchange and elastic scattering of positrons/electrons on the proton.

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COLLABORATION

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The proton electro-magnetic form factors (EMFF) are of fundamental importance for the understanding of its internal structure. Long time they were determined from the analysis of differential cross sections of the elastic ($ep$)-scattering. The EMFF can be identified with the Fourier transform of the nucleon charge and magnetization density distributions.

Figure from:
C. Hyde-Wright and . de Jager
Separation of form factors by Rosenbluth method.
(one–photon approximation, assuming $P$– and $T$–invariance formula)

\[ \sigma_{red} = \tau G_M^2 + \varepsilon G_E^2 \]

\[ \varepsilon = \frac{1}{1 + 2(1+\tau) \tan^2 \theta/2} \]

\[ \tau = \frac{Q^2}{4M^2} \]
At the mid-90's in the study of the proton form factors was the development of methods of polarization experiments. It was found that the new and old methods give conflicting results.

\[
\sigma_R \equiv \frac{d\sigma}{d\Omega} \frac{\varepsilon (1 + \tau)}{\sigma_{\text{Mott}}} = \tau \, G_{pM}^2(Q^2) + \varepsilon \, G_{pE}^2(Q^2)
\]

Rosenbluth, 1950

\[
\frac{G_{pE}}{G_{pM}} = -\frac{P_t}{P_1} \frac{(E_e + E_{e'}) \tan(\theta_e/2)}{2M_p}
\]

Akheizer and Rekalo, 1974
Arnold, Carlson and Gross, 1981
To verify, in TJNAF the new measurements by Rosenbluth method were performed, which confirmed the results of the old Rosenbluth measurements.


Recently the results of new TJNAF polarization measurements are published, which confirmed the existence of the problem.

Figure from
A.J.R. Puckett *et al*
As a reason of disagreement often called the invalidity of the one-photon approximation when interpreting the results differential cross section measurements. Consideration of the corrections of two-photon exchange, however, encounters difficulties, both theoretical and experimental character.

\[
\sigma = (1\gamma)^2 \alpha^2 + (1\gamma)(2\gamma)\alpha^3 + \ldots
\]

\[
e^{-} \leftrightarrow e^{+} \Rightarrow \alpha \leftrightarrow -\alpha
\]

\[
\sigma(\text{electron-proton}) = (1\gamma)^2 \alpha^2 - (1\gamma)(2\gamma)\alpha^3 + \ldots
\]

\[
\sigma(\text{positron-proton}) = (1\gamma)^2 \alpha^2 + (1\gamma)(2\gamma)\alpha^3 + \ldots
\]

\[
R^{e^{+}/e^{-}} = \frac{\sigma(e^+p)}{\sigma(e^-p)} = 1 + (2\alpha) \frac{2\gamma}{1\gamma}
\]
The problem caused the appearance of many new theoretical work performed in
the various approaches


etc.

as well as the suggestions of new experiments for the determination of two-photon
exchange contribution through the measurement $R_{e^+/e^-}$, since old data of 60th
are not accurate enough.

Novosibirsk/VEPP-3  TJNAF/CLAS/PR04-116  OLYMPUS: DORIS/BLAST
Proposal for VEPP-3 storage ring.


$e^+/e^-\text{ beams energy } 1.6\ \Gamma\text{eV,}\n$ $e^+/e^-\text{ scattering angles }\theta \approx 10^\circ, 20^\circ, 60^\circ$

Projected uncertainty (blue circles) for the proposed measurement

Note that the previous measurements have an average $Q^2$ value of approximately $0.5 \text{ GeV}^2$ for the data below $\epsilon = 0.5$, and thus should have a smaller TPE contribution than the proposed measurement. The dashed line is a linear fit to the combined worlds data on $R$, and yields a slope of $-(5.7 \pm 1.8)\%$

$$\epsilon = (1+2(1+\tau)\tan^2(\theta/2))^{-1}$$

$$\tau = \frac{Q^2}{4M}$$
Schematic side view of the particle detection system.

- Plastic scintillators
- Drift chambers
- Proportional chambers
- Storage cell (H₂ target)

Small angles: aperture counters sandwiches

E⁺/E⁻ beam $E = 1.6$ GeV

- $10.6 \times X_0$
- $8.3 \times X_0$

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Photo of the detector and the target are installed at the VEPP-3
Hydrogen gas target

Storage cell: 13 x 24 x 400 mm³
Typical picture of the $e^+/e^-$ currents of VEPP-3 during data taking.
Accumulation of integral beam current VEPP-3 during the experiment.
Selection of the elastic $e-p$ scattering events

1. Correlation between polar angles
2. Correlation between azimuthal angles
3. Correlation between electron scattering angle and proton energy
4. Correlation between electron scattering angle and electron energy
5. $\Delta E-E$ analysis
6. Time–of–flight analysis for proton with low energy

LA events

MA events

SA events

$A$, arb un

$\tau$, ns

$\Theta_e, \Theta_p, (\phi)$
Event selection.

\[ \phi - \text{angles correlation} \]

Entries 77505

\[ \varphi_{e} - \varphi_{p}, \ deg \]

\[ \sigma = 0.7^\circ \]

\[ \theta_{p} - \theta_{p}(e), \ deg \]

\[ \sigma = 0.8^\circ \]

Energy in LA calorimeter

\[ N_{e}, \ LA \]

\[ \Delta E_{e}/E_{e}^0 = 14\% \]

DATA blue

GEANT4 red
Back Compton scattering set up for measurement energy of $e^+/e^-$ beams.
Beams energy measurements during experiment and $E_e$ corrections.

