The Proton Radius Experiment at Jefferson Lab (PRad)

A. Gasparian
NC A&T State University, NC USA
for the PRad collaboration

Outline
- Status of the “Proton Radius Puzzle”
- The PRad experiment
- Status of the run and the data quality
- Summary
The Proton Radius Puzzle (2010)

- Proton radius is one of the most fundamental quantities in physics:
  - Critically important for atomic physics in precision spectroscopy of atom (Rydberg constant)
  - Precision test of nuclear/particle models
  - Connects atomic and subatomic physics

- ~ 8 $\sigma$ discrepancy between the new muonic-hydrogen measurements and all previous results

New muonic-hydrogen result
A. Antognini et al., Science 339, 417 (2013)

The proton rms charge radius measured with
- electrons: 0.8770 ± 0.0045 fm (CODATA2010+Zhan et al.)
- muons: 0.8409 ± 0.0004 fm
New, preliminary value for $R_p$ was reported in PRP-2016 Workshop (Trento, Italy) from ordinary hydrogen
Consistent with the muonic-hydrogen result!
Is the Puzzle solved? No, new measurements are needed (spectroscopy, ep-scattering)
Extraction of $r_p$ from $ep\rightarrow ep$ Experiments

- In the limit of first Born approximation the elastic $ep$ scattering (one photon exchange):

\[
\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \left( \frac{E'}{E} \right) \frac{1}{1 + \tau} \left( G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2) \right)
\]

\[
Q^2 = 4EE' \sin^2 \frac{\theta}{2} \quad \tau = \frac{Q^2}{4M_p^2} \quad \varepsilon = \left[ 1 + 2(1 + \tau) \tan^2 \frac{\theta}{2} \right]^{-1}
\]

- Structureless proton:

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} = \frac{\alpha^2 \left[ 1 - \beta^2 \sin^2 \frac{\theta}{2} \right]}{4k^2 \sin^4 \frac{\theta}{2}}
\]

- $G_E$ and $G_M$ were extracted using Rosenbluth separation (or at extremely low $Q^2$ the $G_M$ can be ignored, like in the PRad experiment)

- The Taylor expansion at low $Q^2$:

\[
G_E^p(Q^2) = 1 - \frac{Q^2}{6} \langle r^2 \rangle + \frac{Q^4}{120} \langle r^4 \rangle + \ldots
\]

\[
\langle r^2 \rangle = -6 \left. \frac{dG_E^p(Q^2)}{dQ^2} \right|_{Q^2=0}
\]
A New ep→ep Experiment?

- Practically all ep-experiments are done with magnetic spectrometers!

- Limitation on minimum $Q^2$: $10^{-3}$ GeV/C$^2$
  - Limitation on min. scattering angle: $\theta_e \approx 5^0$
  - Typical beam energies: $\sim 0.1 \div 1$ GeV

- Absolute cross section measurement is needed ($d\sigma/d\Omega$):
  - Statistics is not a problem ($<0.2\%$)
  - Control of systematic errors???
    - Electron beam flux;
    - Target thickness and windows;
    - Geometrical acceptances;
    - Detection efficiencies, …
    - Typical uncertainty: $\sim 2 \div 3\%$

- A possible solution (the PRad approach):
  - Non-magnetic-spectrometer method
  - No target windows
  - Calibrate with other well-known QED processes
PRad Experiment

- Experimental goals:
  - reach to very low $Q^2$ range ($\sim 10^{-4}$ GeV/C$^2$)
  - reach to sub-percent precision in cross section
  - large $Q^2$ range in one experimental setting

- Suggested solutions:
  - use high resolution high acceptance calorimeter:
    - reach smaller scattering angles: ($\Theta = 0.7^0 - 7.0^0$)
    - ($Q^2 = 1 \times 10^{-4} \div 6 \times 10^{-2}$) GeV/c$^2$
    - large $Q^2$ range in one experimental setting!
    - essentially, model independent $\rho_p$ extraction
  - Simultaneous detection of $ee \rightarrow ee$ Moller scattering
    - (best known control of systematics)
  - Use high density windowless H$2$ gas flow target:
    - beam background fully under control
    - minimize experimental background

- Two beam energies: $E_0 = 1.1$ GeV and 2.2 GeV to increase $Q^2$ range
- Will reach sub-percent precision in $R_p$ extraction
- Approved by JLab PAC39 (June, 2012) with high “A” scientific rating

Recent Mainz low $Q^2$ data set from Phys. Rev. C 93, 065207, 2016
PRad Experiment Timeline

