The Proton Charge Radius Puzzle: Current Status & Outlook

Dipangkar Dutta
Mississippi State University

ISMD 2019
Sept 13, 2019
Santa Fe, NM
1. Introduction
2. The Proton Charge Radius Puzzle
3. A New Experiment (PRad)
   - windowless target
   - high resolution calorimeter
   - simultaneous detection of elastic and Möller
4. Preliminary Results
5. Other experiments & future prospects
The study of the proton has revolutionized physics.

The proton is the primary, stable building block of all visible matter in the Universe.

The proton is the key to understanding the nature of the forces that hold the nucleus and thus the cosmos together.

In the last 110 yrs. since it discovery, the proton has evolved from Positively charged structure-less point particle to Bag of quarks and gluons, with 99% of Its mass due to the quark gluon interaction. (and hence 99% of the visible mass in the Universe.)

Proton’s basic properties such as its RMS charge radius is interesting on its own right, but also needed for determining fundamental constants such as the Rydberg constant.
H - spectroscopy and elastic e-p scattering are the two traditional methods for determining proton charge radius.

The forces defining the surface of a proton do not come to an abrupt end, its boundary is somewhat fuzzy.

If the proton has no definite boundaries how do you define its radius?

RMS charge radius ($r_p$) is obtained from a consistent interpretation of hydrogen spectroscopy and electron-proton scattering experiments.
Corrections to H - spectroscopy due to the extended charge distribution of the proton used to extract $r_p$

Comparing measurements to QED calculations that include corrections for the finite size of the proton provide a precise value of the rms proton charge radius.

Also, yields $R_\infty$ (the most precisely known constant in Physics)
The slope of the electric form factor down to zero $Q^2$ used to extract $r_p$ from elastic e-p scattering.

At very low $Q^2$, cross section dominated by $G_E$:

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

\[
G_E(Q^2) = 1 - \frac{Q^2}{6} <r^2> + \frac{Q^4}{120} <r^4> + ....
\]

Charge radius given by the slope at $Q^2 = 0$:

\[
<r^2> = -6 \left. \left| \frac{dG_E^2}{dQ^2} \right| \right|_{Q^2=0}
\]

This definition has been rigorously shown to be consistent with all experimental measurements. G. Miller, Phys. Rev., C 99, 035202 (2019)

Point like proton with $G_E = 1$ and $G_M = \mu_p = 2.79$

Data show proton has finite size

Prior to 2010 the $r_p$ extracted from H - spectroscopy and elastic e-p scattering were consistent with each other.

CODATA average: $0.8751 \pm 0.0061$ fm
ep-scattering average (CODATA): $0.879 \pm 0.011$ fm
Regular H-spectroscopy average (CODATA): $0.859 \pm 0.0077$ fm
A new method based on muonic hydrogen spectroscopy was used to extract $r_p$ for the first time in 2010.

Probability of lepton to be inside proton

$$\sim \left( \frac{r_p}{a_B} \right)^3 \left( r_p \alpha \right)^3 m^3$$  

$m =$ reduced mass  
$\sim 186 \text{ Me}$

$\mu H$ is $\sim 6 \times 10^6$ times more sensitive to $r_p$

$Lamb shift in \mu H: \Delta E = 206.0668(25) - 5.2275(10) r_p^2 \ [\text{meV}]$

finite proton size is $\sim 2\%$ correction to $\mu H$ Lamb shift

$r_p$ was extracted with 10 times higher precision ($\sim 0.1\%$) compared to all previous measurements
The results from the muonic hydrogen spectroscopy led to the so called “proton radius puzzle.”

~8\sigma discrepancy between muon and electron based measurements

Proton rms charge radius measured using
  electrons: 0.8770 \pm 0.0045 (CODATA2010 + Zhan et al.)
  muons: 0.8409 \pm 0.0004

Pohl et al., Nature 466, 213 (2010)
There was a world wide effort to explore numerous possible resolutions to the “proton radius puzzle.”

★ Are the state of the art QED calculations incomplete?

★ Are there additional corrections to the muonic Lamb shift due to proton structure (such as proton polarizability $\propto m_1^4$)?

