What is so puzzling about the electric charge of the proton?

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Outline

**Proton** electric and magnetic form factors $G_E$ and $G_M$ describe the charge and magnetization

- Introduction, motivation and formalism
- Traditional and new techniques
- Overview of experimental data

**High $Q^2$: Energy frontier**
- Proton form factor ratio
- Transition to pQCD
- **Two-photon exchange: $G_E(Q^2)$ uncertain**

**Low $Q^2$: Precision frontier**
- Pion cloud effect
- Deviations from dipole form
- **The Proton Radius Puzzle: 7σ discrepancy**

A. Thomas, W. Weise, The Structure of the Nucleon (2001)
Nucleon elastic form factors ...

- Fundamental quantities
  - Defined in context of single-photon exchange

- Describe internal structure of the nucleons
  - Related to spatial distribution of charge and magnetism

- Rigorous tests of nucleon models
  - Determined by quark structure of the nucleon
  - Role of orbital angular momentum and diquark correlation
  - Ultimately calculable by Lattice-QCD
  - Input to nuclear structure and parity violation experiments

50 years of ever increasing activity

- Tremendous progress in experiment and theory over last decade
  - New techniques / polarization experiments
  - Unexpected results
### Present form factor and TPE experiments

**Recoil polarization and polarized target**
- 2-Gamma – $\varepsilon$ dependence of recoil pol. – published (2011)
- E08-007 – low-$Q^2$ recoil polarization – published (2011)
- E08-007 – low-$Q^2$ polarized target – analysis in progress
- SANE – high-$Q^2$ polarized target – to be published
- GEp-V (& GMp) – high $Q^2$ at Jlab-12 – proposed

**Rosenbluth separation**
- Super-Rosen – high-$Q^2$ Rosenbluth – analysis in progress

**Positron-electron comparisons**
- Novosibirsk/VEPP-3
- CLAS/Jlab
- OLYMPUS/DESY – completed, analysis started

**Proton radius measurements**
- MAMI / A1 (e-scattering) – published (2010) + proposed
- Jlab / PRad (e-scattering) – proposed
- PSI / MUSE (e$^\pm$, $\mu^\pm$ scattering) – proposed
Hadronic structure and EM interaction

Factorization!

\[ |\text{Form factor}|^2 = \frac{\sigma(\text{structured object})}{\sigma(\text{pointlike object})} \]

One-Photon Exchange Approximation
Lepton scattering from a nucleon:

\[ \mu^\pm, e^\pm \]

\[ N \]

\[ \gamma \]

Vertex currents:

\[ J^\mu_e = -e \bar{u}_e \gamma^\mu u_e \]

\[ J^\mu_N = \bar{\psi}_N \left[ F_1(Q^2)\gamma^\mu + F_2(Q^2) \frac{i\sigma^{\mu\nu}q_\nu}{2M_N} \right] \psi_N \]

F\(_1\), F\(_2\) are the Dirac and Pauli form factors

Sachs form factors:

\[ G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2) \]

\[ G_M(Q^2) = F_1(Q^2) + F_2(Q^2) \]

Fourier transform (in the Breit frame) gives spatial charge and magnetization distributions

Derivatives in \( Q^2 \to 0 \) limit: Radii

\[ \langle r_E^2 \rangle = -6 \left. \frac{dG_E^p(Q^2)}{dQ^2} \right|_{Q^2 \to 0} \]

\[ \langle r_M^2 \rangle = -6 \left. \frac{dG_M^p(Q^2)/\mu_p}{dQ^2} \right|_{Q^2 \to 0} \]
The beginnings

Robert Hofstadter
Nobel prize 1961

ep-elastic
finite size of the proton
$R_p \sim 0.8 \text{ fm}$

R. Hofstadter, Rev. Mod. Phys. 56 (1956) 214

Fig. 26. Typical angular distribution for elastic scattering of 400-Mev electrons against protons. The solid line is a theoretical curve for a proton of finite extent. The model providing the theoretical curve is an exponential with $\text{rms radii} = 0.80 \times 10^{-18} \text{ cm}$.

ed-elastic
Finite size + nuclear structure

Fig. 31. Introduction of a finite proton core allows the experimental data to be fitted with conventional form factors (McIntyre).
In One-photon exchange, form factors are related to radiatively corrected elastic electron-proton scattering cross section:

\[
\frac{d\sigma}{d\Omega} = S_0 = A(Q^2) + B(Q^2) \tan^2 \frac{\theta}{2}
\]

\[
= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1 + \tau} + 2\tau G_M^2(Q^2) \tan^2 \frac{\theta}{2}
\]

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

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

\[\Rightarrow \text{Determine } |G_E|, |G_M|, |G_E/G_M|\]
$G_{E}^p$ and $G_{M}^p$ from unpolarized data

Diagram showing $G_{E}^p / G_D$ and $G_{M}^p / \mu G_D$ as functions of $Q^2 / (\text{GeV}/c)^2$. The plots include data from various experiments such as Gittani (Jlab 2005), Christy (Jlab 2004), Andivahis (SLAC 1994), Walker (SLAC 1994), Simon (Mainz 1980), Borkowski (Mainz 1975), Murphy (Saskatoon 1974), Bartel (DESY 1973), Berger (Bonn 1971), Litt (SLAC 1970), Bartel (DESY 1967), and Janssens (SLAC 1966).
$G_p^E$ and $G_p^M$ from unpolarized data

