The MUSE experiment at PSI: Status and Plans

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(for the MUSE collaboration)
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The Proton Radius Puzzle
• What is the problem?
• How do we solve it: MUSE?
The Proton Radius Puzzle
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What exactly is the puzzle?
How do you measure proton radius?

- **Scattering experiments**
  
  (Hofstadter @ Stanford: 1950s - electron scattering)

\[
\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega} \bigg|_{\text{point}} \times \left( G(Q^2) \right)^2
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\langle r_E^2 \rangle = -6 \frac{dG(Q^2)}{dQ^2} \bigg|_{Q^2=0}
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- **Atomic Energy Levels**

\[
\Delta E_1 = \frac{2\pi\alpha}{3} \left| \phi^2(0) \right| \langle r_E^2 \rangle
\]

- **Lamb Shift**: Finite size of proton changes hydrogen energy level
  (only affects s states significantly, not p states)

- **Extract from** hydrogen spectroscopy
Electron Scattering Measurements

- Cross section for ep scattering (Born approximation)

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{\text{Mott}} \left( 1 + \tau \right) \frac{\tau G_M^2 + \varepsilon G_E^2}{\varepsilon (1 + \tau)}$$

with

$$\tau = \frac{Q^2}{4M^2}$$

$$\varepsilon = \left[ 1 + 2(1 + \tau) \tan^2 \frac{\theta}{2} \right]^{-1}$$

$$G_E^2(0) = 1; G_M^2(0) = \mu_p$$

- Classical Rosenbluth separation
  - measure the reduced cross section at several values of $\varepsilon$ (angle/beam energy combination) while keeping $Q^2$ fixed
  - linear fit to get intercept and slope

- Note: $G_M$ is suppressed at low $Q^2$
  $\rightarrow G_E$ dominates cross section at low $Q^2$
Electron Scattering Measurements

- Cross section for ep scattering (Born approximation)

\[
\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{\text{Mott}} \left( \frac{1}{\varepsilon(1+\tau)} \right) \left[ \tau G_M^2 + \varepsilon G_E^2 \right]; \quad \text{with} \quad \tau = \frac{Q^2}{4M^2}; \quad \varepsilon = \left[ 1 + 2(1+\tau) \tan^2 \frac{\theta}{2} \right]^{-1}
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- Note: \(G_M\) is suppressed at low \(Q^2\)
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- Alternatively: direct fits of \(G_M(Q^2)\) and \(G_E(Q^2)\) to experimental cross section data
Hydrogen Spectroscopy Measurements

The Proton Radius from H Lamb Shift

Comparing measurements with QED calculations that include corrections for finite size of proton provide indirect but very precise value for \( \langle r_E^2 \rangle \)
Hydrogen Spectroscopy Measurements

The Proton Radius from H Lamb Shift

Energy

n=3

n=2

2P_{3/2}

n=1

2S_{1/2}, 2P_{1/2}

2P_{1/2}

2S_{1/2}

F=1

F=0

0.15 MHz

Shift:
-43.5 GHz

8.2 GHz

1.4 GHz

1.2 MHz

Lamb

hfs-splitting

r_p

Bohr

Dirac

E = R_{\infty}/n^2

V \sim 1/r

e^- spin

relativity

QED

proton-spin

H^{hfs} \sim \vec{\mu}_p \cdot \vec{\mu}_e

proton size

V \sim 1/r

comparing measurements with QED calculations that include corrections for finite size of proton provide indirect but very precise value for \( \langle r_E^2 \rangle \)
Hydrogen Atom Spectroscopy

\[ E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3} \]

Lamb shift: \[ L_{1S}(r_p) = 8171.636(4) + 1.5645 \langle r_p^2 \rangle \text{ MHz} \]

- 2 measurements required to determine \( R_\infty \) and \( r_p \)
  - A single narrow transition: 1S-2S (\( \Delta \nu = 1.3 \text{ Hz} \)) measured with high accuracy.
  - Other transitions: natural width \( \sim \text{ MHz} \).

