Latest on the Proton Charge Radius from the PRad Experiment

Haiyan Gao
Duke University and Duke Kunshan University
Lepton scattering: powerful microscope!

- Clean probe of hadron structure
- Electron (lepton) vertex is well-known from QED
- One-photon exchange dominates, higher-order exchange diagrams are suppressed (two-photon physics)
- Vary the wave-length of the probe to view deeper inside

\[
\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \frac{E'}{E} \left( \frac{G_E^2 + \tau G_M^2}{1 + \tau} \cos^2 \frac{\theta}{2} + 2\tau G_M^2 \sin^2 \frac{\theta}{2} \right)
\]

\[\tau = -\frac{q^2}{4M^2}\]

Virtual photon 4-momentum

\[q = k - k' = (\vec{q}, \omega)\]

\[Q^2 = -q^2\]
What is inside the proton/neutron?

1933: Proton’s magnetic moment

Nobel Prize in Physics 1943
Otto Stern

"for ... and for his discovery of the magnetic moment of the proton".

\[ g \neq 2 \]

1969: Deep inelastic e-p scattering

Nobel Prize in Physics 1990
Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

"for their pioneering investigations concerning deep inelastic scattering of electrons on protons ...".

Jian-Wei Qiu

1960: Elastic e-p scattering

Nobel Prize in Physics 1961
Robert Hofstadter

"for ... and for his thereby achieved discoveries concerning the structure of the nucleons"

Form factors → Charge distributions

1974: QCD Asymptotic Freedom

Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

"for the discovery of asymptotic freedom in the theory of the strong interaction".
Proton Charge Radius

• An important property of the nucleon
  – Important for understanding how QCD works
  – Challenge to Lattice QCD (exciting new results, Alexandrou et al.)
  – An important physics input to the bound state QED calculations, affects muonic H Lamb shift \((2S_{1/2} \rightarrow 2P_{1/2})\) by as much as 2%

• Electron-proton elastic scattering to determine electric form factor (Nuclear Physics)

\[
\sqrt{\langle r^2 \rangle} = \sqrt{-6 \frac{dG(q^2)}{dq^2} \bigg|_{q^2=0}}
\]

• Spectroscopy (Atomic physics)
  – Hydrogen Lamb shift
  – Muonic Hydrogen Lamb shift
Proton Charge Radius Puzzle

- p Lamb shift measurements by CREMA (2010, 2013)
  - Unprecedented precision, <0.1%

Electron: 0.8751 ± 0.0061 fm
Muon: 0.8409 ± 0.0004 fm
Unpolarized electron-nucleon scattering
(Rosenbluth Separation)

- Elastic e-p cross section

\[
\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2 \frac{\theta}{2} E'}{4E^2 \sin^4 \frac{\theta}{2} E} \left( \frac{G_E^p \theta + \tau G_M^p \theta^2}{1 + \tau} + 2\tau G_M^p \tan^2 \frac{\theta}{2} \right)
\]

\[
= \sigma_M f_{rec}^{-1} \left( A + B \tan^2 \frac{\theta}{2} \right)
\]

- At fixed $Q^2$, fit $d\sigma/d\Omega$ vs. $\tan^2(\theta/2)$
  - Measurement of absolute cross section
  - Dominated by either $G_E$ or $G_M$
    - Low $Q^2$ by $G_E$
    - High $Q^2$ by $G_M$

\[
\sigma_R = \tau G_M^2 + \epsilon G_E^2
\]

\[
\tau = \frac{Q^2}{4M^2}
\]

\[
\epsilon = (1 + 2(1 + \tau) \tan^2 \frac{\theta}{2})^{-1}
\]
Electron-proton elastic scattering with longitudinally polarized electron beam and recoil proton polarization measurement

**Polarization Transfer**

\[
\frac{G_P^E}{G_M^p} = -\frac{P_t E + E'}{P_l 2M} \tan \frac{\theta}{2}
\]

- Recoil proton polarization

- Focal Plane Polarimeter
  - recoil proton scatters off secondary $^{12}$C target
  - $P_t, P_l$ measured from $\varphi$ distribution
  - $P_b$, and analyzing power cancel out in ratio