- $G(Q^2)$ Fourier $\rho(r)$ charge and magnetization density (Breit fr.)
- Dipole form factor $G_D = \frac{1}{\left(1 + \frac{Q^2}{0.71}\right)^2} \quad \leftrightarrow \quad \rho_D(r) = \rho_0 e^{-\sqrt{0.71}r}$
- $G_p^E \approx G_p^M/\mu_p \approx G_n^M/\mu_n \approx G_D$ within 10% for $Q^2 < 10$ (GeV/c)$^2$
Double polarization in elastic $ep$ scattering:
Recoil polarization or (vector) polarized target

$^1H(e,e'p), \quad ^1H(e,e'p)$

Polarized cross section

$$\sigma = \sigma_0 \left(1 + P_e \vec{P}_p \cdot \vec{A}\right)$$

Double polarization observable = spin correlation

$$-\sigma_0 \vec{P}_p \cdot \vec{A} = \sqrt{2\tau \epsilon (1-\epsilon)} G_E G_M \sin \theta^* \cos \phi^* + \tau \sqrt{1 - \epsilon^2} G_M^2 \cos \theta^*$$

Asymmetry ratio (“Super ratio”)

$$\frac{P_\perp}{P_\parallel} = \frac{A_\perp}{A_\parallel} \propto \frac{G_E}{G_M}$$

independent of polarization or analyzing power
Proton form factor ratio

Jefferson Lab 2000–

- All Rosenbluth data from SLAC and Jlab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Multi-photon exchange considered best candidate

Dramatic discrepancy!

>800 citations
Polarized Target:
Independent verification of recoil polarization result is crucial

Polarized internal target / low $Q^2$: **BLAST**
$Q^2 < 0.65 (\text{GeV}/c)^2$ not high enough to see deviation from scaling

**RSS / Hall C:** $Q^2 \approx 1.5 (\text{GeV}/c)^2$

M.K. Jones et al., PRC74 (2006) 035201
Polarized Target:
Independent verification of recoil polarization result is crucial

Polarized internal target / low $Q^2$: BLAST
$Q^2 < 0.65 \text{(GeV/c)}^2$ not high enough to see deviation from scaling

RSS / Hall C: $Q^2 \approx 1.5 \text{(GeV/c)}^2$

SANE/Hall C: completed March 2009
BigCal electron detector
Recoil protons in HMS parasitically
$G_E/G_M$ at $Q^2 \approx 2.1$ and $5.7 \text{(GeV/c)}^2$

Decline of $G_E/G_M$ has been confirmed!

Future precision measurements at high $Q^2$ are feasible

A. Liyanage, M.K. et al., to be published
DNP2013 DH.00004
Effect of two-photon exchange

per constructionem, theorists sought mechanism that affects the “slope” in the Rosenbluth plot

At high $Q^2$, the contribution of $G_E$ to the cross section is of similar order as the TPE effect (few %)
Two-photon exchange: exp. evidence

Two-photon exchange theoretically suggested

TPE can explain form factor discrepancy

J. Arrington, W. Melnitchouk, J.A. Tjon,

Rosenbluth data with two-photon exchange correction

Polarization transfer data
Lepton-proton elastic scattering

Interference term depends on lepton charge sign (C-odd)

$$\sigma_{e^\pm p} = |M_{1\gamma}|^2 \pm 2 \Re\{M_{1\gamma}^\dagger M_{2\gamma}\} + \cdots$$

$e^+/e^-$ ratio deviates from unity by two-photon contribution

$$\frac{\sigma_{e^+ p}}{\sigma_{e^- p}} \approx 1 + 4 \frac{\Re\{M_{1\gamma}^\dagger M_{2\gamma}\}}{|M_{1\gamma}|^2}$$
Empirical extraction of TPE amplitudes

J. Guttmann, N. Kivel, M. Meziane, and M. Vanderhaeghen, EPJA 47 (2011) 77

$\varepsilon_{\text{min}}$ grows with $Q^2$!

Expect $\sim 6\%$ effect for OLYMPUS@2.0GeV

$Q^2 \sim 2.2 \ (\text{GeV/c})^2$
Projected results for OLYMPUS

Data from 1960’s

Many theoretical predictions with little constraint

OLYMPUS:
- E = 2.0 GeV
- 0.4 < Q^2/(GeV/c)^2 < 2.2
- Acquire 3.6 fb^{-1} for <1% projected uncertainties

Data taking completed in 2012
pOsitron-proton and eLectron-proton elastic scattering to test the hypothesis of Multi-Photon exchange Using DoriS
The OLYMPUS experiment

- Electrons/positrons (100mA) in 2.0–4.5 GeV storage ring DORIS at DESY, Hamburg, Germany

- Unpolarized internal hydrogen target (buffer system) $3 \times 10^{15}$ at/cm$^2$ @ 100 mA $\rightarrow L = 2 \times 10^{33}$ / (cm$^2$s)

- Large acceptance detector for e-p in coincidence BLAST detector from MIT-Bates available

- Redundant monitoring of luminosity
  Pressure, temperature, flow, current measurements
  Small-angle elastic scattering at high epsilon / low $Q^2$
  Symmetric Moller/Bhabha scattering

- Measure ratio of positron-proton to electron-proton unpolarized elastic scattering to 1% stat.+sys.
OLYMPUS kinematics at 2.0 GeV

- Electron
- Positron
- Proton

TOF, WC, GC, TGT

2 m

and vice versa

Proton
The designed OLYMPUS detector

- Drift Chambers
- Time-of-Flight Detectors: University of Glasgow, YerPhI, Yerevan, University of New Hampshire, Arizona State University
- Internal Hydrogen Target: MIT, INFN Ferrara
- 12° Tracking Telescopes: Hampton University, INFN Rome, Genova, PNPI St. Petersburg
- Symmetric Møller/Bhabha Monitor: University of Mainz
- DORIS Upgrade, Toroid Support: DESY
- Trigger, DAQ, Online-Monitor: University of Bonn

based on a figure by R. Russell
The realized OLYMPUS detector

July 2011
Target and vacuum system

Designed and built in 2010
Very stable operation after repairs
Wire chambers and TOF scintillators