★ Are higher moments of the charge distribution accounted for in the extraction of rms charge radius?

★ Is there an extrapolation problem in electron scattering data?

★ Has new physics been discovered (violation of Lepton Universality)?

★ New force carriers?
Clearly more experiments were needed!

- Redo atomic hydrogen spectroscopy (3 different groups)
- Muon-proton scattering (MUSE experiment-2020)
- Electron scattering experiments (PRad-2016, ISR, ProRad, ULQ²...)

The status of “proton radius puzzle” in 2018

![Proton radius graph with data points and error bars from different experiments.](Figure courtesy of W. Xiong)
PRad: a novel electron scattering experiment

- High resolution, Hybrid calorimeter *(magnetic spectrometer free)*
- Windowless, high density H$_2$ gas flow target *(reduced backgrounds)*
- Simultaneous detection of elastic and Möller electrons *(control of systematics)*
- Vacuum chamber, one thin window, large area GEM chambers *(better resolution)*
- $Q^2$ range of $10^{-4} – 6 \times 10^{-2}$ GeV$^2$ *(lower than all previous electron scattering expts.)*

Ran in Hall-B at JLab in 2016, using 1.1 GeV and 2.2 GeV electron beam
The first experiment to use a windowless target & a magnetic spectrometer free method to measure $r_p$

### Reused PrimEx Hybrid Calorimeter
- PbWO$_4$ and Pb-glass calorimeter (118x118 cm$^2$)
- 34x34 matrix of 2.05 x 2.05 cm$^2$ x18 cm PbWO$_4$
- 576 Pb-glass detectors (3.82x3.82 cm$^2$ x45 cm)
- 5.5 m from the target, PbWO$_4$ resolution: $\sigma_E/E = 2.6%/\sqrt{E}$
- Pb-glass: 2.5 times worse
- $\sigma_{xy} = 2.5$ mm/$\sqrt{E}$

Allows coverage of extreme forward angle (0.7° - 7.5°) and complete azimuthal angle coverage

### Used a cryo-cooled windowless gas flow hydrogen target.

Empty target runs used to subtract background

- Target cell (8 cm dia x 4 cm long copper)
  - 7.5 µm kapton foil with 2mm hole

- Density:
  - ~2x10$^{18}$ atoms/cm$^2$

- Cell / chamber / tank pressure:
  - 470 / 2.3 / 0.3 mtorr
Key innovations in the design allowed a unique high precision measurement.

Simultaneous detection of the Møller (e-e) and e-p elastic events within the same acceptance.

Experimental design allows:
- control of systematics
- eliminates need to monitor luminosity

Large forward angle acceptance with high energy resolution (HyCal) and 72 µm position resolution (GEM).

Experimental design allows:
- fill in the very low $Q^2$ range
- large $Q^2$ range in a single setting ($\sim 2 \times 10^{-4} - 6 \times 10^{-2}$ GeV$^2$)

Mainz low $Q^2$ data set
Angle dependent energy cuts are used to select the Möller (e-e) and e-p elastic events.

Additional constraints for double arm Möller events on: co-planarity, elasticity, z-vertex

GEM and HyCal detector hits must match for all (e-p) and (e-e) events

Angle dependent energy cuts for (e-p) and (e-e) events based on kinematics with the cut size based on local resolution.
e-p elastic cross section extracted by normalizing to Møller cross section.

bin-by-bin normalization (double arm Møller)

\[
\frac{d\sigma}{d\Omega}_{\text{ep}}(Q^2) = \left[ \frac{N_{\text{yield}}(e^-e^+ \text{ in } \theta, \pm \Delta \theta)}{N_{\text{yield}}(e^-e^- \rightarrow e^-e^-)} \right] \times \frac{\varepsilon_{\text{geom}}\varepsilon_{\text{det}}}{\varepsilon_{\text{geom}}\varepsilon_{\text{det}}} \frac{d\sigma}{d\Omega}_{\text{Møller}}
\]

or

integrated over HyCal acceptance

\[
\frac{d\sigma}{d\Omega}_{\text{ep}}(Q^2) = \left[ \frac{N_{\text{yield}}(e^-e^+ \text{ in } \theta, \pm \Delta \theta)}{N_{\text{yield}}(e^-e^- \text{, on PWO})} \right] \times \frac{\varepsilon_{\text{geom}}(\text{all PWO})\varepsilon_{\text{det}}}{\varepsilon_{\text{geom}}(\text{geom})\varepsilon_{\text{det}}(\text{geom})} \frac{d\sigma}{d\Omega}_{\text{ep}}
\]