Each measurement, combined with 1S-2S, yields a correlated pair \((R_\infty, r_p)\).
The Proton Radius from H Lamb Shift and ep

proton rms charge radius measured with electrons: $0.8770 \pm 0.0045$ fm (CODATA2010+Zhan et al.)
The Proton Radius from H Lamb Shift and ep

All is good:
scattering data and H-atom data agree very well

But can we do better?
use Muonic Hydrogen

proton rms charge radius measured with electrons:
0.8770 ± 0.0045 fm (CODATA2010+Zhan et al.)
Why Measure with $\mu$H?

Regular hydrogen:

\[ \text{electron} \quad e^- \quad + \quad \text{proton} \quad p \]

Muonic hydrogen:

\[ \text{muon} \quad \mu^- \quad + \quad \text{proton} \quad p \]

muon mass \quad m_\mu = 207 \quad m_e

Bohr radius \quad a_{B,\mu} = \frac{1}{207} \quad a_{B,e}

figure not to scale
Why Measure with $\mu H$?

Regular hydrogen:

\[ \text{electron } e^- + \text{proton } p \]

Muonic hydrogen:

\[ \text{muon } \mu^- + \text{proton } p \]

- Muon mass $m_\mu = 207 \ m_e$
- Bohr radius $a_{B,\mu} = 1/207 \ a_{B,e}$

Probability for $\mu^-$ to be inside proton:

\[
3 \left( \frac{r_p}{a_B} \right)^3 \approx \left( r_p \alpha \right)^3 m^3
\]

\[ \rightarrow 207^3 \approx 8 \text{ million} \]

Muon is much more sensitive to proton radius.
The Proton Radius from H & $\mu$H Lamb Shift and ep
The Proton Radius Puzzle

Proton radius measured with

atomic physics and electron scattering: \(0.8751 \pm 0.0061\) fm

muonic hydrogen: \(0.8409 \pm 0.0004\) fm

Radius from Muonic Hydrogen 4\% below previous best value

→ 12\% smaller (volume), 12\% denser than previously believed
Why do the muon and electron give different proton radii?
Why do the muon and electron give different proton radii?

- Experimental error in $\mu p$ measurement?

\[ \Delta E \left( 2P_{3/2}^F - 2S_{1/2}^F \right) = 209.9779(49) - 5.2262r_p^2 + 0.0347r_p^3 \text{ [meV]} \]

0.84184 ± 0.00067 fm: 5σ off 2006 CODATA
Why do the muon and electron give different proton radii?

- **Experimental error in μp measurement?**
  - seems unlikely
- **Experimental error in ep measurements?**
  - both scattering and H-spectroscopy are wrong?
  - Rydberg constant off by 5σ?
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- **Theory Error?**