- 2x18 TOFs for PID, timing and trigger
- 2 WCs for PID and tracking ($z, \theta, \phi, p$)
- WC and TOF refurbished from BLAST
  - WC re-wired at DESY
  - TOF rewrapped, efficiency tested
- Installed in OLYMPUS Apr-May 2011
- Stable operation

Glasgow, Yerevan, UNH, ASU
Luminosity monitors: GEM + MWPC

- Forward elastic scattering of lepton at 12° in coincidence with proton in main detector
- Two GEM + MWPC telescopes with interleaved elements operated independently
- SiPM scintillators for triggering and timing
- Sub-percent (relative) luminosity measurement per hour at 2.0 GeV
- High redundancy – alignment, efficiency
  Two independent groups (Hampton/INFN, PNPI)

Designed to fit into forward cone
Luminosity monitors: GEM + MWPC

Telescopes of three GEMs and MWPCs interleaved
Mounted on wire chamber forward end plate
Extensively tested at DESY test beam facility
Symmetric Møller/Bhabha monitor

- Symm. angle $1.3^\circ$ @ 2.0 GeV
- Matrix of 3x3 PbF$_2$ crystals
- Tested at DESY and MAMI
Performance of DORIS

- DORIS top-up mode established
- Typically 65mA / 0.5 sccm
- Refills every ~2 minutes by few mA
- PETRA refills every 30 minutes

Doris Current on Dec. 2nd

Top-up mode: refills every 2 min.

Top-up paused during PETRA refill

<1h for lepton switch
Analysis framework

ROOT based C++ analysis framework ("cooker") with plug-ins and recipes and full MC integration (J. Bernauer)
Run 4975, event 78
Very preliminary …

Based on 100 runs (~2% of the data)
Timeline of OLYMPUS

- 2007 Letter of Intent
- 2008 Proposal
- 2009 Technical review
- 2010 Approval and funding
- Summer 2010 BLAST transfer
- Spring 2011 Target test run
- Summer 2011 Detector installed
- Fall 2011 Commissioning

First run Jan 30 – Feb 27, 2012
... acquired < 0.3 fb-1

- Summer 2012 Repairs and upgrades

... acquired > 4.0 fb-1

- Spring 2013 Survey & field mapping
- Smooth performance of machine, target, detector
- Analysis underway
OLYMPUS collaboration

~50 physicists from 13 institutions in 6 countries

D. Hasell / U. Schneekloth (2013– )

- **Arizona State University**: TOF support, particle identification, magnetic shielding
- **DESY**: Modifications to DORIS accelerator and beamline, toroid support, infrastructure, installation
- **Hampton University**: GEM luminosity monitor
- **INFN Bari**: GEM electronics
- **INFN Ferrara**: Target
- **INFN Rome**: GEM electronics
- **MIT**: BLAST spectrometer, wire chambers, tracking upgrade, target and vacuum system, transportation to DESY, simulations, slow control, analysis framework
- **Petersburg Nuclear Physics Institute**: MWPC luminosity monitor
- **University of Bonn**: Trigger, data acquisition, and online monitor
- **University of Mainz**: Trigger, DAQ, Symmetric Moller monitor
- **University of Glasgow**: TOF scintillators
- **University of New Hampshire**: TOF scintillators
- **A. Alikhanyan National Laboratory (AANL), Yerevan**: TOF scintillators
New proton measurements at low $Q^2$

Hall A PR07-004, PR08-007 (PAC31/33)

- Recoil polarization, completed 2008
- Polarized target, completed 2012

◊ BLAST (polarized target)
C. Crawford et al., PRL98 (2007) 052301

• LEDEX PR05-004 (recoil polarization)
G. Ron et al., PRL99 (2007) 202002
New proton measurements at low $Q^2$

Hall A PR07-004, PR08-007 (PAC31/33)

- Recoil polarization, completed 2008
- Polarized target, completed 2012

◊ BLAST (polarized target)
  C. Crawford et al.,
  PRL98 (2007) 052301

X. Zhan,
E08-007 + LEDEX update

2-sigma difference
lower than BLAST

Charge and magnetic rms radii:

$R_E = 0.875 \pm 0.010$ fm
$R_M = 0.867 \pm 0.020$ fm
Rosenbluth separation at low $Q^2$
Precise charge and magnetic rms radii:

$R_E = 0.879 \pm 0.008$ fm
$R_M = 0.777 \pm 0.017$ fm
PSI muonic hydrogen measurements

  \[ \Delta E(\text{meV}) = 209.9779(49) - 5.2262 \, r_p^2 + 0.0347 \, r_p^3 \implies r_p = 0.84184 \pm 0.00067 \text{ fm} \]
  Possible issues: atomic theory & proton structure

  \[ \Delta E_L(\text{meV}) = 206.0336(15) - 5.2275(10) r_p^2 + 0.0332(20)_{\text{TPE}} \implies r_p = 0.84087 \pm 0.00039 \text{ fm} \]
The proton radius puzzle

- >7σ discrepancy between muonic and electronic measurements
- High-profile articles in Nature, NYTimes, etc.
- Puzzle unresolved, possibly New Physics

\[ R_p = 0.88 \text{ fm} \]

\[ R_p = 0.84 \text{ fm} \]

Muonic

Electronic

Sick (2003)
Bernauer (2010)
Pohl (2010)
Zhan (2011)
Antognini (2013)

\[ R_p = 0.84184(67) \text{ fm} \]
\[ R_p = 0.875(10) \text{ fm} \]
\[ R_p = 0.8775(51) \text{ fm} \]
\[ R_p = 0.84087(39) \text{ fm} \]
The proton radius puzzle in the media

For a Proton, a Little Off the Top (or Side) Could Be Big Trouble
By DENNIS OVERBYE
Published July 12, 2010

For most of us, 4 percent off around the waist — a couple of belt notches — would be a great triumph.

