Status of the PRad Experiment

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JLab Users Group Meeting
Outline

• Proton charge radius puzzle and PRad experiment

• PRad experimental apparatus

• Analysis and preliminary cross section

• Summary
Proton Charge Radius Puzzle

**Electron:** \(0.8751 \pm 0.0061\) fm
**Muon:** \(0.8409 \pm 0.0004\) fm

- \(\mu p\) Lamb shift measurements by CREMA (2010, 2013)
  - Unprecedented precision, <0.1%
Proton Charge Radius from ep Elastic Scattering

- Elastic ep scattering, in the limit of Born approximation (one photon exchange):

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

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

- 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 \( G_M \) can be extracted using Rosenbluth separation

- For PRad, cross section dominated by \( G_E \)

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

• Covers two orders of magnitude in low $Q^2$
  with the same detector setting
  • $\sim 2 \times 10^{-4} - 6 \times 10^{-2}$ GeV$^2$

• Normalize to the simultaneously measured Møller scattering process
  • best known control of systematics

• Aims to extract cross section and radius to sub-percentage precision
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PRad Timeline

- 2011 – 2012 Initial proposal
- 2012 Approved by JLab PAC39
- 2012 Funding proposal for windowless H2 gas flow target
- 2012 – 2015 Development, construction of the target
- 2013 Funding proposals for the GEM detectors
- 2013 – 2015 Development, construction of the GEM detectors
- 2015, 2016 Experiment readiness reviews
- Jan - Apr 2016 Beam line installation
- May 2016 Beam commissioning
- May 24 - 31 2016 Detectors calibration
- Jun 4 - 22 2016 Data taking
PRad Experimental Apparatus

PRad Setup (Side View)

New Cylindrical Vacuum Chamber

Electron beam
- 8 cm dia x 4 cm long target cell
- 2 mm holes open at front and back kapton foils, allows beam to pass through
- Target thickness: $\sim 2 \times 10^{18}$ H atoms / cm$^2$
PRad Experimental Apparatus

- 5 m long two stage vacuum chamber, further remove possible background source
- vacuum chamber pressure: 0.3 mTorr
PRad Experimental Apparatus

PRad Setup (Side View)

- Two large area GEM detectors
- Small overlap region in the middle
- Excellent position resolution (72 µm)
- Improve position resolution of the setup by > 20 times
- Large improvement for Q^2 determination
PRad Experimental Apparatus

PRad Setup (Side View)

- Hybrid EM calorimeter (HyCal)
  - Inner 1156 PWO$_4$ modules
  - Outer 576 lead glass modules
- 5.8 m from the target
- Scattering angle coverage: $\sim 0.6^\circ$ to $7.5^\circ$
- Full azimuthal angle coverage
- High resolution and efficiency
HyCal Resolution and Efficiency

- HyCal energy resolution and trigger efficiency extracted using high energy photon beam from Hall B at Jlab
  - > 99.5% trigger efficiency obtained for $E_{\gamma} > 500$ MeV, for various parts of HyCal
  - Energy resolution ~2.5% for PWO$_4$ part, lead glass part about 2.5 time worse
Performance of GEM Detectors

- GEM detection efficiency measured in both photon beam calibration (pair production) and production runs (ep and ee)
- Using overlap region of GEMs to measure position resolution (72 \( \mu m \))

GEM Efficiency in Active Area

Position Resolution

Plots courtesy of X. Bai
Cluster Energy $E'$ vs. Scattering Angle $\theta$

(after cluster matching between GEMs and HyCal, and background subtraction)

- Clear separation of $ep$ and $ee$ elastic scattering peak at both energy settings
$ep$ Experimental Yield

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

Very preliminary

~10% of data

$1.1 \text{ GeV}$

$2.2 \text{ GeV}$
Extraction of \( ep \) Elastic Cross Section

- To reduce the systematic uncertainty, the \( ep \) cross section is normalized to the Møller cross section:

\[
\left( \frac{d\sigma}{d\Omega} \right)_{ep} = \frac{N_{\text{exp}}(ep \rightarrow ep \text{ in } \theta_i \pm \Delta\theta)}{N_{\text{exp}}(ee \rightarrow ee)} \cdot \frac{\varepsilon_{\text{geom}}^{ee}}{\varepsilon_{\text{geom}}^{ep}} \cdot \frac{\varepsilon_{\text{det}}^{ee}}{\varepsilon_{\text{det}}^{ep}} \left( \frac{d\sigma}{d\Omega} \right)_{ee}
\]

- Event generators for unpolarized elastic \( ep \) and Møller scatterings have been developed based on complete calculations of radiative corrections beyond ultra relativistic approximation

- A Geant4 simulation package is used to study the radiative effects:

\[
\sigma_{ep}^{\text{Born}} = \left( \frac{\sigma_{ep}}{\sigma_{ee}} \right)^{\text{exp}} / \left( \frac{\sigma_{ep}}{\sigma_{ee}} \right)^{\text{sim}} \cdot \left( \frac{\sigma_{ep}}{\sigma_{ee}} \right)^{\text{Born}} \cdot \sigma_{ee}
\]
Preliminary Elastic $ep$ Cross Section

- Plots show the extracted differential cross section v.s. scattering angle and $Q^2$, with 2.2 GeV data in $0.7 \sim 3.5$ deg range (very preliminary)
- Statistical error at this stage: $\sim 0.2\%$ per point
- Systematic errors are conservatively assigned at $\sim 2\%$ at current stage (shown as shadow area)

$ep$ elastic scattering cross section

~50% 2.2 GeV data

Very Preliminary

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Systematic errors are conservatively assigned at $\sim 2\%$ at current stage (shown as shadow area)

~50% 2.2 GeV data

Very Preliminary
Analysis Plan

• We are currently still working on reducing and determining the syst. errors:
  • Cosmic contamination, GEM efficiency, background subtraction, RC…
• Finish cross section extraction for 2.2 GeV, include all runs and full angular range (0.7 ~ 6.0 deg)
• Finalize syst. error on 2.2 GeV cross section (by Sep 2017)
• Fit to extract proton charge radius from 2.2 GeV data (preliminary, Oct 2017, DNP meeting)
• Parallel work to extract cross section from 1.1 GeV runs (preliminary, Dec 2017)
• Finalize cross sections for both energy runs (Jul 2018)
• Final extraction of proton charge radius (Dec 2018)
Summary

• The *Proton Radius Puzzle* is still unsolved after seven years

• PRad experiment is uniquely designed to address the puzzle
  • Performed in May – June, 2016
  • Lowest $Q^2$ data set ($\sim 2 \times 10^{-4}$ GeV$^2$) has been collected for the first time in ep elastic scattering experiment
  • Data with two orders of magnitude in low $Q^2$ range ($\sim 2 \times 10^{-4} - 6 \times 10^{-2}$ GeV$^2$)

• Very preliminary cross section extracted from 2.2 GeV data, covering $Q^2$ from $7 \times 10^{-4}$ to $1.5 \times 10^{-2}$ GeV$^2$

• Expect to obtain proton charge radius from 2.2 GeV data by Oct 2017

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Backup
Stability

Beam spot position v.s. run

GEM efficiency v.s. run

Integrated ep/ee v.s. run

Very preliminary

After removing spacers