Analysis and Preliminary Results of the PRad Experiment at JLab

Weizhi Xiong
Duke University
for the PRad Collaboration
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Outline

• Proton charge radius puzzle and PRad experiment
• Experimental apparatus
• Analysis and preliminary results
• Summary
Electron scattering: $0.8751 \pm 0.0061$ fm (CODATA 2014)
Muon spectroscopy: $0.8409 \pm 0.0004$ fm (CREMA 2010, 2013)
H spectroscopy (2017): $0.8335 \pm 0.0095$ fm (A Beyer et al. Science 358 (6359). 2017)
H spectroscopy (2018): $0.877 \pm 0.013$ fm (H Fleurbaey et al. PRL.120.183001 (2018))
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:

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

• \( G_{E} \) 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

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

• PRad goal: Measuring proton charge radius using ep elastic scattering

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

• Covers two orders of magnitude in low $Q^2$
  with the same detector setting
  1. $~2 \times 10^{-4} - 6 \times 10^{-2} \text{ GeV}^2$

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

• Extract the radius with precision from sub-
  percent cross section measurement
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PRad Experimental Apparatus

PRad Setup (Side View)

- Electron beam
- Tagger
- Collimator
- 2H00 Harp
- Cryocooler
- Hydrogen gas
- bellows
- target cell
- New Cylindrical Vacuum Chamber
- GEM chamber
- HyCal

Dimensions:
- 0.3 m
- 1.7 m
- 1.2 m
- 1.5 m
- 5.0 m
PRad Experimental Apparatus

- 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 \((72 \mu m)\)
- 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\textsubscript{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
Analysis – Background Subtraction

- Runs with different target condition taken for background subtraction and studies for the systematic uncertainty
- Developed simulation program for target density (COMSOL finite element analysis)
Analysis – Background Subtraction (2.2 GeV)

- $ep$ background rate ~ 10% at forward angle (<1.3 deg, dominated by upstream collimator), less than 2% otherwise
- $ee$ background rate ~ 0.8% at all angles

Residual hydrogen gas: hydrogen gas filled during background runs

\[ \text{Preliminary Background Contribution} \]
Analysis – Event Selection

Event selection method

1. For all events, require hit matching between GEMs and HyCal

2. For ep and ee events, apply angle dependent energy cut based on kinematics
   1. Cut size depend on local detector resolution

3. For ee, if requiring double-arm events, apply additional cuts
   1. Elasticity
   2. Co-planarity
   3. Vertex z
Analysis – Event Selection

Co-planarity for ee scattering

Preliminary

2.2 GeV data after kinematic and elasticity cuts

production runs
bg runs, gas in, cell in

E' (MeV)

2 GeV data

Q^2 \sim 7.1 \times 10^{-3} \text{ GeV}^2
2.0^\circ < \theta < 2.5^\circ

elasticity cut for ep scattering

production runs
bg runs, gas in, cell in

elasticity cut

Preliminary

count/MeV

count/MeV

count/MeV
Extraction of $ep$ Elastic Scattering Cross Section

- To reduce the systematic uncertainty, the $ep$ cross section is normalized to the Møller cross section:

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

- Event generators for unpolarized elastic $ep$ and Møller scatterings have been developed based on complete calculations of radiative corrections:


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

$$
\sigma_{ep}^{\text{Born}}(\text{exp}) = \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{\text{exp}} / \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{\text{sim}} \cdot \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{\text{Born(model)}} \cdot \sigma_{ee}^{\text{Born(model)}}
$$

- Iterative procedure applied for radiative correction
Differential Cross Sections (Preliminary)

- Differential cross section v.s. $Q^2$, with 2.2 and 1.1 GeV data (preliminary)
- Statistical uncertainties at current stage: $\sim 0.18\%$ for 2GeV, $\sim 0.3\%$ for 1GeV per point
- Systematic uncertainties at current stage: $0.8\% \sim 2.0\%$ for 2GeV, $0.9\% \sim 2.0\%$ for 1GeV (shown as shadow area)

$ep$ elastic scattering cross section

- Graph showing differential cross section $d\sigma/dQ^2_{ep}$ for 2.2 GeV and 1.1 GeV data, with statistical uncertainties, and systematic uncertainties shown as shadow area.
**Form Factor $G_E$ (Preliminary)**

- Proton electric form factor $G_E$ v.s. $Q^2$, with 2.2 and 1.1 GeV data (preliminary)

- Systematic uncertainties shown as colored error bars

- Preliminary $G_E$ slope seems to favor smaller radius
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\[
G_E = 0.9^{+0.1}_{-0.05}
\]

1.1 GeV data (PRad Preliminary)

2.2 GeV data (PRad Preliminary)

$G_E$, J. C. Bernauer et al. PRC 90 (2014) 015206, $R = 0.8868$ fm

$G_E$, J. J. Kelly. PRC 70 (2004) 068202, $R = 0.8630$ fm

$G_E$, S. Venkat et al. PRC 83(2011)015203, $R = 0.8779$ fm
Finalize cross sections for both energy runs (summer 2018)

Preliminary extraction of radius (summer 2018)

Final extraction of proton charge radius (end of 2018)

We are currently still working on a number of corrections and systematic uncertainties

1. Background subtraction and pile-up effects at small angle ($\theta<1.1^\circ$)
2. Radiative correction
3. Inelastic ep contribution
4. Trigger efficiency
5. Bremsstrahlung photon from target
6. ...

Radius fitting study is ongoing: https://arxiv.org/abs/1803.01629
Summary

• PRad experiment is uniquely designed to address the Proton Radius Puzzle
  1. Discrepancy between electron scattering and muon spectroscopy results
  2. Unprecedented low $Q^2$ data set ($\sim2x10^{-4}$ GeV$^2$) has been collected in $e$-$p$ elastic scattering experiment
  3. Data with two orders of magnitude in low $Q^2$ range ($\sim2x10^{-4} – 6x10^{-2}$ GeV$^2$) in one experimental setting

• Preliminary cross section and $G_E$ extracted, covering $Q^2$ from $3x10^{-4}$ to $5x10^{-2}$ GeV$^2$
• Preliminary $G_E$ slope seems to favor smaller radius

• Ongoing work:
  1. Finalizing systematic uncertainties
  2. Utilizing the full $Q^2$ data range

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