Not so for the proton, the subatomic particle that anchors atoms and is the building block of all ordinary matter, of stars, planets and people. Physicists announced last week that a new experiment had shown that the proton is about 4 percent smaller than they thought.

Instead of celebration, however, the result has caused consternation. Such a big discrepancy, say the physicists, led by Randolf Pohl of the Max Planck Institute for Quantum Optics in Garching, Germany, could mean that the most accurate theory in the history of physics, quantum electrodynamics, which describes how light and matter interact, is in trouble.

“What you have is a result that actually shocked us,” said Paul Rabinowitz, a chemist from Princeton University, who was a member of Dr. Pohl’s team.

Proton Mass Mystery Could Mean New Physics

APR 15, 2013 08:35 PM ET // BY STEPHANIE PAPAS, LIVESCIENCE
The proton radius puzzle in the media

April 2013
The proton radius puzzle in the media

July 2013
The proton radius puzzle in the media

January 2014
**Possible resolutions to the puzzle**

- **The ep (scattering) results are wrong**
  Fit procedures not good enough
  $Q^2$ not low enough, structures in the form factors

- **The ep (spectroscopy) results are wrong**
  Accuracy of individual Lamb shift measurements?
  Rydberg constant could be off by 5 sigma

- **The µp (spectroscopy) result is wrong**
  Discussion about theory and proton structure for extracting the proton radius from muonic Lamb shift measurement

- **Proton structure issues in theory**
  Off-shell proton in two-photon exchange leading to enhanced effects differing between µ and e
  Hadronic effects different for µp and ep:
  e.g. proton polarizability ($\text{effect } \propto m_i^4$)

- **Physics beyond Standard Model differentiating µ and e**
  Lepton universality violation, light massive gauge boson
  Constraints on new physics from kaon decays
New measurements are on their way

- Additional measurements needed / in preparation
  - Spectroscopy with $\mu$D, $\mu$He, and regular H; Rydberg constant
  - ep-, ed-scattering
    (PRad at Jlab, ISR-ep and ed elastic at MAMI; MESA)
  - $\mu^\pm p$- and $e^\pm p$-scattering in direct comparison at PSI (MUSE)
  - Searches for lepton universality violating light bosons
    (e.g. kaon decay such as TREK/E36 at J-PARC)

<table>
<thead>
<tr>
<th>$r_p$ (fm)</th>
<th>ep</th>
<th>$\mu p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectroscopy</td>
<td>$0.8758 \pm 0.077$</td>
<td>$0.84087 \pm 0.00039$</td>
</tr>
<tr>
<td>Scattering</td>
<td>$0.8770 \pm 0.060$</td>
<td>???</td>
</tr>
</tbody>
</table>

Need more precision for extraction from scattering
More insights from comparison of ep and $\mu p$ scattering
Lepton scattering from a nucleon:

Vertex currents:

\[ J_e^\mu = -e \bar{u}_e \gamma^\mu u_e \]

\[ J_N^\mu = \bar{\psi}_N \left[ F_1(Q^2) \gamma^\mu + F_2(Q^2) \frac{i \sigma^{\mu\nu} q_\nu}{2M_N} \right] \psi_N \]

F₁, F₂ are the Dirac and Pauli form factors

Sachs form factors:

\[
G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)
\]

\[
G_M(Q^2) = F_1(Q^2) + F_2(Q^2)
\]

Fourier transform (in the Breit frame) gives spatial charge and magnetization distributions

Derivative in \( Q^2 \to 0 \) limit:

\[
\langle r_E^2 \rangle = -6 \frac{dG_E^p(Q^2)}{dQ^2} \bigg|_{Q^2 \to 0}
\]

\[
\langle r_M^2 \rangle = -6 \frac{dG_M^p(Q^2)/\mu_p}{dQ^2} \bigg|_{Q^2 \to 0}
\]

Expect identical result for ep and μp scattering
The PRad proton radius proposal (JLAB)

- Low intensity beam in Hall B @ Jlab into windowless gas target
- Scattered ep and Moller electrons into HYCAL at 0°
- Lower $Q^2$ than Mainz. Very forward angle, insensitive to $2\gamma$, $G_M$
- Conditionally approved by PAC38 (Aug 2011): ``Testing of this result is among the most timely and important measurements in physics.”
- Approved by PAC39 (June 2012), graded “A”
- Could run in Hall B in 2015
Motivation for $\mu p$ scattering

Electronic hydrogen
$0.877\pm0.007$

Muon scattering

Muonic hydrogen
$0.842\pm0.001$
$0.84087\pm0.00039$

Lamb shift

Electron scattering
$0.875\pm0.006$

Elastic scattering

Muon scattering

???
Use the world’s most powerful low-energy separated e/π/μ beam for a direct test if μp and ep scattering are different:

- Simultaneous, separated beam of (e+/π+/μ+) or (e-/π-/μ-) on liquid H\textsubscript{2} target
  - Separation by time of flight
  - Measure absolute cross sections for ep and μp
  - Measure e+/μ+, e-/μ- ratios to cancel certain systematics

- Directly disentangle effects from two-photon exchange (TPE) in e+/e-, μ+/μ-

- Multiple beam momenta 115-210 MeV/c to separate G\textsubscript{E} and G\textsubscript{M} (Rosenbluth)
Appollo and the nine muses
MUSE beamline and experiment layout

\[ \pi, \mu, e \]

