Studying the Proton ``Radius'' Puzzle with $\mu p$ Elastic Scattering

R Gilman (Rutgers, The State University of New Jersey) with E. J. Downie (GWU), G. Ron (Hebrew U), and the MUSE collaboration

see: http://www.physics.rutgers.edu/~rgilman/elasticmup/muse-collaboration.html

- Introduction
- The Puzzle
- Status report on the MUon proton Scattering Experiment (MUSE)
- Outlook
What is a radius, how do we measure it?

Classical physics radius: \( r^2 = \int \rho(r) \ r^2 \ d^3r \)

Non-relativistic quantum mechanics radius: \( r^2 = \int \langle \psi^*(r)|r^2|\psi(r)\rangle \ d^3r \)

Relativistic quantum mechanics ``radius'': \( r^2 = -6 \ \frac{dG(Q^2)}{dQ^2}|_{Q^2=0} \).

Electron scattering

\[ G_E \approx 1 - \frac{Q^2<r^2>}{6} + \frac{Q^4<r^4>}{120} - \ldots \]

``r^2'' = \( -6 \ \frac{dG}{dQ^2} \approx <r^2> - \frac{Q^2<r^4>}{10} + \ldots \)

Atomic energy levels

NRQM: finite size of proton perturbs energies of s states - \( r_p \llll r_{\text{atomic}} \), so effect proportional to \( \psi^2_a(r=0) \).

\[ \begin{align*}
2P & \quad \text{Laser} \\
2S & \quad 2 \text{ keV} \\
1S & \quad \gamma
\end{align*} \]
The Radius vs Time

Chambers and Hofstadter, Phys Rev 103, 14 (1956)

From Pohl, Gilman, Miller, Pachucki review, arXiv:1301.0905, AnnRevNPS, modified
The Proton Radius Puzzle I

Randolf Pohl et al., Nature 466, 213 (2010):

0.84184 ± 0.00067 fm

5σ off 2006 CODATA

\[ \Delta E = 209.9779(49) - 5.2262 \, r_p^2 + 0.0347 \, r_p^3 \, (\text{meV}) \]

Water-line/laser wavelength:
300 MHz uncertainty

\( \Delta \nu \) water-line to resonance:
200 kHz uncertainty

CODATA-06

our value

e-p scattering

H₂O calib.

Statistics: 700 MHz
Systematics: 300 MHz

Friday, March 15, 2013
Aldo Antognini et al., Science 339, 417 (2013):
0.84087 ± 0.00039 fm
7σ off 2010 CODATA

\[ \Delta E = 206.0336(15) - 5.22275(10)r^2 + E_{\text{TPE}} \text{ (meV)} \]

Fig. 3. Muonic hydrogen resonances (solid circles) for singlet \( \nu_s \) (A) and triplet \( \nu_t \) (B) transitions. Open circles show data recorded without laser pulses. Two resonance curves are given for each transition to account for two different classes, I and II, of muon decay electrons (12). Error bars indicate the standard error. (Insets) The time spectra of \( K_\alpha \) x-rays. The vertical lines indicate the laser time window.
The Proton Radius vs Time

From Pohl, Gilman, Miller, Pachucki review, arXiv: 1301.0905, AnnRevNPS, modified

Focusing in on recent results...
There are reasons to think that the scattering analyses giving larger radii are better.
It is a feature of the dispersion analyses for \( \approx 20 \) years that they give smaller radii.
What is the Proton Radius?

Atomic hydrogen summary

From Pohl, Gilman, Miller, Pachucki review, arXiv: 1301.0905, AnnRevNPS

Electron scattering model dependence

From J. Bernauer's thesis
Do the muon and electron give different proton radii?

Muonic hydrogen looks to be the best experimental measurement - 200$^3$ times more sensitive than atomic hydrogen.

Odd, but possible, that atomic hydrogen and ep scattering give the same wrong result.

But individual atomic hydrogen measurements do not disagree with muonic hydrogen too much, and

Some competing ep scattering analyses favor small slope.

I think the answer right now is yes, though the issue needs to be investigated more with new experiments - because if the answer is yes, there is interesting new physics!
Why do the muon and electron give different proton radii?

Assuming the experimental results are not bad, what are viable theoretical explanations of the Radius Puzzle?

**Novel Beyond Standard Model Physics:** Pospelov, Yavin, Carlson, ...: the electron is measuring an EM radius, the muon measures an (EM+BSM) radius

**Novel Hadronic Physics:** G. Miller: currently unconstrained correction in proton polarizibility affects $\mu$, but not $e$ (effect $\propto m_4$)

Basically everything else suggested has been ruled out - missing atomic physics, structures in form factors, anomalous 3rd Zemach radius, ...