Focal-plane polarimeter
Asymmetry Super-ratio Method
Polarized electron-polarized proton elastic scattering

- Polarized beam-target asymmetry

\[
A_{\text{exp}} = \frac{P_b P_t}{(1+\tau)G_E^p G_M^p} \left( -2\tau v_T' \cos \theta^* G_M^p \right) + 2\sqrt{2\tau(1+\tau)v_{TL}' \sin \theta^* \cos \phi^* G_M^p G_E^p} + 2\tau v_T G_M^p \right)
\]

- Super-ratio

\[
R_A = \frac{A_1}{A_2} = \frac{a_1 - b_1 \cdot G_E^p / G_M^p}{a_2 - b_2 \cdot G_E^p / G_M^p}
\]

BLAST pioneered the technique, later also used in Jlab Hall A experiment
The absolute frequency of H energy levels has been measured with an accuracy of $1.4 \times 10^{-14}$ via comparison with an atomic cesium fountain clock as a primary frequency standard. Yields $R_\infty$ (the most precisely known constant).

Comparing measurements to QED calculations that include corrections for the finite size of the proton provide an indirect but very precise value of the rms proton charge radius. Proton charge radius effect on the muonic hydrogen Lamb shift is 2%.
2010: new value is $r_p = 0.84184(67)$ fm
New PSI results reported in Science 2013

2013: \( r_p = 0.84087(39) \) fm, A. Antognini et al., Science 339, 417 (2013)
Recent ep Scattering Experiments

- Large amount of overlapping data sets
- Statistical error $\leq 0.2\%$
- Luminosity monitoring with spectrometer
  - $Q^2 = 0.004 - 1.0 \ (\text{GeV/c})^2$
  - result: $r_p = 0.879(5)_{\text{stat}}(4)_{\text{sys}}(2)_{\text{mod}}(4)_{\text{group}}$

J. Bernauer, PRL 105, 242001, 2010

5-7$\sigma$ higher than muonic hydrogen result!
**JLab Recoil Proton Polarization Experimental**

**E_e**: 1.192 GeV  
**P_b**: ~83%

**BigBite**

- Non-focusing Dipole
- Big acceptance.
  - Δp: 200-900 MeV
  - ΔΩ: 96 msr
- PS + Scint. + SH

**LHRS**

- Δp/p0: ± 4.5%
- out-of-plane: ± 60 mrad
- in-plane: ± 30 mrad
- ΔΩ: 6.7 msr
- QQDQ
- Dipole bending angle 45°
- VDC+FPP
- P_p: 0.55 ~ 0.93 GeV/c

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**References**

C. Crawford et al. PRL98, 052301 (2007)
Proton Charge Radius from recent experiments and analyses

![Proton Charge Radius Graph](image-url)

- **Sick**
- **Bernauer et al**
- **Zhan et al**
- **Arrington & Sick**
- **CODATA**
  (Spectroscopy data, 2012)
- **Pohl et al**
- **Antognini et al**

Proton Charge radius (fm)
Revisits QED Calculations....