**Intermediate Focus**
Dispersion 7cm/%

**LH$_2$ target**

\[ \pi \text{M1: } 100-500 \text{ MeV/c} \]
Momentum measurement
RF+TOF separated $\pi, \mu, e$

Beam particle tracking
Liquid hydrogen target
Scattered lepton detection
Requirements for beamline detectors

Beamline Elements:

- Precise time-of-flight measurements for $e/\pi/\mu$ PID at trigger level
- TOF for beam momentum measurement to 0.1-0.2%
- Suppression of background from in-flight decay
- Beam particle tracking to 0.5 mr for accurate scattering angle

Particles are well separated at IFP and at target.
- Limited beam flux (5 MHz) → Large angle, non-magnetic detectors
- Secondary beam → Tracking of beam particles to target
- Mixed beam → Identification of beam particle in trigger
Target sci-fi array and scintillator:
→ Flux, PID, Trigger, TOF, momentum

Beam Cerenkov (quartz or sapphire)
→ Timing, PID, trigger: beam TOF, momentum, scattered particle TOF

GEM telescope
→ Determine incident angle to 0.5 mr
→ Third GEM to reject ghost tracks
→ Existing chambers from OLYMPUS
Main detector instrumentation

- 2 planes of scintillators (CLAS12 design)
- 94 bars (2 sides + beam)
- High precision (40-50ps) timing
- PID and trigger, background rejection

- Straw Tube Tracker (STT), ~3000 straws
- Determine scattered particle trajectory
- Existing PANDA design - 140µm resolution
- Thin walled (25µm), overpressured (2 bar)
- Directly coupled to fast readout boards
Trigger and DAQ

- FPGA design for beam PID (custom or v1495)
- SciFi + Beam RF + Cerenkov -> Beam PID
- Count particles and reject pions
- Need 99.9% pion rejection efficiency

- Custom signal splitters
- FPGAs as front end discriminator/amplifier, custom designed TDCs (PADIWA/TRB3)
- High channel density (256ch/board)
- Standard CAEN ADCs
## Responsibilities for new equipment

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<tr>
<th>Detector</th>
<th>Who</th>
<th>Technology</th>
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<tbody>
<tr>
<td>Beam SciFi</td>
<td>Tel Aviv</td>
<td>conventional</td>
</tr>
<tr>
<td>GEMs</td>
<td>Hampton</td>
<td>detector exists</td>
</tr>
<tr>
<td>Sapphire Cerenkov</td>
<td>Rutgers</td>
<td>prototyped (Albrow et al)</td>
</tr>
<tr>
<td>FPGAs</td>
<td>Rutgers</td>
<td>conventional</td>
</tr>
<tr>
<td>Target</td>
<td>George Washington</td>
<td>conventional - very low power</td>
</tr>
<tr>
<td>Straw Tube Tracker</td>
<td>Hebrew U</td>
<td>copy existing system (PANDA)</td>
</tr>
<tr>
<td>scintillators</td>
<td>South Carolina</td>
<td>copy existing system</td>
</tr>
<tr>
<td>DAQ</td>
<td>George Washington</td>
<td>conventional, except TRB3</td>
</tr>
</tbody>
</table>
First beam tests

Beam spot with GEM telescope – May 23, 2013

Time of flight relative to RF time (Fall 2012)
Composition of the πM1 secondary beam

Beam test result from December 2013
Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing e-p extractions, but not better

Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, µ+/µ-, and µ/e comparisons
Projected sensitivity

Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing e-p extractions, but not better

Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, $\mu$+/\(\mu\)-, and $\mu$/e comparisons

Relative comparison reduces errors by factor of 2

MUSE suited to verify $7\sigma$ effect with similar significance
MU on Scattering Experiment – MUSE

- Proton Radius Puzzle – still unresolved ~4 years later

- MUSE Experiment at PSI
  - Measure $\mu^+e^-$ and $e^+\mu^-$ scattering and compare $\mu^+/e^+$ and $\mu^-/e^-$ directly
  - Measure $e^+/e^-$ and $\mu^+/\mu^-$ to study/constrain TPE effects

- Technical Challenges
  - PID, timing, background rejection, momentum and flux determination

- Timeline
  - Initial proposal February 2012
  - Technical review July 2012
  - First beam tests in fall 2012
  - PAC-approved in January 2013
  - Further beam tests in summer and December 2013
  - Funding & construction 2014–2015
  - Production running 2016–2017 (2x 6 months)
47 MUSE collaborators from 24 institutions in 6 countries:

R. Gilman (Contact person),
E.J. Downie (Spokesperson),
G. Ron (Spokesperson),
A. Afanasev,
J. Arrington,
O. Ates,
C. Ayerbe-Gayoso,
F. Benmokhtar,
J. Bernauer,
E. Brash,
W. J. Briscoe,
K. Deiters,
J. Diefenbach,
C. Djalali,
B. Dongwi,
L. El Fassi,
S. Gilad,
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A. Sarty,
Y. Shamai,
N. Sparveris,
S. Strauch,
V. Sulkosky,
A.S. Tadepalli,
M. Taragin,
and L. Weinstein

Rutgers University, George Washington University, Hebrew University of Jerusalem, Argonne National Lab, Hampton University, College of William & Mary, Duquesne University, Massachusetts Institute of Technology, Christopher Newport University, Paul Scherrer Institut, Johannes Gutenberg-Universität Mainz, University of Iowa, University of Virginia, University of South Carolina, Jefferson Lab, Tel Aviv University, Duke University, Temple University, Norfolk State University, Technical University of Darmstadt, St. Mary’s University, Soreq Nuclear Research Center, Weizmann Institute, Old Dominion University
Jaeckel, Roy (arXiv:1008.3536)
- Hidden U(1) photon can decrease charge radius for muonic hydrogen, however even more so for regular hydrogen