### Table

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<td>NR One loop electron VP</td>
<td>[31, 32]</td>
<td>205.0074</td>
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<td>Relativistic correction (corrected)</td>
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<td>Polarization insertion in two Coulomb lines</td>
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<td>NR three-loop electron VP</td>
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<td>Wichmann-Kroll</td>
<td>[34, 37, 38]</td>
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<td>Light by light electron loop contribution (Virtual Delbrück scattering)</td>
<td>[39]</td>
<td>0.00135</td>
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<td>Radiative photon and electron polarization in the Coulomb line $\alpha^2(2\alpha)^4$</td>
<td>[31, 32]</td>
<td>0.00103</td>
<td>-0.00103</td>
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<td>Electron loop in the radiative photon of order $\alpha^2(2\alpha)^4$</td>
<td>[33–42]</td>
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<td>Mixed electron and muon loops</td>
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<td>0.000377</td>
<td>0.00038</td>
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<td>Hadronic polarization of $(Z\alpha)^3 \mu$</td>
<td>[44–46]</td>
<td>0.010770</td>
<td>0.00038</td>
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<td>Racel contribution</td>
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<td>Recall finite size</td>
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<td>0.00410</td>
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<td>Recall correction to VP</td>
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<td>-0.00410</td>
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<td>Radiative corrections of order $\alpha^3(2\alpha)^4 \mu$</td>
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<td>-0.067</td>
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<td>Muon Lamb shift 4th order</td>
<td>[34]</td>
<td>-0.00169</td>
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<td>Racel corrections of order $\alpha^3(2\alpha)^4 \mu$</td>
<td>[19, 32, 34, 36]</td>
<td>-0.01477</td>
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<td>Racel of order $\alpha^3$</td>
<td>[33]</td>
<td>0.00030</td>
<td>0.00030</td>
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<td>Radiative recall corrections of order $\alpha^3(2\alpha)^4 \mu$</td>
<td>[19, 31, 32]</td>
<td>0.000683</td>
<td>0.000683</td>
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<td>Nuclear structure correction of order $(Z\alpha)^2 \mu$</td>
<td>[32, 34, 45, 46]</td>
<td>0.015</td>
<td>0.004</td>
<td>0.012</td>
<td>0.002</td>
<td>0.015</td>
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<tr>
<td>(Proton polarizability contribution)</td>
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<td>Polarization operator induced correction to nuclear polarizability of $(Z\alpha)^2 \mu$</td>
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<td>0.00019</td>
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<td>Radiative photon induced correction to nuclear polarizability of $(Z\alpha)^2 \mu$</td>
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<td>-0.00001</td>
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<tr>
<td>Sum</td>
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<td>206.05373</td>
<td>0.00425</td>
<td>206.05423</td>
<td>0.00723</td>
<td>206.05856</td>
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  - **BSM Physics**
    - violation of lepton universality
  - **Novel Hadronic Physics**
    - proton polarizability affects $\mu$, but not $e$ (effect $\propto m_l^4$)
    - two-photon exchange corrections (effects important at high $Q^2$)
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Need More Data
The Quest for New Data

- Experiments include
  - redoing atomic hydrogen
  - light muonic atoms for radius comparison in heavier systems
  - redoing electron scattering at lower $Q^2$
  - Muon scattering!

- New data needed to test that the e and $\mu$ are really different, and the implications of novel hadronic physics
  - **BSM:** compare $ep$ to $\mu p$ scattering
  - **Hadronic:** enhanced $2\gamma$ exchange effects
The Quest for New Data

- **Experiments include**
  - redoing atomic hydrogen
    - conflicting results: more careful systematics?
  - light muonic atoms for radius comparison in heavier systems
    - puzzle seen in H & D, but not in He: (Z=1 radius puzzle?)
  - redoing electron scattering at lower \( Q^2 \)
    - many efforts
    - PRad (windowless \( H_2 \) gas flow target → removes major bkgds) is consistent with \( \mu p \) results!
  - **Muon scattering!**
    - **MUSE** (2019-2021)
    - plans at COMPASS (100 GeV SPS muon beam: 2021-2023)
μp Scattering – The missing Piece

Electronic hydrogen
0.8758 ± 0.0077

Muon scattering

Muonic hydrogen
0.84087 ± 0.00039

Electron scattering
0.8770 ± 0.0060

Scattering

Muon scattering
???
Direct comparison of $\mu p$ and $ep$ scattering!

→ beam of $e^+/\pi^+/\mu^+$ or $e^-/\pi^-/\mu^-$ on LH$_2$ target
  - separate particles by TOF, charge by magnets
→ charge reversal: test two photon effects
→ absolute cross sections for ep and $\mu p$
  - use ratio to cancel systematics
→ momenta: 115 – 210 MeV/c; $Q^2 = 0.002 – 0.07$ GeV$^2$
→ extract $G_E$ and $G_M$ from fits to experimental cross section data
MUSE: an unusual Scattering Experiment

- **Secondary beam** → identify and track beam particles
- **Low beam flux** (3 MHz) → large acceptance, non-magnetic spectrometer
- **Mixed beam** → PID in trigger
Liquid hydrogen target
→ 280 ml Kapton cylinder
→ full and empty targets

Target chamber in PiM1
• **Target Temperature:** $20.67 \pm 0.01$ K  
  – corresponds to a pressure of $\sim 1.1$ bar

• **Target density:** $0.070 \text{ g/cm}^3$ (stable to 0.02%)  
  – once equilibrium concentration of para (>99%) and ortho (<1%) hydrogen has been reached
Current status