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Value [meV]</th>
<th>Uncertainty [10^{-4} meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uehling</td>
<td>205.0282</td>
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<tr>
<td>Källen–Sabry</td>
<td>1.5081</td>
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<tr>
<td>VP iteration</td>
<td>0.151</td>
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<tr>
<td>Mixed $\mu - e$ VP</td>
<td>0.00007</td>
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<tr>
<td>Hadronic VP $[21, 23]$</td>
<td>0.011</td>
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<td>Sixth order VP $[24]$</td>
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<td>Whichmann–Kroll</td>
<td>-0.00103</td>
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<td>Virtual Delbrück</td>
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<td>Light–by–light</td>
<td>-</td>
<td>10</td>
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<tr>
<td>Muon self–energy and muonic VP (2\textsuperscript{nd} order)</td>
<td>-0.66788</td>
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<td>Fourth order electron loops</td>
<td>-0.00169</td>
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<td>VP insertion in self energy $[17]$</td>
<td>-0.0055</td>
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<td>Proton self–energy $[18]$</td>
<td>-0.0099</td>
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<tr>
<td>Recoil $[17, 43]$</td>
<td>0.0575</td>
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<tr>
<td>Recoil correction to VP (one–photon)</td>
<td>-0.0041</td>
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<td>Recoil (two–photon) $[19]$</td>
<td>-0.04497</td>
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<td>Recoil higher order $[19]$</td>
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<td>Recoil finite size $[32]$</td>
<td>0.013</td>
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<tr>
<td>Finite size of order $(Z\alpha)^4$ $[32]$</td>
<td>-5.1975(1) $r_p^2$</td>
<td>-3.979 (620)</td>
</tr>
<tr>
<td>Finite size of order $(Z\alpha)^5$ $[32]$</td>
<td>0.0347(30) $r_p^3$</td>
<td>0.0232 (20)</td>
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<tr>
<td>Finite size of order $(Z\alpha)^6$ $[32]$</td>
<td>-0.0005</td>
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<tr>
<td>Correction to VP $[19]$</td>
<td>-0.0109 $r_p^2$</td>
<td>-0.0058</td>
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<tr>
<td>Additional size for VP $[19]$</td>
<td>-0.0164 $r_p^2$</td>
<td>-0.0128</td>
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<tr>
<td>Proton polarizability $[11, 33]$</td>
<td>0.015</td>
<td>40</td>
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<tr>
<td>Fine structure $\Delta E(2P_{3/2} - 2P_{1/2})$</td>
<td>8.352</td>
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<tr>
<td>$2P_{3/2}^F$ hyperfine splitting</td>
<td>1.2724</td>
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<tr>
<td>$2S_{1/2}^F=1$ hyperfine splitting $[42]$ $(-22.8148/4)$</td>
<td>-5.7037</td>
<td>20</td>
</tr>
</tbody>
</table>

An additional 0.31 meV to match CODATA value

Evaluation by Jentschura, Annals Phys. 326, 500 (2011)
Recent summary by A. Antognini et al., arXiv:1208.2637

Birse and McGovern, arXiv:1206.3030
0.015(4) meV (proton polarizability)

J.M. Alarcon, et al. 1312.1219
0.008 meV

G.A. Miller, arXiv:1209.4667

New experiments at HIGS and Mainz on proton polarizabilities
Revisits of e-p scattering data (just 2015)

• Re-analysis of existing proton form factor data
  • D. W. Higinbotham, arXiv:1510.01293: two parameter dipole form fit describes the data at both low Q^2 and high Q^2 well, and the result is consistent with PSI value
  • M. Horbatsch and E. A. Hessels, arXiv:1509.05644: re-analysis of Mainz data, simple fits (one-parameter model, dipole model, linear model) for low Q2 data, and spline extension to high Q2 data, these fits can all describe data well, but the extracted radius varies from 0.84 ~ 0.89 fm. So current data is not able to resolve the puzzle.
  • J. Arrington, arXiv:1506.00873: re-analysis of world data, found the previous scattering results might underestimate the uncertainty.
  • Distler, Walcher, and Bernauer, arXiv1511.00479

All these studies emphasize even more the importance of low Q^2 e-p scattering data
New Physics or what? - Incomplete list

• New physics: new particles, Barger et al., Carlson and Rislow; Liu and Miller,….New PV muonic force, Batell et al.; Carlson and Freid; Extra dimension: Dahia and Lemos; Quantum gravity at the Fermi scale R. Onofrio;…….

• Contributions to the muonic H Lamb shift: Carlson and Vanderhaeghen,; Jentschura, Borie, Carroll et al, Hill and Paz, Birse and McGovern, G.A. Miller, J.M. Alarcon, Ji, Peset and Pineda…. 

• Higher moments of the charge distribution and Zemach radii, Distler, Bernauer and Walcher,…..

• J.A. Arrington, G. Lee, J. R. Arrington, R. J. Hill discuss systematics in extraction from ep data, no resolution on discrepancy

• Donnelly, Milner and Hasell discuss interpretation of ep data,………

Discrepancy explained by some but others disagree

• Dispersion relations: Lorentz et al.