✓ Initial proposal development: 2011-12

✓ Approved by JLab PAC39: 2012

✓ Funding proposal for windowless H$_2$ gas flow target (NSF MRI #PHY-1229153): 2012

✓ Development, construction of the target: 2012 – 15

✓ Funding proposals for the GEM detectors: 2013 (DOE awards)

✓ Development, construction of the GEM detectors: 2013-15

✓ Experiment Readiness Reviews: 2015, 2016

✓ Beam line installation: January /April 2016

✓ Beam Commissioning: May 2016

✓ Experimental data taking: May, June 2016
Main detector elements:
- windowless \( \text{H}_2 \) gas flow target
- PrimEx HyCal calorimeter
- vacuum box with one thin window at HyCal end
- \( X,Y \) – GEM detector on front of HyCal

Beam line equipment:
- standard beam line elements (0.1 – 10 nA)
- photon tagger for HyCal calibration
- collimator box (6.4 mm collimator for photon beam, 12.7 mm for \( e^- \) beam halo “clean-up”)
- Harp 2H00
- pipe connecting Vacuum Window through HyCal
Jefferson Lab CEBAF accelerator Facility
(aerial view)

Newport News, VA USA

PRad was performed in Hall B
Jefferson Lab CEBAF accelerator Facility
(schematic view)

PRad was performed in Hall B
**P**R**a**d Experimental Setup Installed in the Hall B Beam Line

- Beam line installation completed in May of 2016
Windowless $\text{H}_2$ Gas Flow Target
(Schematics)

- **A windowless** gas target of cryogenically cooled hydrogen
  - Target cell is 4 cm long copper, attached to cryocooler via heat strap
  - Cell diameter: 8 cm
  - Cell covers are 7.5 $\mu$m kapton with 2 mm beam orifices
  - Two additional solid target foils: 1 $\mu$m $12\text{C}$ and Al
  - $\text{H}_2$ input gas temp. 19.5 K

- Four-axis motion system to position the target cell with 10 $\mu$m accuracy
Windowless H$_2$ Gas Flow Target Installed in Hall B Beam Line

✓ Areal density: $1.8 \times 10^{+18}$ H atoms/cm$^2$

  cell pressure: 471 mtorr  
  chamber pressure: 2.34 mtorr

  cell vs. chamber pressures: 200:1 has been reached.

✓ cell vs. first vacuum tank pressures: 1000:1 has been reached (471 mtorr: 0.3 mtorr);

Target installed in Hall B beam line, May 2016
Electromagnetic Calorimeter (PrimEx HyCal)

- Combination of PbWO$_4$ and Pb-glass detectors (118x118 cm$^2$)
  - 34 x 34 matrix of 2.05 x 2.05 x 18 cm$^3$ PbWO$_4$ shower detectors
  - 576 Pb-glass shower detectors (3.82x3.82x45.0 cm$^3$)
  - 2 x 2 PbWO$_4$ modules removed in middle for beam passage
  - 5.5 m from H$_2$ target (~0.5 sr acceptance)

- Resolutions:
  - for PbWO$_4$ shower detectors:
    - energy: $\sigma/E = 2.6 \%/\sqrt{E}$
    - position: $\sigma_{xy} = 2.5 \text{mm}/\sqrt{E}$
  - for Pb-glass shower detectors factor of ~2.5 worse
Electromagnetic Calorimeter in Hall B beam Line
GEM Coordinate Detectors

- Tasks for GEM:
  - factor of >20 improvements in coordinate resolutions
  - similar improvements in $Q^2$ resolution (very important)
  - unbiased coordinate reconstruction (including HyCal transition region)
  - increase $Q^2$ range by including HyCal Pb-glass part

- Designed and built at University of Virginia (UVa)

- Two large size GEM X and Y- coordinate detectors with 100 µm position resolution
GEM Coordinate Detectors in Hall B Beam Line

2 GEM detectors installed in Hall B beam line, May 2016
Vacuum Box

2-stage vacuum box in Hall B beam line

1.7 m diameter, 2 mm Al vacuum window
Done by “harp” scan before the target;
typical size: 20 μm
Experimental Data Collected  
(May/June 2016 Run)

- with $E_e = 1.1$ GeV beam:
  - ✓ 4.2 mC (target areal density: $2 \times 10^{+18} \text{ H atoms/cm}^2$)
  - ✓ 604 M events with target;
  - ✓ 53 M events with “empty” target;
  - ✓ 25 M events with $^{12}\text{C}$ target for calibration.

