Proton Charge Radius (PRad) Experiment at Jefferson Lab

Weizhi Xiong
Duke University
For the PRad Collaboration
Spokespersons: A. Gasparian, H. Gao, M. Khandaker, D. Dutta

SPIN 2016
September 26th, 2016
Outline

• The proton charge radius puzzle

• PRad experiment at Jefferson Lab
  • Experimental goal and approach
  • PRad apparatus
  • Data acquisition status

• Preliminary online analysis results
Proton Charge Radius Puzzle

- Electronic measurement (ep elastic + ordinary H spectroscopy) v.s. muonic measurement (muonic H spectroscopy)

- $\mu p$ Lamb shift measurements by CREMA (2010, 2013)
  - Unprecedented precision, <0.1%
  - $7\sigma$ away from CODATA 2012 recommended value

- The discrepancy is not understood yet. New experiment with different systematic is necessary
Proton Charge Radius from ep Elastic Scattering

- Elastic ep scattering, in the limit of Born approximation (one photon exchange):
  \[
  \frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \left( \frac{E'}{E} \right) \frac{1}{1 + \tau} \left( G_E^p (Q^2) + \frac{\tau}{\epsilon} G_M^p (Q^2) \right)
  \]
  \[
  Q^2 = 4EE' \sin^2 \frac{\theta}{2} \quad \tau = \frac{Q^2}{4M_p^2} \quad \epsilon = \left[ 1 + 2(1 + \tau) \tan^2 \frac{\theta}{2} \right]^{-1}
  \]

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

- \( G_E \) and \( G_M \) were extracted using Rosenbluth separation, or at extremely low \( Q^2 \) the \( G_M \) can be ignored

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

Derivative at low \( Q^2 \) limit
\[
\langle r^2 \rangle = -6 \left. \frac{dG_E^p (Q^2)}{dQ^2} \right|_{Q^2=0}
\]
PRad Experiment Overview

- **PRad goal**: Measuring proton charge radius using ep elastic scattering

- Unprecedented low $Q^2$ ($\sim 2\times 10^{-4}$ GeV$^2$)
  - Fill in very low $Q^2$ region

- Large $Q^2$ range in a single setting
  - $\sim 2\times 10^{-4} - 6\times 10^{-2}$ GeV$^2$

- Calibrate to the simultaneously measured Møller scattering process
  - best known control of systematics

- Aims to extract cross section and radius to sub-percentage level

*Mainz low $Q^2$ data set*

PRad experiment was performed in Hall B at Jefferson Lab.
PRad Experimental Apparatus

- Windowless, high density H$_2$ gas flow target (background control)
- Vacuum box, one thin window at downstream
- High resolution and high efficiency, Hybrid calorimeter (HyCal)
- Two Large area Gas Electron Multipliers, improve position resolution
**Windowless Gas Target**

**Target cell**
(8 cm dia x 4 cm long copper)

7.5 μm kapton foil with 2mm hole

**Electron Beam**

**Areal density:** $\sim 2 \times 10^{18}$ H atoms / cm$^2$

**Cell / chamber / vacuum tank pressure:**
470 mtorr / 2.3 mtorr / 0.3 mtorr
Hybrid Calorimeter (HyCal)

- Used in the PrimEx experiment
- PbWO$_4$ and Pb-glass calorimeter (118x118 cm$^2$)
- 576 Pb-glass detectors (3.82x3.82 cm$^2$ x45 cm)
- 5.8 m from the target
- ~0.5 sr acceptance

**PbWO$_4$ resolution:**
- $\sigma_E/E = 2.6%/\sqrt{E}$
- $\sigma_{xy} = 2.5$ mm/$\sqrt{E}$

**Pb-glass:**
- 2.5 times worse
Gas Electron Multipliers (GEM)

- Two large area GEM detectors with 2D Cartesian readout planes
- ~100 $\mu$m position resolution

- The GEM detectors can provide:
  - >20 times improvement on position resolution
  - Similar improve for $Q^2$ resolution
PRad in Jefferson Lab Hall B

Beam-side view

GEMs mounted on HyCal
Experimental Data Collected

- Experiment ran in May - June 2016
- Large amount of data taken with high quality and stable electron beam from CEBAF
  - Beam position stability: ~250 μm
  - Beam width: ~ 25 μm
- Data taking with 1.1 GeV beam:
  - 604 M events with H₂ in cell
  - 53 M events without H₂ in cell
  - 25 M events with 1μm carbon foil target
  - Collected 4.2 mC on target (2x10^{18} H atoms/cm²)
- Data taking with 2.2 GeV beam
  - 756 M events with H₂ in cell
  - 38 M events without H₂ in cell
  - 10.5 M events with 1μm carbon foil target
  - Collected 14.3 mC on target (2x10^{18} H atoms/cm²)

\[ \sigma_x = 11.9 \mu m \]
\[ \sigma_y = 20.6 \mu m \]
\[ \sigma_r = 19.3 \mu m \]
Preliminary Online Analysis Results

Cluster E vs Scattering Angle \( \theta \)

**e-p elastic**

**Møller**

Initial calibration

(\(~1.5\% 2.2\text{GeV} \) data)
Preliminary Online Analysis Results

Cluster E vs Scattering Angle \( \theta \)

- **e-p elastic**
- **Møller**

Initial calibration (~2% 1.1 GeV data)
Preliminary Online Analysis Results

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

- Good $Q^2$ resolution and large statistics at low $Q^2$ will allow finer binning

~ 5% of data

Very Preliminary

Unnormalized

No acceptance correction

Projected relative statistical uncertainty
at 2.2 GeV for 100% data

Bin size: $2.5 \times 10^{-4} \text{ (GeV)}^2$

Projected relative statistical uncertainty
at 1.1 GeV for 100% data

Bin size: $1 \times 10^{-4} \text{ (GeV)}^2$
The PRad Collaboration

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

Graduate students
Chao Peng (Duke)
Li Ye (MSU)
Weizhi Xiong (Duke)
Xinzhan Bai (UVa)
Abhisek Karki (MSU)

Post-docs
Mehdi Meziane (Duke)
Zhihong Ye (Duke)
Krishna Adhikari (MSU)
Maxime Lavillain (NC A&T)
Rupesh Silwal (MIT)
Summary

• The Proton Radius Puzzle is still unsolved after six years

• The PRad experiment is a unique piece to the Puzzle:
  • Lowest $Q^2$ data set ($\sim 2 \times 10^{-4}$ GeV) has been collected for the first time in ep elastic scattering experiment
  • Data in a large $Q^2$ range ($\sim 2 \times 10^{-4} - 6 \times 10^{-2}$ GeV$^2$) has been collected with the same experimental setting
  • Large statistics, high quality, rich data has been collected
  • Systematic uncertainty well under control by simultaneous measurement of ep elastic and Møller processes

• Analysis is ongoing, first preliminary result expected soon

This work was supported by NSF-MRI grant PHY-1229153 and US DOE grant DE-FG02-07ER41528