• Frame transformation: D. Robson

• New experiments: Mainz (e-d, ISR), JLab (PRad), PSI (Lamb shift, and MUSE), H Lamb shift
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)
Update on proton radius puzzle

- Deuteron radius puzzle
  - Deuteron rms charge radius from muonic deuterium spectroscopy (R. Pohl et al., *Science* 353, 6300, 669, 2016)
  - $7.5\sigma$ smaller than the CODATA-2010 value, and $3.5\sigma$ smaller than the value from electronic deuterium spectroscopy (R. Pohl et al., *Metrologia* 54, L1, 2017)
  - Confirms proton radius puzzle

- Analysis of electron scattering data
  - Focusing on the low-q data yields a consistent result with CREMA’s value
    (*Phys. Rev. C* 93, 055207, 2016)
  - However, I. Sick and D. Trautmann (*Phys. Rev. C* 95, 012501(R), 2017) claim that the above analyses led to a systematically smaller proton rms-radius because of the ignorance of the correlations from higher moments $<r^{2n}>$
Deuteron Charge Radius?

- “Proton Charge Radius Puzzle” is still unsolved after seven years.
- There is a newly developing “Deuteron Charge Radius Puzzle”

H/D isotope shift: \[ r_d^2 - r_p^2 = 3.82007(65) \text{ fm}^2 \]
Muonic deuterium: \[ r_d = 2.12562(13)_{\text{exp}}(77)_{\text{theory}} \text{ fm} \]
Electronic deuterium: \[ r_d = 2.14150(450) \text{ fm} \]

calls for new independent experiments with possible highest accuracy!
New ed- cross sections at low \( Q^2 \) will be a critical input to reduce theory error in \( r_d \) extracted from \( \mu D \) spectroscopy.

(R. Pohl, 2017)
Charge Radius of Helium Nuclei

Electron scattering consistent with μ-spectroscopy
High resolution, large acceptance, hybrid HyCal calorimeter (PbWO₄ and Pb-Glass)

Windowless H₂ gas flow target

Simultaneous detection of elastic and Moller electrons

Q² range of 2x10⁻⁴ – 0.14 GeV²

XY – veto counters replaced by GEM detector

Vacuum chamber

Spokespersons: D. Dutta, H. Gao, A. Gasparian, M. Khandaker

Sub 1% measurements:
(1) ep elastic scattering at Jlab (PRad)
(2) μp elastic scattering at PSI - 16 U.S. institutions! (MUSE)
(3) ISR experiments at Mainz

Ongoing H spectroscopy experiments
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 tank 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
- Similar improvement for $Q^2$ determination at small angle

More details see presentation of X. Bai in session E12
PRad Experimental Apparatus

PRad Setup (Side View)

- Hybrid EM calorimeter (HyCal)
  - Inner 1156 PWO₄ modules
  - Outer 576 lead glass modules
- 5.8 m from the target
- Scattering angle coverage: ~0.6° to 7.5°
- 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 PbWO$_4$ part, lead glass part about 2.5 time worse

Plots courtesy of M. Levillain
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 μm)

Plots courtesy of X. Bai

\[ \sigma_{\text{gem}} = 72 \mu m \]
Preliminary Results:

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

Very preliminary

~10% of data

1.1 GeV
2.2 GeV

$Q^2$ (GeV)$^2$
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 ~ 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)

\[ d\sigma/dQ^2 \times 10^{-3} \]

\[ \Omega/d\sigma \times 10^{-1} \]

\[ \theta \] (deg)

\[ (mb/sr) \]

\[ \sim50\% 2.2\text{ GeV data} \]

\[ \text{Very Preliminary} \]

\[ (deg) \]

\[ (mb/sr) \]
Control of background in the PRad experiment.

Consistency of two practically independent measurements (within the ~ 0.2% statistical errors) demonstrates that we control the background, and PRad will reach its goal of sub-percent extraction of the Proton Radius!!!

Very Preliminary
PRad Projected Result with world data

- Po.hl et al
- Antognini et al
- Bernauer et al
- Zhan et al
- Arrington & Sick
- CODATA
- CODATA (spectroscopy data)
Summary and outlook

• After several years, the proton charge radius remains puzzling, and perhaps also the deuteron charge radius
• PRad experiment had a successful data taking in May/June 2016
• PRad collaboration is making good progress in data analysis and preliminary cross section results (partial data) announced in June 2017
• Preliminary radius result is anticipated in the fall 2017 – Stay tuned!

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