Tucker-Smith, Yavin (arXiv:1011.4922)
- Can solve proton radius puzzle
- MeV particle coupling to p and µ (not e) consistent with $g_\mu^{-2}$

Batell, McKeen, Pospelov (arXiv:1103.0721):
- Can solve proton radius puzzle
- New e/µ differentiating force consistent with $g_\mu^{-2}$
- <100 MeV vector or scalar gauge boson V (poss. dark photon)
- Resulting in large PV µp scattering

Carlson, Rislow (arXiv:1310.2786):
- Can solve proton radius puzzle
- New e/µ differentiating force consistent with $g_\mu^{-2}$
- Two fine-tuned scalar/pseudoscalar or vector/axial gauge bosons

Barger, Chiang, Keung, Marfatia (arXiv:1109.6652):
- Should be constrained by $K \rightarrow \mu\nu$ decay
Measurement of $\Gamma(K^+ \rightarrow e^+\nu)/\Gamma(K^+ \rightarrow \mu^+\nu)$

and

Search for heavy sterile neutrinos

using the TREK detector system
Target & E246/TREK detector upgrade

- C1 GEM
- Target
- Aerogel Cerenkov
- TOF, Leadglass
- CsI(Tl) readout
Target & E246/TREK detector upgrade

- C1 GEM
- Target
- Aerogel Cerenkov
- TOF, Leadglass
- CsI(Tl) readout
E246: Superconducting toroidal magnet
Search for a new particle in $K^+ \rightarrow \mu^+ \nu e^+ e^-$

- Light mediator of dark force U(1) coupled to SM via kinetic mixing; motivated by astrophysics, $g_\mu - 2$, (and proton radius puzzle $R_p$)
- Possibly enhanced coupling to muons, not probed by electroproduction
- Measure all charged decay particles and search for peak in the $e^+e^-$ invariant mass spectrum in the range 0-380 MeV

$K_{\mu 2}$: $K^+ \rightarrow \mu^+ \nu \sim 10^{10}$ events

$K_{\mu 2\gamma}$: $K^+ \rightarrow \mu^+ \nu \gamma \sim 10^7$ events

Signal: $\text{BR}(K^+ \rightarrow \mu^+ \nu A') \sim 10^{-8}$

$A' \rightarrow e^+e^- \sim 100$ events

Background:

$\text{BR}(K^+ \rightarrow \mu^+ \nu e^+ e^-) \sim 2.5 \times 10^{-5}$
Search for a new particle in $K^+ \rightarrow \mu^+ \nu e^+ e^-$

Investigated for E36:

- Detect $\mu^+$ in toroid, $e^+e^-$ in CsI(Tl)
- Simulate achievable resolution for invariant mass $m_{ee}$
- Simulate QED background (radiative decay $K^+ \rightarrow \mu^+ \nu e^+ e^-$)
- Sensitivity from background fluctuation

$\rightarrow$ Exclusion limits for $\varepsilon^2$ versus $m_{ee}$

P. Monaghan, B. Dongwi
Mixing parameter: dark photon framework, universal coupling

Simulated signal channel $K^+ \rightarrow \mu^+ \nu e^+ e^-$ for resolution

Simulated background distribution with $\text{BR}(K^+ \rightarrow \mu^+ \nu e^+ e^-) = 2.5 \times 10^{-5}$

Obtain exclusion limit for signal $> 2 \times$ background fluctuation

Exclusion limit dependent on resolution and number of accepted $K^+$

TREK/E36:
Kaons delivered: $1.0 \times 10^{12}$
&& stopped: $2.5 \times 10^{11}$
&& $\mu^+$ accepted: $1.8 \times 10^{10}$
&& $e^+e^-$ accepted: $1.0 \times 10^{10}$
Search for a new particle in $K^+ \rightarrow \mu^+ \nu e^+ e^-$

**QED background:** $K^+ \rightarrow \mu^+ \nu e^+ e^-$
- $\Gamma(K^+ \rightarrow \mu^+ \nu ee) \sim 2.5 \times 10^{-5}$
- Expect $10^{10}$ stopped $K^+$ in E36
- 250k QED evts or $\sim 1000 / \text{MeV}$

**Signal:** $K^+ \rightarrow \mu^+ \nu A', A' \rightarrow e^+ e^-$

C. Carlson, B. Rislow, hep-ph/1310.2786

**Dark photon model** (universal coupling)
$\Gamma(K^+ \rightarrow \mu^+ \nu A') \sim 10^{-9}$

B. Batell, D. McKeen, and M. Pospelov, PRL107, 011803 (2011), 1103.0721

**Batell model** (univ.-violating, right-handed muons)
$\Gamma(K^+ \rightarrow \mu^+ \nu A') \sim 10^{-4} - 10^{-1}$

same background!
Search for a new particle in $K^+ \rightarrow \mu^+ \nu \, e^+ \, e^-$

**QED background:** $K^+ \rightarrow \mu^+ \nu \, e^+ e^-$
- $\Gamma(K^+ \rightarrow \mu^+ \nu \, e^+ e^-) \sim 2.5 \times 10^{-5}$
- Expect $10^{10}$ stopped $K^+$ in E36
- 250k QED evts or $\sim 1000 / \text{MeV}$

**Signal:** $K^+ \rightarrow \mu^+ \nu \, A', \, A' \rightarrow \, e^+ \, e^-$

C. Carlson, B. Rislow, hep-ph/1310.2786

same background!

