The PRad Experiments at Jefferson Lab

A. Gasparian
NC A&T State University, NC USA

for the PRad collaboration

Outline

- the proton radius puzzle
- PRad approach for a new ep-experiment
- PRad experiment and the results
- planned new experiment, PRad-II
- summary
Proton Charge Radius

One of the most fundamental quantities in physics:

- atomic physics:
  - precision atomic spectroscopy (QED, Lamb shifts, Rydberg constant $R_\infty$);
  - $r_p$ is strongly correlated to $R_\infty$
- nuclear physics:
  - QCD, test of nuclear/particle models
- connects atomic and subatomic physics.

Methods to measure the Proton rms charge radius ($r_p$):

- Hydrogen spectroscopy (lepton-proton bound state, Atomic Physics):
  - regular hydrogen
  - muonic hydrogen
- Lepton-proton elastic scattering (Nuclear Physics):
  - $e^-$p- scattering (like PRad)
  - $\mu$p- scattering (like MUSE, next talk by E. Cline)
Difference between energy levels has been measured
- with accuracy of 1.4 part in $10^{14}$
- using atomic cesium as a frequency standard
- also yields the Rydberg constant, $R_\infty$

- electron in S states is sometimes inside the proton.
  - S-states are shifted by the size of proton
  - shift is proportional to the size of the proton
- in P states electron is not inside the proton.
- P-S transitions better for proton radius measurement
Proton Radius from $ep\rightarrow ep$ Scattering Experiments

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

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

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

- 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 $G_M$ can be extracted using Rosenbluth separation
- for extremely low $Q^2$, the cross section is dominated by $G_E$
- Taylor expansion of $G_E$ at low $Q^2$

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

**definition of the proton rms charge radius**

$\langle r^2 \rangle = -\left.\frac{dG_E^p(Q^2)}{dQ^2}\right|_{Q^2=0}$

Mainz low $Q^2$ data set
The First Measurement of the Proton Radius

- Robert Hofstadter, experiments in 1955-1956
  - ep-elastic scattering
  - $E_e = 188$ MeV electron beam
  - at Stanford University

- Nobel prize in 1961:
  "for his pioneering studies of electron scattering in atomic nuclei and for his consequent discoveries concerning the structure of nucleons"

  "proton has a diameter of \(0.74 \pm 0.24 \times 10^{-13}\) cm"

  \[ r_p = 0.74 \ \text{fm} \quad \text{with a 32\% uncertainty} \]

Hofstadter, McAllister, Phys. Rev. 102, 851 (1956)

- Over 60 years of experimentation!
  - started from 0.74 fm
  - ended to 0.895 fm by 2010.
  - where we are now ???
Proton Radius before the Puzzle (2010)

CODATA average: 0.8751 ± 0.0061 fm
ep-scattering average (CODATA): 0.879 ± 0.011 fm
Regular H-spectroscopy average (CODATA): 0.859 ± 0.0077 fm

Very good agreement between ep-scattering and H-spectroscopy results!
The Proton Radius Puzzle before the PRad Experiment (2016)

Regular hydrogen average (CODATA): \(0.8751 \pm 0.0061\) fm

Muonic hydrogen (CREMA coll. 2013): \(0.8409 \pm 0.0004\) fm
Muonic hydrogen (CREMA coll. 2010): \(0.84184 \pm 0.00067\) fm
Possible Resolutions to the *Proton Radius Puzzle*

- Some initial open questions about QED calculations:
  - additional corrections to muonic-hydrogen. Not found
  - missing contributions to electronic-hydrogen. Not found
  - higher moments in electric form factor; Not significant
  - …

- Is the ep-interaction the same as μp-interaction (the *lepton universality principle*)?