- with $E_e = 2.2$ GeV beam:
  - ✓ 14.3 mC (target areal density: $2 \times 10^{+18} \text{ H atoms/cm}^2$)
  - ✓ 756 M events with target;
  - ✓ 38 M events with “empty” target;
  - ✓ 10.5 M events with $^{12}\text{C}$ target for calibration.
Fresh Results from On-Line Analysis
(HyCal - GEM single-cluster event matching)

- $ep \rightarrow ep$ event candidate
Fresh Results from On-Line Analysis
(HyCal-GEM double-cluster event matching)

- $ee \rightarrow ee$ event candidate
Fresh Results from On-Line Analysis
(clear signature of Møller events)

Very Preliminary

Møller opening angle (deg)

Very Preliminary

Møller $\Delta \varphi$ (deg)
Fresh Results from On-Line Analysis
(2D distribution of cluster energy vs. scattering angle)

\[ E_0 = 2.2 \text{ GeV} \]

Cluster Energy \( E \) vs Scattering Angle \( \theta \)

Very Preliminary
Fresh Results from On-Line Analysis

$N_{ep\rightarrow ep}$ vs. Scattering Angle $\theta$

$E_0 = 1.092$ GeV

0.3% of Data

Preliminary
Fresh Results from On-Line Analysis

$N_{e^p \rightarrow e^p}$ vs. $Q^2$

$E_0 = 2.147$ GeV, 0.5% of data

$E_0 = 1.099$ GeV, 0.3% of data

Preliminary
Currently 16 collaborating universities and institutions

- Jefferson Laboratory
- NC A&T State University
- Duke University
- Idaho State University
- Mississippi State University
- Norfolk State University
- University of Virginia
- Argonne National Laboratory
- University of North Carolina at Wilmington
- University of Kentucky
- Hampton University
- College of William & Mary
- Tsinghua University, China
- Old Dominion University
- ITEP, Moscow, Russia
- Budker Institute of Nuclear Physics, Novosibirsk, Russia
Summary

- PRad was uniquely designed to address the “Proton Radius Puzzle”

- Experiment had been performed in May/June of 2016

- Large statistics, high quality, rich data have been collected:
  - Lowest $Q^2$ data set ($\sim 10^{-4}$ GeV/C$^2$) has been collected for the first time in ep-scattering experiments;
  - Simultaneous measurement of Moller and Mott scattering processes has been demonstrated to control systematic uncertainties.

- Data analysis has been started, first preliminary results for this year are possible

- PRad is supported in part by NSF MRI award #PHY-1229153 as well as DOE awards for GEM
- my research work is supported in part by NSF awards: PHY-1506388 and PHY-0855543
The End
The CEBAF Electron Beam at JLab

- Beam current monitoring (55 nA)

- X and Y position stability (± 0.1 mm)
Beam energy monitoring, $E_e = 2147.4$ MeV \ ($\Delta E/E = \pm 5 \times 10^{-4}$)
Fresh Results from On-Line Analysis
(2D distribution of cluster energy vs. scattering angle)

\[ E_0 = 1.1 \text{ GeV} \]

Cluster Energy \( E \) vs Scattering Angle \( \theta \)

Very Preliminary
Fresh Results from On-Line Analysis

$N_{ep ightarrow ep}$ vs. $Q^2$

$E_0 = 1.099$ GeV

0.3% of Data

Preliminary
Fresh Results from On-Line Analysis

$N_{ep\rightarrow ep}$ vs. $Q^2$

$E_0 = 2.147 \text{ GeV}$

$0.5\%$ of Data

$N_{ep} / (0.001 \text{ GeV})$

Preliminary

A. Gasparian

MENU2016
Estimated Uncertainties

<table>
<thead>
<tr>
<th>Contributions</th>
<th>Estimated Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical error</td>
<td>0.2</td>
</tr>
<tr>
<td>Acceptance (including $Q^2$ determination)</td>
<td>0.4</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>0.1</td>
</tr>
<tr>
<td>Radiative corrections</td>
<td>0.3</td>
</tr>
<tr>
<td>Background and PID</td>
<td>0.1</td>
</tr>
<tr>
<td>Fitting error</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Total Error</strong></td>
<td><strong>0.6%</strong></td>
</tr>
</tbody>
</table>

- Estimated error budget (added quadratically)
Muonic Deuterium

\[ r_d \] from \( \mu D \) 2S-2P:
J. Krauth, PSAS2016
+ PRP2016 (Trento), submitted


There is a deuteron radius puzzle:
7.5 \( \sigma \) between \( r_d \) (\( \mu D \)) and CODATA-2010