See Trento Workshop on PRP for more details:

http://www.mpq.mpg.de/~rnp/wiki/pmwiki.php/Main/WorkshopTrento
How do we Resolve the Radius Puzzle

- New data needed to test that the e and $\mu$ are really different, and the implications of novel BSM and hadronic physics

- **BSM**: scattering modified for $Q^2$ up to $m^2_{BSM}$ (typically expected to be MeV to 10s of MeV), enhanced parity violation

- **Hadronic**: enhanced $2\gamma$ exchange effects

- Experiments include:
  - Redoing atomic hydrogen
  - Light muonic atoms for radius comparison in heavier systems
  - Redoing electron scattering at lower $Q^2$
  - **Muon scattering!**
How do we Resolve the Radius Puzzle

New data needed to test that the $e$ and $\mu$ are really different, and the implications of novel BSM and hadronic physics

BSM: modify scattering probability for $Q^2$ up to $m^2_{BSM}$, enhanced parity violation

Hadronic: enhanced 2$\gamma$ exchange effects

Experiments include:

- Redoing atomic hydrogen
- Light muonic atoms for radius comparison in heavier systems
- Redoing electron scattering at lower $Q^2$
- Muon scattering!

Possible 2nd generation experiment

MUSE tests these

Preceding and following talks

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Previous e-μ Scattering Comparisons

In the 1970s / 1980s, several scattering experiments tested whether ep and μp interactions are equal, to within the 10% precision of the experiments. In light of the proton “radius” puzzle, the 10% experiments are not as good as one would like.

Ellsworth et al.: form factors from elastic μp

Kostoulas et al. parameterization of μp vs. ep elastic differences

Entenberg et al DIS: \( \frac{\sigma_{\mu p}}{\sigma_{ep}} \approx 1.0\pm0.04 \) (±8.6% systematics)
Two-photon exchange tests in $\mu p$ elastics

Camilleri et al. PRL 23: No evidence for two-photon exchange effects, but very poor constraints by modern standards.

No difference between $\mu^+ p$ and $\mu^- p$ elastic scattering

Rosenbluth plot is linear.
C Radius and e-μ Universality

The $^{12}\text{C}$ radius was determined with eC scattering and μC atoms. The results agree:

Offermann et al. eC: $2.478 \pm 0.009$ fm
Schaller et al. μC X rays: $2.4715 \pm 0.016$ fm
Ruckstuhl et al. μC X rays: $2.483 \pm 0.002$ fm
Sanford et al. μC elastic: $2.32^{+0.13}_{-0.18}$ fm

Perhaps carbon is right, e’s and μ’s are the same.

Perhaps hydrogen is right, e’s and μ’s are different.

Perhaps both are right - opposite effects for proton and neutron cancel with carbon.

But perhaps the carbon radius is insensitive to the nucleon radius, and μd or μHe would be a better choice?

Also: A. Antognini et al: Muonic H + eH/D isotope shift $\rightarrow r_d = 2.12771(22)$ fm vs. $2.130(10)$ fm from ed scattering.
MUSE – PSI R12-01.1 Technique

\[ \frac{d \sigma}{d \Omega(Q^2)} = \text{counts} / (\Delta \Omega \ N_{\text{beam}} \ N_{\text{target/area}} \times \text{corrections} \times \text{efficiencies}) \]

\[
\left[ \frac{d \sigma}{d \Omega} \right] = \left[ \frac{d \sigma}{d \Omega} \right]_{ns} \times \left[ \frac{G^2_E(Q^2) + \tau G^2_M(Q^2)}{1 + \tau} + \left( 2\tau - \frac{m^2}{M^2} \right) G^2_M(Q^2) \frac{\eta}{1 - \eta} \right]
\]

\[
\left[ \frac{d \sigma}{d \Omega} \right]_{ns} = \frac{\alpha^2}{4E^2} \frac{1 - \eta}{\eta^2} \frac{1/d}{\left[ 1 + \frac{2E d}{M} \sin^2 \frac{\theta}{2} + \frac{E}{M} (1 - d) \right]}
\]

\[
d = \frac{\left[ 1 - \frac{m^2}{E^2} \right]^{1/2}}{\left[ 1 - \frac{m^2}{E'^2} \right]^{1/2}}
\]

\[
\eta = \frac{Q^2}{4EE'}
\]

following Preedom & Tegen,
PRC36, 2466 (1987)
Experiment Overview

PSI πM1 channel
≈115, 153, 210 MeV/c mixed beams
of e\(^\pm\), μ\(^\pm\) and π\(^\pm\)
θ ≈ 20° - 100°
Q^2 ≈ 0.002 - 0.07 GeV^2
About 5 MHz total beam flux,
≈2-15% μ's, 10-98% e's, 0-80% π's
Beam monitored with SciFi,
``quartz`` Cerenkov, GEMs
Scattered particles detected with
wire chambers and scintillators