- New Physics (forces) beyond the Standard Model? Not found yet
  - many models, discussions, suggestions …

- Potential solutions:
  - need new high precision, *high accuracy* experiments:
    - ep-scattering experiments:
      - reaching extremely low $Q^2$ range ($10^{-4}$ GeV/c$^2$)
      - possibly with new independent methods
      - measure absolute cross sections in ONE experimental setting!
        - MUSE at PSI, ISR at Mainz, ULQ$^2$ in Japan, AMBER at CERN …
    - ordinary hydrogen spectroscopy experiments:
      - York University in Canada, LKB in Paris, France, CREMA in Germany …
Practically all ep-scattering experiments were performed with magnetic spectrometers and LH$_2$ targets!
- high resolutions but, very small angular and momentum acceptances,
- need many different settings of angle ($\Theta_e$), energies ($E_e, E'_e$) to cover a reasonable $Q^2$ fitting interval
- limitation on minimum $Q^2$: $10^{-3}$ GeV/C$^2$
- limits on accuracy of cross sections ($d\sigma/d\Omega$): $\sim 2 \div 3\%$
  - statistics is not a problem (<0.2%)
  - control of systematic uncertainties???

PRad experimental approach:
- use large acceptance, high resolution el.-magnetic calorimeter (HyCal)
- all measurements with one experimental setting: $\Theta_e = 0.6^0 - 7.0^0$
- reach to smaller $Q^2$ range: $(Q^2 = 2 \times 10^{-4} - 6 \times 10^{-2})$ GeV/c$^2$
- windowless H$_2$ gas flow target (minimize experimental background)
- simultaneous detection of $ee \rightarrow ee$ Moller scattering process (best known control of systematics).
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
- Beam line installation, commissioning, data taking in Hall B at JLab: January/June 2016
- Data analysis: 2016 – 2019
- Publication in Nature journal: November, 2019
PRad Experiment Performed in Hall B at Jefferson Lab

PRad was performed in Hall B at JLab in January – June of 2016
Main detector elements:
- windowless $H_2$ gas flow target
- PrimEx HyCal calorimeter
- vacuum box with one thin window at HyCal end
- X,Y – GEM detectors on front of HyCal

Beam line equipment:
- standard beam line elements (0.1 – 50 nA)
- photon tagger for HyCal calibration
- collimator box (6.4 mm collimator for photon beam, 12.7 mm for e$^-$ beam halo “cleanup”)
- Harp 2H00 l
PRad Experimental Apparatus

A. Gasparian

QNP2022
Data Analysis: Event Selection

- Experimental data was taken with two beam energies:
  - 1.1 GeV (604 M events)
  - 2.2 GeV (756 M events)

- For all events, require hit matching between GEMs and HyCal

- For $ep$ event:
  - scattered angle dependent energy conservation (elasticity)

- For $ee$, events (double-arm events):
  - Energy conservation (elasticity)
  - co-planarity
  - vertex z (kinematics)
Data Analysis: Empty Target Runs for Background Subtraction

- ep background rate ~ 10% at forward angle (<1.1 deg, dominated by upstream beam halo blocker), less than 2% otherwise
- ee background rate ~ 0.8% at all angles

Residual hydrogen gas: hydrogen gas filled during background runs
Data Analysis: *ep-inelastic* Contribution

- Using Christy 2018 empirical fit* to study inelastic ep contribution
- Good agreement between data and simulation
- Negligible for the PbWO$_4$ region (<3.5°)
- Less than 0.2% (2.0%) for 1.1GeV (2.2GeV) in the Lead glass region

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* M. E. Christy and P. E. Bosted, PRC 81, 055213 (2010)
Extraction of the $ep \rightarrow ep$ Elastic Scattering Cross Section

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

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

- method 1: bin by bin method – taking $ep/ee$ counts from the same angle bin
- method 2: integrated Moller method – integrate Møller in a fixed angle range and use it as common normalization for all angle bins

- Luminosity cancelled for both methods

- Radiative effects corrected by Monte Carlo method:
  - GEANT4 based simulation package with full geometry setup
  - event generators with complete calculations of radiative corrections$^{1,2}$
  - iterative procedure applied for radiative corrections

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

Extracted $ep \rightarrow ep$ Elastic Differential Cross Sections

- Extracted differential cross sections vs. $Q^2$, with 1.1 and 2.2 GeV data.
- Statistical uncertainty: ~0.2% for 1.1 GeV and ~0.15% for 2.2 GeV per point.
- Systematic uncertainties: 0.3% - 0.5% for 1.1 GeV and 0.3 – 1.1% for 2.2 GeV per point.
Fit to Extract the Proton Radius