Event generator for e-p elastic and Møller include radiative corrections beyond the ultra-relativistic approximation & two photon exchange (used iteratively within a Geant4 simulation)


Systematic uncertainties: 0.3\% - 0.5\% at 1.1 GeV and 0.3\% - 1.1\% at 2.2 GeV

Figures courtesy of W. Xiong
The proton electric form factor was extracted at the lowest $Q^2$ ever achieved in electron scattering.

The slope of $G_E(Q^2)$ as $Q^2 \to 0$ is proportional to $r_p^2$.

Typically $r_p$ is obtained by fitting $G_E(Q^2)$ to a functional form and extrapolating to $Q^2 = 0$.

The truncation of the higher-order moments of $G_E(Q^2)$ introduces a model dependence which can bias the determination of $r_p$.

Figure courtesy of W. Xiong
A wide range of functional forms were systematically tested for their robustness in extracting $r_p$.

- Numerous functional forms were tested with a wide range of $G_E$ parameterizations, using PRad kinematic range and uncertainties: X. Yan et al. Phys. Rev. C98, 025204 (2018)

- Rational (1,1), 2nd order z transformation and 2nd order continuous fraction are identified as robust fitters with also reasonable uncertainties

The robustness = root mean square error (RMSE)

$$\text{RMSE} = \sqrt{(\delta R)^2 + \sigma^2},$$

$\delta R = \text{difference between the input and extracted radius}$

$\sigma = \text{statistical variation of the fit to the mock data}$

Rational (1,1)

$$p_0 \frac{1 + p_1 Q^2}{1 + p_2 Q^2}$$

2nd order z transformation

$$p_0 (1 + p_1 z + p_2 z^2)$$

2nd order continuous fraction

$$z = \frac{\sqrt{T_c + Q^2} - \sqrt{T_c - T_0}}{\sqrt{T_c + Q^2} + \sqrt{T_c - T_0}}$$

Figure courtesy of W. Xiong
The rational (1,1) functional forms provides the most robust extraction of $r_p$ from the PRad data.

This slide was removed
The PRad current result for the proton charge radius.

This slide was removed
There has been some rapid and dramatic development over the last few months.

A new H-spectroscopy results was reported in Science Magazine last week.

This slide was removed.
There has been some rapid and dramatic development over the last few months.

Recently, CODATA released, online, their revised value of $r_p$

CODATA has also shifted the value of the Rydberg constant.

This slide was removed
Several new experiments are currently being prepared and some are expected to run as soon as Fall 2019.

The MUon proton Scattering *Experiment (MUSE)* at the PSI will simultaneous measure elastic $\mu^\pm$-$p$ and elastic $e^\pm$-$p$ scattering to determine $r_p$.

Spokespersons: R. Gilman, E. Downie, & G. Ron

Absolute errors

Relative errors

Individual radius extractions from $e^\pm$, $\mu^\pm$ each to 0.01 fm

→ Test of lepton universality
→ Determination contribution of two-photon exchange in $\mu$-$p$ scattering.

Figures courtesy of J. Arrington and PSI
The ProRad and ULQ$^2$ experiments will use very low energy electron beams to reach ultra low $Q^2$.

ProRad at IPNO will use a 30-70 MeV electron beam on a laminar liquid hydrogen jet target to measure the cross section in the $6^\circ$ - $15^\circ$ angular range with a 32 cell detector where each cell consists of a sci-fi coordinate detector and a BGO crystal. ProRad plans to cover a $Q^2$ range of $10^{-6}$ - $10^{-4}$ (GeV/c)$^2$. Spokesperson: E. Voutier

ULQ$^2$ collaboration at Tohoku U, will use a 20-60 MeV electron beam on a CH$_2$ target to measure the cross section in the $30^\circ$ - $150^\circ$ angular range with double arm high resolution spectrometers. ULQ$^2$ plans to cover a $Q^2$ range of $3\times10^{-4}$ - $8\times10^{-3}$ (GeV/c)$^2$. Spokesperson: T. Suda
Proton charge radius will be measured at COMPASS and at Mainz using a hydrogen gas TPC.