- 18 test runs (2012 – 2019) (beam studies, detector development, and commissioning) demonstrate simulation agreement & reliable performance
- Construction completed
  - commissioning almost complete
  - 12 months total data-taking in 2019 - 2021
Two-photon exchange at low $Q^2$

- **High precision** test of TPE for electron and muons at low $Q^2$
- TPE largest theor. uncertainty in low-energy proton structure
- expect sign change for $e^+$ and $e^-$

- projected relative uncertainty in $\mu^+p$ to $\mu^-p$ elastic cross sections
- systematics: 0.2%
Comparison of ep to μp cross sections

- projected relative statistical uncertainties in the ratio of ep to μp elastic cross sections (mass difference removed in ratio)
- systematics: 0.5%

- relative statistical uncertainties in the form factors are half as large
Projected sensitivity for MUSE

- **absolute radius** extraction uncertainty similar to current experiments
  \[ \sigma(r_e), \sigma(r_\mu) \approx 0.009 \text{ fm} \]

- **radius difference**: common uncertainties cancel
  - comparison of \( \mu \) to \( e \), or \( \mu^+ \) to \( \mu^- \)
    insensitive to many syst. errors
  \[ \sigma(r_e - r_\mu) \approx 0.005 \text{ fm} \]
  \[ \rightarrow \text{almost factor two more sensitive than absolute radius extraction} \]
  \[ \rightarrow \text{almost factor ten better than current discrepancy} \]
Summary

- We are still (possibly more) puzzled!

- Proton radius puzzle
  - discrepancy between muonic and electronic measurements remains a serious problem
  - need new data

- Expect new results in the coming years

- MUSE (w/ electron & muon scattering)
  - give first precise muon scattering results
  - will test existing values of radius
  - will test two photon exchange / proton polarizability
  - lepton universality
Backup slides
Finite-size shift of atomic energy levels

S states: max. at r=0

Electron sometimes inside the proton.

S states are shifted.

Shift is proportional to the size of the proton

P states: zero at r=0

Electron is not inside the proton.

Orbital pictures from Wikipedia

Pictures: R. Pohl
Redoing Atomic Hydrogen

MPQ (Garching): NEW proton is small in regular hydrogen, too!

LKB (Paris): Prelim. No, it’s not!

Systematics need to be carefully determined

$\mu H$ and $eH$ difference is only significant when results are averaged
• CREMA Collaboration moved on to heavier atoms!

• Deuterium radius from $\mu D$ agrees with $\mu H$
  - deuteron charge radius: $r_d$ again $7\sigma$ away from CODATA

• Helium isotopes seem to agree (preliminary results)

• Puzzle seen in H & D ($Z=1$ radius puzzle?)

Pictures: R. Pohl
Redoing electron scattering at lower $Q^2$

- **Jlab: PRad**
  - low intensity beam in Hall B @ JLab into windowless gas target (1.3 billion H events)
  - Preliminary $G_E$ slope favors smaller radius

- **Mainz: ISR**
  - exploit information in radiative tail
  - dominated by coherent sum of ISR and FSR
  - investigate $G_E$ down to $Q^2 = 10^{-4}$ GeV$^2$/c$^2$
  - results not precise enough $\rightarrow$ upgrades underway

- **LPSC, Grenoble: ProRad**
  - New accelerator to be built in France
  - constrain $Q^2$-dependence of $G_E$ and extrapolation to zero
  - non-magnetic spectrometer, frozen hydrogen wire / film target
MUon Scattering Experiment (MUSE) at PSI

58 MUSE collaborators from 25 institutions in 5 countries:

George Washington University, Montgomery College, Argonne National Lab, Temple University, College of William & Mary, Duquesne University, Massachusetts Institute of Technology, Christopher Newport University, Rutgers University, Hebrew University of Jerusalem, Tel Aviv University, Paul Scherrer Institut, Johannes Gutenberg-Universität, Hampton University, University of Michigan, University of Virginia, University of South Carolina, Jefferson Lab, Los Alamos National Laboratory, Norfolk State University, Technical University of Darmstadt, St. Mary’s University, Soreq Nuclear Research Center, Ieizmann Institute, Old Dominion University