Proton Electric Form Factor $G'_E$

PRad final result: $R_p = 0.831 \pm 0.007$ (stat.) $\pm 0.012$ (syst.) fm

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The Proton Radius Puzzle before the PRad Publication

Regular hydrogen average (CODATA): $0.8751 \pm 0.0061$ fm

Muonic hydrogen (CREMA coll. 2013, PSI): $0.8409 \pm 0.0004$ fm

Regular H-spectr. (2S $\rightarrow$ 4P, Garching, PSI): $0.8335 \pm 0.0095$ fm

Regular H-spectr. (1S $\rightarrow$ 3S, LKB, Paris): $0.877 \pm 0.013$ fm

Regular H-spectr. (2S$_{1/2} \rightarrow$ 2P$_{1/2}$, York Un. Canada) $0.833 \pm 0.010$ fm
The PRad Final Result on the Radius

PRad final result: \( R_p = 0.831 \pm 0.007 \text{ (stat.)} \pm 0.012 \text{ (syst.)} \text{ fm} \)

Planed New Experiment: PRad-II at JLab

- **PRad-II** is planning to improve the PRad accuracy by a factor of 3.8 (to $\pm 0.43\%$ on $r_{p}$) by:
  - Significantly improved statistics (4 times less uncertainties);
  - Hardware upgrades:
    - adding full tracking capability (second plane of GEM/$\mu$Rwell detectors).
    - small-size scintillator detectors just downstream the target to veto Moller electrons to reach the $10^{-5}$ GeV$^2$ $Q^2$ range.
    - adding new “beam halo blacker” just before the Tagger.
    - upgrade DAQ/electronics to fADC based electronics:
    - possible HyCal upgrade to all PbWO$_4$ crystals, essential for the ep-inelastic background suppression at relatively higher $Q^2$ range ($\approx 10^{-2}$ GeV$^2$) and uniformity over full acceptance.

PRad-II Experimental Setup (Side View)
Major Goals of the PRad-II Experiment

- reach to 0.43% total uncertainty in the proton radius extraction (4 times improvement over PRad).
- will address the differences between PRad and all modern ep-experiments.
- reach to the lowest $Q^2$ range: $10^{-5} \text{ GeV}^2$ for the first time.

Normalized Proton Electric Form Factor $G_E$

From J. Bernauer
PRad-II: Projected Result

- Approved by JLab’s PAC-48 in August, 2020
- Projected total uncertainty on radius: 0.43%
Current Status of the Prad-II Experiment

- Approved by JLab’s PAC-48 in August, 2020, (E12-004)

- Funding proposals to upgrade HyCal to all (or partial) PbWO4 crystals.
- Second GEM detector plane.
- Upgrade the readout electronics to fADC based DAQ system.

- For the calorimeter upgrade, we are also looking for used crystal detectors from other experiments/institutions matching the PbWO₄ part of the HyCal.

- Estimated experiment readiness time: in 2-3 years.
Summary

- PRad was uniquely designed and performed in 2016 to address the “Puzzle”:
  - Data in a large $Q^2$ range have been recorded with the same experimental setting, $[2 \times 10^{-4} \div 6 \times 10^{-2}]$ GeV/C$^2$.
  - 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 the Moller and Mott scattering processes has been demonstrated to control systematic uncertainties.

- PRad final result supports small proton charge radius (Nature 575, 145–150 (2019)):
  - $R_p = 0.831 \pm 0.007$ (stat.) $\pm 0.012$ (syst.) fm ($\pm 1.67\%$ total)
  - Significant input in changing the CODATA recommendation on radius.

- The PRad-II will improve the radius measurement by a factor of 3.8
  - Will address the differences between PRad and all modern ep-experiments;
  - Will reach the $Q^2 \sim 10^{-5}$ GeV$^2$ range, for the first time in ep-experiments
  - Are there any possible systematic uncertainties in $\mu$H results?