Not run like a normal cross section experiment – 7-10 orders of magnitude lower luminosity.
But there are some benefits: count every beam particle, no beam heating of target, low rates in detectors, ...
MUSE: $\mu p$ Scattering at PSI

$\mu p$ and $ep$ comparison:

- BSM physics could lead to different FF and radii although the effect in scattering experiments could go away once $Q^2 > m^2_{new}$

- Measure both $\mu^\pm p$ and $e^\pm p$ for $2\gamma$ exchange

- Proton polarizibility effect enhances $2\gamma$ exchange

- MUSE is in the low $Q^2$ region, 0.002 - 0.07 GeV$^2$, (similar to Mainz and JLab experiments) for sensitivity to radius

- A variety of 2nd generation experiments (lower $Q^2$, $\mu^\pm n$, higher $Q^2$, PV, "heavy" nuclei ...) are already being considered.
PSI πM1 Channel Characteristics

\[ \approx 100 - 500 \text{ MeV/c mixed beam of } \mu's + e's + \pi's \]

Beam spot (nominal):
1.5 cm X x 1 cm Y,
35 mr X' x 75 mr Y'

Dispersion at IFP: 7cm/%

Spot sizes from 0.7x0.9 cm² up to 16x10 cm², and \( \Delta p/p \) from 0.1-3.0%, used previously.

Momentum acceptance: 3% resolution: 0.1%

Used in past as pion line, so muon properties were not well studied

-270 MeV/c

\[ +160 \text{ MeV/c} \]

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MUSE Test Run Report
The MUon proton Scattering Experiment collaboration (MUSE):

W.J. Briscoe,¹ K. Deiters,² E. Downie,¹ R. Gilman,³ K.E. Myers,³ E. Piasecki,⁴ D. Reggiani,² P. Reimer,⁵ G. Ron,⁶ V. Sulkosky,⁷ and M. Taragin⁸

Recycled (3 mm) SciFi + prototype SC scintillators (5 cm x 5 cm)

test run report on website:
http://www.physics.rutgers.edu/~rgilman/elasticmup

NIM trigger, VME read out, working physicists
Obtained RF time spectra for several momenta from \( \approx 110 \) to 225 MeV/c, and used these to determine relative particle fluxes.

RF peaks broader with 2.2 mA protons, \( \approx 350 \) ps (\( \sigma \)) for e's and 400 - 500 ps (\( \sigma \)) for \( \mu \)'s and \( \pi \)'s.
### πM1 Channel – particle fluxes

Limiting flux to 5 MHz total, by cutting the 3% momentum bite

<table>
<thead>
<tr>
<th>$p$ (MeV/c)</th>
<th>$\pi$ (MHz)</th>
<th>$\mu$ (MHZ)</th>
<th>$e$ (MHz)</th>
<th>momentum bite (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$+115$</td>
<td>0.43</td>
<td>0.43</td>
<td>4.0</td>
<td>1.8</td>
</tr>
<tr>
<td>$+153$</td>
<td>2.10</td>
<td>0.59</td>
<td>2.3</td>
<td>0.9</td>
</tr>
<tr>
<td>$+210$</td>
<td>4.1</td>
<td>0.39</td>
<td>0.54</td>
<td>0.2</td>
</tr>
<tr>
<td>$-115$</td>
<td>0.01</td>
<td>0.14</td>
<td>4.9</td>
<td>2.0</td>
</tr>
<tr>
<td>$-153$</td>
<td>0.55</td>
<td>0.17</td>
<td>4.3</td>
<td>1.3</td>
</tr>
<tr>
<td>$-210$</td>
<td>2.23</td>
<td>0.77</td>
<td>2.0</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Flux of $e$'s 1.4 – 35 times larger than flux of $\mu$'s
Beam Line Summary

- Good flux of µ's at target, much better flux of e's
- Beam spot smaller than nominal (σ)
- Beam properties independent of particle type
- Protons not an issue at our momenta
- Particles can be separated by ≈ns level RF timing at ≈115, 153, 210 MeV/c for our geometry
- Beam emittance requires event by event tracking into target with GEMs
- Time width of particles appears to be 500 ps (σ), except electrons appear to be ≈350 ps ⇒ necessitates high timing precision beam Cerenkov for rejection of µ decays
## Next Few Years for MUSE