Carlson&Rislow model
(universality-violating, fine tuned); $\Gamma(K^+ \rightarrow \mu^+ \nu \, A') \sim 10^{-6} - 10^{-5}$

HUGE signals predicted, E36 very stringent test
Summary

- The limits of OPE have been reached with available today’s precision
  ➔ Nucleon elastic form factors, particularly $G_E^p$ under doubt

- The TPE hypothesis is suited to remove form factor discrepancy, however calculations of TPE are model-dependent

- Experimental probes: Real part of TPE –
  - $\varepsilon$-dependence of polarization transfer
  - $\varepsilon$-nonlinearity of cross sections
  - Comparison of positron and electron elastic scattering

- The Proton Radius Puzzle has been standing since 2010
  - Muonic hydrogen Lamb shift: Proton rms radius
    7$\sigma$ smaller than with electronic hydrogen and electron scattering
  - PRad at JLab
  - MUon Scattering Experiment MUSE
  - New Physics tested with TREK/E36

The nine muses
Backup
The proposed GEp-V experiment in Hall A

- Luminosities up to $8 \times 10^{38} \text{ e/s} \times \text{nucleon/cm}^2$
- Full acceptance for 40cm long target
- v.good angular resolution
- good momentum resolution
Observables involving real part of TPE

\[
P_i = - \sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}} \frac{G_M^2}{d\sigma_{\text{red}}} \left\{ R + \text{Re} \left( \delta \tilde{G}_M \right) G_M + \text{Re} \left( \delta \tilde{G}_E \right) \right\}
\]

\[
P_i = \sqrt{(1+\varepsilon)(1-\varepsilon)} \frac{G_M^2}{d\sigma_{\text{red}}} \left\{ 1 + 2 \text{Re} \left( \delta \tilde{G}_M \right) \frac{G_M}{G_M} + 2 \frac{\varepsilon Y_{2\gamma}}{1+\varepsilon} \right\}
\]

\[
\frac{P_i}{P_i} = - \sqrt{\frac{2\varepsilon}{(1+\varepsilon)\tau}} \left\{ R - \text{Re} \left( \delta \tilde{G}_M \right) \frac{G_M}{G_M} + \text{Re} \left( \delta \tilde{G}_E \right) \right\}
\]

\[
d\sigma_{\text{red}} / G_M^2 = 1 + \frac{\varepsilon R^2}{\tau} + 2 \text{Re} \left( \delta \tilde{G}_M \right) \frac{G_M}{G_M} + 2 R \frac{\varepsilon \text{Re} \left( \delta \tilde{G}_E \right)}{\tau G_M} + 2 \left( 1 + \frac{R}{\tau} \right) \varepsilon Y_{2\gamma}
\]

\[
\text{Re} \left( \tilde{G}_E \right) = G_E(Q^2) + \text{Re} \left( \delta \tilde{G}_E(Q^2, \varepsilon) \right)
\]

\[
\text{Re} \left( \tilde{G}_M \right) = G_M(Q^2) + \text{Re} \left( \delta \tilde{G}_M(Q^2, \varepsilon) \right)
\]

\[
R = \frac{G_E}{G_M} \quad Y_{2\gamma} = 0 + \frac{\sqrt{\tau(1+\tau)(1+\varepsilon)}}{1-\varepsilon} \frac{\text{Re} \left( \tilde{F}_3(Q^2, \varepsilon) \right)}{G_M}
\]

Born Approximation

Beyond Born Approximation


Slide idea:
L. Pentchev

E04-019 (Two-gamma)
\varepsilon \text{ dependence of recoil polarization}

Rosenbluth non-linearity
E05-017
\varepsilon^+/\varepsilon^- x-section ratio
CLAS, VEPP3, OLYMPUS
TPE experiments: Novosibirsk/VEPP-3

Run I (2009)  
E = 1.6 GeV

Run II (2011/12)  
E = 1.0 GeV

A. Gramolin, Workshop on Radiative Corrections in Annihilation and Scattering Experiments, Orsay, October 7-8, 2013
TPE experiments: CLAS (E04-116)

Dasuni Adikaram (ODU), DH.00005

Dipak Rimal (FIU), DH.00006
Jefferson Lab E04-019 (Two-gamma)

Jlab – Hall C

$Q^2 = 2.5 \text{ (GeV/c)}^2$

$G_E/G_M$ from $P_t/P_l$ constant vs. $\varepsilon$

- no effect in $P_t/P_l$
- some effect in $P_l$

Expect larger effect in e+/e-!

M. Meziane et al., hep-ph/1012.0339v2
## Comparison of $e^+/e^-$ 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><strong>beam energy</strong></td>
<td>3 fixed</td>
<td>1 fixed</td>
<td>wide spectrum</td>
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<tr>
<td><strong>equality of $e^\pm$ beam energy</strong></td>
<td>measured</td>
<td>measured</td>
<td>reconstructed</td>
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<td><strong>$e^+/e^-$ swapping frequency</strong></td>
<td>half-hour</td>
<td>8 hours</td>
<td>simultaneously</td>
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<tr>
<td><strong>$e^+/e^-$ lumi monitor</strong></td>
<td>elastic low-$Q^2$</td>
<td>elastic low-$Q^2$, Möller/Bhabha</td>
<td>from simulation</td>
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<tr>
<td><strong>energy of scattered $e^\pm$</strong></td>
<td>EM-calorimeter</td>
<td>mag. analysis</td>
<td>mag. analysis</td>
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<tr>
<td><strong>proton PID</strong></td>
<td>$\Delta E/E$, TOF</td>
<td>mag. analysis, TOF</td>
<td>mag. analysis, TOF</td>
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<tr>
<td><strong>$e^+/e^-$ detector acceptance</strong></td>
<td>identical</td>
<td>big difference</td>
<td>big difference</td>
</tr>
<tr>
<td><strong>luminosity</strong></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><strong>beam type</strong></td>
<td>storage ring</td>
<td>storage ring</td>
<td>secondary beam</td>
</tr>
<tr>
<td><strong>target type</strong></td>
<td>internal H target</td>
<td>internal H target</td>
<td>liquid H target</td>
</tr>
<tr>
<td><strong>data taken</strong></td>
<td>2009, 2011-12</td>
<td>2012</td>
<td>2011</td>
</tr>
</tbody>
</table>
Comparison of $e^+/e^-$ experiments