Two-photon exchange and $(e^+p)/(e^-p)$

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The information on the $e^+/e^-$ beam positions came from three sources:

1. Beam position monitors of VEPP-3. They are located rather far from the target center and give only information on beams position stability.

2. Four beam scrapers. They are located more close to the target and provide the information about absolute position of beams. But they are rarely used because with them the data taking should be interrupted.

3. Coordinate systems of the detector give the possibility in the off-line regime to determine both the horizontal and the vertical relative shift of $e^+/e^-$ beams with an accuracy of $\sim 0.1$ mm
The measurement of differences in the vertical position $e^+ / e^+$ beams on the events SA scattering.
Dependence counting rate of the detectors from vertical shift of the beam.
Dependence counting rate of the detectors from vertical shift of the beam.

absolute position $0.5 \pm 0.2 \text{ mm}$

with $\Delta Z_{e^+/e^-} = 0.1 \text{ mm}$

$\Delta (N1+N2) / (N1+N2) = 0.12 \%$
Raw ratio $R^{e+}/e^-$ (no corrections) for MA and LA, both are monitoring to SA.

**MA with monitoring to SA**

$R = 1.00412 \pm 0.00094$

**LA with monitoring to SA**

$R = 1.057 \pm 0.011$
Radiative corrections for $ep$ scattering.

**Born**

Bremsstrahlung

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Two-photon exchange and $(e^+p) / (e^-p)$

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Radiative corrections with real photons emission, integration on photon angles.

\[ E_e = 1.6 \text{ GeV} \]

\[ R \text{ vs } \theta_e \text{ by Maximon&Tjon, PRC 62 (2000) 054320} \]

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

\[ Q^2, \text{ GeV}^2 \]

\[ \Theta_e, \text{ degree} \]
Soft Photon Approximation (SPA)

Reaction:

\[ k + p = k' + p' + \omega, \]

where \( k, k' \) — initial and final lepton four-momenta, \( p, p' \) — initial and final proton four-momenta, \( \omega \) — photon four-momentum.

\[ \omega^0 \ll |\vec{k}|, |\vec{k'}|, |\vec{p'}| \]

In this case, the total cross section for single-photon bremsstrahlung is given by

\[
\frac{d\sigma}{d\Omega_e \ d\Omega_{\gamma} \ d\omega^0} = \left. \frac{d\sigma^{(1)}}{d\Omega_e} \right|_{ep} \frac{-\alpha \omega^0}{4\pi^2} \left[ \pm \frac{k'}{\omega \cdot k'} - \frac{p'}{\omega \cdot p'} \mp \frac{k}{\omega \cdot k} + \frac{p}{\omega \cdot p} \right]^2,
\]

where

\[
\left. \frac{d\sigma^{(1)}}{d\Omega_e} \right|_{ep}
\]

is the one-photon exchange (Born) electron-proton cross section. The first and third terms in brackets have different signs in the case of \( e^- p \) and \( e^+ p \) scattering.
SPA, dependence on emission photon angle.

$E_e = 1.6 \text{ GeV}$
$\Theta_e = 60^\circ$
$E_{\gamma} > 100 \text{ MeV}$

- Blue: $\text{e}^-$
- Red: $\text{e}^+$

$\Theta_{\gamma}$, $^\circ$
SPA, LA, GEANT4, dependence cuts on the correction for $R^{e+/e-}$.

<table>
<thead>
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<th>Cuts</th>
<th>Correction for $R^{e+/e-}$</th>
<th>Cuts:</th>
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<td>$C_{\phi} C_{\theta} C_E$</td>
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More correct calculation of radioactive corrections (V. Fadin and A. Feldman, Private communication), where no restriction on the photon energy and also proton form factor is taken into account, will be used soon.
Preliminary result for $R^{e^+/e^-}$ in comparison with calculations of P.G. Blunden et al.

$\varepsilon = 0.58, \, Q^2 = 1.43 \, \text{GeV}^2$
Conclusion.

1. Experiment on a precise comparison \((e^+ p)\) and \((e^- p)\) scattering cross sections had performed.

2. The preliminary result is in agreement with the TPE hadron calculations of P.G. Blunden et al.