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 2012</td>
<td>First PAC presentation</td>
</tr>
<tr>
<td>July 2012</td>
<td>PAC/PSI Technical Review</td>
</tr>
<tr>
<td>fall 2012</td>
<td>1st test run in πM1 beamline</td>
</tr>
<tr>
<td>Jan 2013</td>
<td>PAC approval</td>
</tr>
<tr>
<td>summer 2013</td>
<td>2nd test run in πM1 beamline</td>
</tr>
<tr>
<td>fall 2013</td>
<td>funding requests</td>
</tr>
<tr>
<td>summer 2014</td>
<td>money arrives? - start construction</td>
</tr>
<tr>
<td>summer 2015</td>
<td>start assembling equipment at PSI</td>
</tr>
<tr>
<td>late 2015</td>
<td>set up and have dress rehearsal</td>
</tr>
<tr>
<td>2016-2017</td>
<td>2 6-month experiment production runs</td>
</tr>
</tbody>
</table>

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Second Test Run

- Use GEMs to more thoroughly characterize beam
- "Quartz" Cerenkov test
- Mini-scattering experiment
Beam passes though IFP SciFi array, shielding wall, target SciFi array, beam quartz Cerenkov, GEM chambers, target, and beam monitor scintillators.

Wire chambers and scintillator walls detect scattered particles.

Generally standard technology.

Geant4 estimates of background singles and trigger rates. Target / collimator backgrounds are very sensitive to beam distributions.

Need custom FPGA trigger to trigger on scattering events while rejecting all π-induced events.
## New Equipment Summary

<table>
<thead>
<tr>
<th>Detector</th>
<th>Who</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam SciFi</td>
<td>Tel Aviv, St. Mary's</td>
<td>conventional</td>
</tr>
<tr>
<td>GEMs</td>
<td>Hampton</td>
<td>detector exists</td>
</tr>
<tr>
<td>Quartz Cerenkov</td>
<td>Hebrew</td>
<td>prototyped</td>
</tr>
<tr>
<td>FPGAs</td>
<td>Rutgers</td>
<td>conventional</td>
</tr>
<tr>
<td>target</td>
<td>Hebrew</td>
<td>conventional</td>
</tr>
<tr>
<td>wire chambers</td>
<td>MIT</td>
<td>copy existing system</td>
</tr>
<tr>
<td>scintillators</td>
<td>SC</td>
<td>copy existing system</td>
</tr>
<tr>
<td>DAQ</td>
<td>GWU</td>
<td>conventional, except TRB3 prototyped</td>
</tr>
</tbody>
</table>
Estimated Results!

- statistical uncertainties only
- similar results for $e^-p$ and $\mu^-p$
- $\pi M1$ channel, with $p_{in} = 115, 153, \text{and } 210 \text{ MeV/c}$: PID reasons.
- 6 month run, equal time for each setting
- Choose $\theta_{scatter} = 20 - 100^\circ$: rates, backgrounds, systematics.
- Statistical uncertainties include end cap subtractions and $\mu$ decay subtractions (for $\mu$'s) - the issue for 210 MeV/c at larger $Q^2$
Estimated Results!

- statistical uncertainties only
- endcap BG mainly at $\epsilon$ near 1

$\mu^+p$'s are limited by $\mu$ decay rejection - here with very conservative estimate - rather than by systematics

$e^+/e^-$ generally limited by radiative corrections, but here $1\gamma$ radiative corrections cancel and a concern is detection response systematics from $e^+$ annihilation (One check: $2\gamma \rightarrow 0$ as $\epsilon \rightarrow 1$)

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Radius extraction from J Arrington.

Left: independent absolute extraction.

Right: extraction with only relative uncertainties.
The proton radius puzzle is a high-profile issue

Explanation unclear

PSI MUSE tests interesting possibilities: Are $\mu p$ and $ep$ interactions different? If so, does it arise from $2\gamma$ exchange effects ($\mu^+\neq\mu^-$) or BSM physics ($\mu^+\approx\mu^+\neq e^-$)?

Within 3–4 years (budgets willing) we should have new electron scattering results and start to see the muon scattering results, and possibly start to resolve the puzzle, perhaps seeing new physics!
Collaboration

The MUon proton Scattering Experiment collaboration (MUSE):

R. Gilman (Contact person),¹ E.J. Downie (Spokesperson),² G. Ron (Spokesperson),³
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