- Novosibirsk experiment ($E_{\text{beam}} = 1.6, 1$ and $0.6$ GeV)
- CLAS @ JLab experiment ($E_{\text{beam}} = 0.5 \div 4$ GeV)
- OLYMPUS @ DESY experiment ($E_{\text{beam}} = 2$ GeV)
The PRad proton radius proposal (JLAB)

E12-11-106: Experimental method

(1) minimize experimental background:
high density windowless H₂ gas flow target

(2) Non-magnetic-spectrometer method:
high resolution, high acceptance crystal calorimeter

(3) Effective separation of Møller events from the ep elastic scattered events for angles \( \theta_e > 0.7^\circ \).

0.7° < \( \theta_e < 4^\circ \)
E12-11-106: Very-low $Q^2$ elastic ep-scattering

Very low $Q^2$ range: $2 \times 10^{-4}$ to $2 \times 10^{-2}$ GeV$^2$ → Model independent $r_p$ extraction

\[
\left( \frac{d\sigma}{d\Omega} \right)_{ep}(Q_i^2) = \frac{N(ep \rightarrow ep \text{ in } \theta_i \pm \Delta \theta)}{N(e^-e^- \rightarrow e^-e^-)} \cdot \frac{\epsilon_{e^-e^-}^{\text{geom}}}{\epsilon_{e^-e^-}^{\text{geom}}} \cdot \frac{\epsilon_{e^-e^-}^{\text{det}}}{\epsilon_{e^-e^-}^{\text{det}}} \left( \frac{d\sigma}{d\Omega} \right)_{e^-e^-}
\]

Møller scattering - well known QED process

Simultaneous detection of two processes

- $ep \rightarrow ep$  → $N_e$ and $N_{tgt}$ cancel
- $ee \rightarrow ee$ (Møller scattering)
Requirement: particle separation in time for PID

50 MHz RF $\rightarrow$ 20 ns between bunches

Timing of particles in target region wrt electron ($\beta = 1$)

Minimum time separation of particles in target region

$p = 115, 153, \text{ and } 210 \text{ MeV/c}$
Target: $\rightarrow$ 4 cm LH2, thickness constrained by effects of multiple scattering

% change in cross section for $\theta_{ms} = 10$ mr $\rightarrow$ Limits acceptance to $> 20^\circ$

Beamline Cerenkov: provide redundant PID, and provide cross check for RF timing calibration
Background considerations

Requirement: low backgrounds or background rejection

Scattering from electrons:

- $\pi$, $\mu$ at forward angles
- $e^-, e^+ < 10$ MeV above $15^\circ$
- Recoil e's low momentum

Muons from $\pi$ decays

- $210$ MeV/$c$ $\pi \rightarrow \mu \nu$
- $153$ MeV/$c$ $\pi \rightarrow \mu \nu$
- $115$ MeV/$c$ $\pi \rightarrow \mu \nu$

→ Will have $\pi$ RF time
   (3 orders of magnitude suppression)
→ Track will not point back to the target

Suppression of $\mu \rightarrow e\nu\nu$ background with offline time-of-flight (8-20 $\sigma$)
Scattered particle considerations

Recoil protons E loss so large that all except forward angle recoil protons stopped in target.

Large angle, very low energy Moller / Bhabha e’s lose large fraction of energy in target.

All the low-energy electron and proton backgrounds are ranged out in the first scintillator layer.
Possible kaon decay channels in E36

$K^+$ decays $\sim 10^{10}$

**Signal:** $K^+ \rightarrow \pi^+ A', \ A' \rightarrow e^+e^-$

**Background:** $\text{BR}(K^+ \rightarrow \pi^+ e^+ e^-) \sim 2.9 \times 10^{-7} \sim 2,900 \text{ ev.}$

**Signal:** $K^+ \rightarrow \mu^+ \nu A', \ A' \rightarrow e^+e^-$

**Background:** $\text{BR}(K^+ \rightarrow \mu^+ \nu e^+ e^-) \sim 2.5 \times 10^{-5} \sim 250,000 \text{ ev.}$

Add. background from $K^+ \rightarrow \mu^+ \nu \pi^0 \rightarrow \mu^+ \nu \ e^+ e^- (\gamma)$

---

$\pi^0$ decays $\sim$

1) $3 \times 10^8$; 
2) $2 \times 10^9$

$\pi^0$ production:

1) $K^+ \rightarrow \mu^+ \nu \pi^0 (3.27\%);$ 
2) $K^+ \rightarrow \pi^+ \pi^0 (21.13\%)$

**Signal:** $\pi^0 \rightarrow \gamma A', \ A' \rightarrow e^+e^-$

**Background:** $\text{BR}(\pi^0 \rightarrow \gamma e^+ e^-) \sim 1.2\% \sim 0.3 (2.3) \times 10^7 \text{ ev.}$

P. Adlarson et al., 1304.0671 [hep-ex] (WASA/COSY): “World’s largest sample” $5 \times 10^5$