Determination of the Proton’s Charge Radius by Simultaneous Measurement of Electron- and Muon-Proton Elastic Scattering with the MUSE Experiment at PSI

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Atomic Spectroscopy

- Quantum Mechanics—solve the hydrogen atom.
- Coulomb field is distorted because the proton is not a point charge.
- This shifts atomic levels.
- Measure atomic levels.

Elastic Scattering

- Quantum Mechanics—scatter electron on point Coulomb
- Coulomb field is distorted because the proton is not a point charge.
- Define

\[ \langle r \rangle^2 \equiv 6 \left. \frac{dG_E}{dQ^2} \right|_{Q^2=0} \]

- Cross section adding a form factor

\[ \frac{d\sigma}{d\Omega}|_{\text{lab}} = \left( \frac{G_E^2}{1 + \tau} + \frac{G_M^2}{2} \cos^2 \frac{\theta}{2} \right) \]

\[ + 2\tau G_M^2 \sin^2 \frac{\theta}{2} \]

\[ G_E \text{ Classically} \approx \int e^{iQ\cdot r} \rho(r) d^3r \approx 1 - \frac{1}{3!} Q^2 \langle r \rangle^2 + \frac{1}{5!} Q^4 \langle r \rangle^4 + \cdots \]
Measurements of the Proton's Charge Radius Disagree

The proton RMS charge radius measured with:
- Electrons: $0.8751 \pm 0.0061$ fm (CODATA2014)
- Muons: $0.8409 \pm 0.0004$ fm
## Proton’s Size vs Probe and Method

<table>
<thead>
<tr>
<th>Probe</th>
<th>Method</th>
<th>Spectroscopy</th>
<th>Elastic scattering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>Spectroscopy</td>
<td>0.876(8)</td>
<td>0.877(6)</td>
</tr>
<tr>
<td>Muon</td>
<td>Spectroscopy</td>
<td>0.8409(4)</td>
<td>??</td>
</tr>
</tbody>
</table>
Many explanations have been offered

- The $\mu p$ (spectroscopy) result is wrong
  - Discussion about theory and proton structure for extracting the proton radius from muonic Lamb shift measurement

- The $e p$ (spectroscopy) results are wrong
  - Accuracy of individual Lamb shift measurements?
  - Rydberg constant could be off by 5 standard deviations?

- The $e p$ (scattering) results are wrong
  - Fit procedures not good enough
  - $Q^2$ not low enough, structures in the form factors
The world has become more confused!

Not here to critique new experiments, re-analyses or meta-analyses
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- Proton structure issues in theory
  - Off-shell proton in *two-photon* exchange leading to enhanced effects differing between $\mu$ and $e$
  - Hadronic effects different for $\mu p$ and $e p$: *e.g.* proton polarizability ($\text{effect } \sim m_1^4$)

- Physics beyond Standard Model differentiating $\mu$ and $e$
  - Lepton universality violation, light massive gauge boson
  - Constraints on new physics *e.g.* from kaon decays (TREK@J-PARC)
**Many Explanations Have Been Offered**

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

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  - Fit procedures not good enough
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- Proton structure issues in theory
  - Off-shell proton in *two-photon* exchange leading to enhanced effects differing between \( \mu \) and \( e \)
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MuSE at PSI

- **Muon Scattering Experiment**

- $\mu^+$, $\mu^-$, $e^+$, $e^-$—proton elastic scattering
- Incident momenta 115, 153, and 210 MeV/c
- Like sign leptons measured simultaneously
  - reduce syst. $\mu^+\leftrightarrow e^+$ and $\mu^-\leftrightarrow e^-$ comparisons

- Compact—roughly table top to room size experiment
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**MuSE Spectrometer in a Nutshell**

- Located on the πM1 beam line
- Measure incoming particle
  - position and direction with GEM
  - Timing with Beam Hodoscope and Scattered Particle Scintillators
BEAM HODOSCOPES & GEMs

BEAM HODOSCOPE

- Beam flux, TOF start
- 16 Channels/plane
- SiPM readout
- Resolution better than 80 ps
- 99.8% efficiency

- Beam trajectory particle-by-particle
- 3 planes 70 µm resolution
- Reused from Olympus
MuSE INSTALLATION
Cryo Target

- Successful cool down test w/Ne Tuesday
- Prerequisite for Safety Review for Hydrogen cool down test

Ne Cooldown 30 May 2018

Looking directly upstream
Straw Tube Tracker

- Straw Tube assembly almost complete at PSI

Straw Tube Tracker Mounting frame
SCATTERED PARTICLE SCINTILLATOR

- Timing resolution exceeded requirements for PID
  - $\sigma = 46$ ps (120 cm bars)
  - $\sigma = 52$ ps (220 cm bars)
- 1MHz rate capabilities
THE MUSE COLLABORATION

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**Estimated Uncertainty: Two Photon?**

\[
\sigma_{e^\pm p} = |\mathcal{M}_{1\gamma}|^2 \pm 2 \Re \left\{ \mathcal{M}_{1\gamma}^\dagger \mathcal{M}_{2\gamma} \right\} + \cdots
\]

\[
\frac{\sigma_{e^- p}}{\sigma_{e^+ p}} \approx 1 + 4 \frac{\Re \left\{ \mathcal{M}_{1\gamma}^\dagger \mathcal{M}_{2\gamma} \right\}}{|\mathcal{M}_{1\gamma}|^2}
\]
ESTIMATED UNCERTAINTY: LEPTON UNIVERSALITY?

Does

\[ G_\mu^E (Q^2) = G_e^E (Q^2) \]

MUSE Pseudodata: Estimated Errors for $\mu/e$ $G^p_E$

Relative Uncertainties

- Solid Angle: 0.10%
- Scintillator Efficiency: 0.10%
- Beam Mom. Sensitivity: 0.10%
- Angle Determination: 0.10%
- Magnetic Contributions: 0.10%
- Multiple Scattering: 0.30%
- Radiative Corr. $\mu$: 0.10%
- Radiative Corr. e: 0.50%

Plot from K. Mesick
**SUMMARY OF SYSTEMATIC UNCERTAINTIES IN MuSE**

Table 1: Estimated MUSE relative systematic cross section uncertainties for the shape of angular distributions, the ratio of muon and electron scattering cross sections, and the ratio of + charge to − charge cross sections.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>angular distribution (%)</th>
<th>μ/e (%)</th>
<th>+/− (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector efficiencies</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Solid angle</td>
<td>0.1</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>Luminosity</td>
<td>small</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>Scattering angle offset</td>
<td>0.2</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>Multiple scattering correction</td>
<td>0.15</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>Beam momentum offset</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Radiative correction</td>
<td>0.1 (µ), 0.5 (e)</td>
<td>0.5</td>
<td>1γsmall</td>
</tr>
<tr>
<td>Magnetic contribution</td>
<td>0.15</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>Subtraction of µ decay from µp</td>
<td>0.1</td>
<td>0.1</td>
<td>small</td>
</tr>
<tr>
<td>Subtraction of target walls</td>
<td>0.3</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>Subtraction of pion-induced events</td>
<td>small</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>Beam PID / reaction misidentification</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Subtraction of µ decay from ep</td>
<td>small</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>Subtraction of ee from ep</td>
<td>small</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>0.5 (µ), 0.7 (e)</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>
**Estimated Uncertainty—Radius Extraction**

For technical details on the MuSE spectrometer, please see arXiv:1709.09753.