PRad was supported in part by NSF MRI #PHY-1229153 and DOE DE-FG02-03ER41231 awards. My research work is supported in part by NSF award: PHY-1812421
Thank you!
Other New Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam</th>
<th>Laboratory</th>
<th>$Q^2$ (GeV/c)$^2$</th>
<th>$\delta r_p$ (fm)</th>
<th>Status</th>
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<tbody>
<tr>
<td>MUSE</td>
<td>$e^\pm, \mu^\pm$</td>
<td>PSI</td>
<td>0.0015 - 0.08</td>
<td>0.01</td>
<td>Ongoing</td>
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<tr>
<td>AMBER</td>
<td>$\mu^\pm$</td>
<td>CERN</td>
<td>0.001 - 0.04</td>
<td>0.01</td>
<td>Future</td>
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<tr>
<td>PRad-II</td>
<td>$e^-$</td>
<td>Jefferson Lab</td>
<td>$4 \times 10^{-5}$ - $6 \times 10^{-2}$</td>
<td>0.0036</td>
<td>Future</td>
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<tr>
<td>PRES</td>
<td>$e^-$</td>
<td>Mainz</td>
<td>0.001 - 0.04</td>
<td>0.6% (rel.)</td>
<td>Future</td>
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<tr>
<td>A1@MAMI (jet target)</td>
<td>$e^-$</td>
<td>Mainz</td>
<td>0.004 - 0.085</td>
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<td>Ongoing</td>
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<tr>
<td>MAGIX@MESA</td>
<td>$e^-$</td>
<td>Mainz</td>
<td>$\geq 10^{-4}$ - 0.085</td>
<td>~ 1% (rel.)</td>
<td>Future</td>
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<tr>
<td>ULQ$^2$</td>
<td>$e^-$</td>
<td>Tohoku University</td>
<td>$3 \times 10^{-4}$ - $8 \times 10^{-3}$</td>
<td></td>
<td>Future</td>
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</tbody>
</table>
Data Analysis: Beam Background Subtraction

- $ep$ background rate $\sim 10\%$ at forward angles ($<1.3^0$, dominated by upstream “collimator”), less than 2% otherwise.
- $ee$ background rate $\sim 0.8\%$ at all angles.
## PRad Systematic Uncertainties

<table>
<thead>
<tr>
<th>Item</th>
<th>$r_p$ uncertainty [fm]</th>
<th>$n_1$ uncertainty</th>
<th>$n_2$ uncertainty</th>
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<td>Event selection</td>
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<td>Radiative correction</td>
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<td>Detector efficiency</td>
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<td>Beam background</td>
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<td>0.0017</td>
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<tr>
<td>HyCal response</td>
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<td>Acceptance</td>
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<td>Inelastic $ep$</td>
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<td>$G^p_M$ parameterization</td>
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<tr>
<td>Total</td>
<td>0.0115</td>
<td>0.0020</td>
<td>0.0013</td>
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</table>
Recent Developments in Fitting Procedures

- The input form factors (with known $r_p$) are used to generate pseudo data using PRad kinematic range and uncertainties.
- All combinations of input functions and fit functions can then be tested repeatedly against regenerated pseudo data.
- Since the input radius is known, this allowed to find fitting functions that are robust for proton radius extractions in an objective fashion.

- The following fitters:
  - two-parameter rational function
  - two-parameter continued fraction
  - second-order polynomial expansion of $z$

are identified as robust fitters with small uncertainties

$$\text{RMSE} = \sqrt{\text{bias}^2 + \sigma^2}$$

- X. Yan, et al.  
  "Robust extraction of the proton charge radius from electron-proton scattering data",  
  PRC 98, 2, 025204, 2018
Currently 14 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, Hampton University, College of William & Mary, Tsinghua University, China, Old Dominion University, ITEP Moscow, Russia.

Graduate students:
Chao Peng (Duke), Weizhi Xiong (Duke), Xinzhan Bai (UVa), Li Ye (MSU)

Postdocs:
Chao Gu (Duke), Xuefei Yan (Duke), Mehdi Meziane (Duke), Zhihong Ye (Duke), Tyler Hague (NC A&T SU), Maxime Lavilain (NC A&T), Krishna Adhikari (MSU), Latif-ul Kabir (MSU), Chandra Akondi (NC A&T)