$\mu^-p$ scattering will used to measure $r_p$ at COMPASS using a high pressure hydrogen gas TPC as an active target and recoil proton detector. COMPASS plans to cover a $Q^2$ range of $10^{-4} - 1$ (GeV/c)$^2$.

The same high pressure hydrogen gas TPC will be used as an active target and recoil proton detector for an $e-p$ scattering experiment at Mainz to determine $r_p$. 
We are also preparing a proposal for PRad-II to push the precision frontier of electron scattering.

Upgrade HyCal to be replace all lead-glass modules with PbWO$_4$ modules to have uniform high resolution.

Convert to FADC based readout of HyCal

Add a second GEM plane between HyCal and vacuum chamber to further reduce the backgrounds and improve vertex resolution.

Will improve the precision of $r_p$ measurements and start a new program of high precision measurements using the PRad method.
Summary

- The proton charge radius is a fundamental quantity in Physics
  - Important for precision atomic spectroscopy
  - Precision tests of future lattice QCD calculations
  - “New Physics”

- The “proton radius puzzle” arose in 2010 with the first µH spectroscopy measurement of $r_p$.

- A novel electron scattering experiment (PRad) was completed at JLab Hall-B in 2016
  - lowest $Q^2$ ($\sim 2 \times 10^{-4}$ GeV/C$^2$) in ep-scattering experiments was achieved;
  - simultaneous measurement of the Møller and elastic scattering processes was demonstrated to control systematic uncertainties;
  - data in a large $Q^2$ range ($2 \times 10^{-4}$ - $6 \times 10^{-2}$ GeV$^2$) was recorded in the same experimental setting, for the first time in ep-scattering experiments.

- The PRad current result points to a small proton charge radius.
- Several other recent results seem to confirm the small proton radius.
- Several new experiments are being prepared to help further establish these results.

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

Duke University,
NC A&T State University,
Mississippi State University,
Idaho State University,
University of Virginia
Jefferson Lab,
Argonne National Lab,
University of North Carolina at Wilmington,
Kharkov Institute of Physics and Technology,
MIT
Old Dominion University,
Alikhanov Institute for Theoretical and
Experimental Physics NRC ”Kurchatov Institute”
University of Massachusetts, Amherst
Hampton University
College of William & Mary,
Norfolk State University,
Yerevan Physics Institute

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

Post-docs
Chao Gu (Duke)
Xuefei Yan (Duke)
Mehdi Meziane (Duke)
Zhihong Ye (Duke)
 Krishna Adhikari (MSU)
Maxime Lavillain (NC A&T)
Rupesh Silwal (MIT)
Backup Slides
Two large GEM based X and Y- coordinate detectors with 100 µm position resolution

The GEM detectors provided:
- factor of >20 improvements in coordinate resolutions
- similar improvements in $Q^2$ resolution
- unbiased coordinate reconstruction (including HyCal transition region)
- increase $Q^2$ range by enabling use of Pb-glass part of calorimeter

Designed and built at University of Virginia (UVa)
HyCal and GEMs on the beamline
Vacuum chamber with one thin window

- Vacuum chamber with one thin window
- Two stage, 5 m long vacuum box
- 1.7 m dia, 2 mm thick Al window
High quality, stable CEBAF electron beam
electron beam profile at target
(measured with harp scan)

typical width 25 µm

position stability : ± 250 µm

Experiment ran during May/June 2016

With $E_e = 1.1$ GeV beam
collected 4.2 mC on target ($2 \times 10^{18}$ H atoms/cm$^2$)
604 M events with H and
53 M events without H in target
25 M events on 1µm Carbon foil target

With $E_e = 2.2$ GeV beam
collected 14.3 mC on target ($2 \times 10^{18}$ H atoms/cm$^2$)
756 M events with H and
38 M events without H in target
10.5 M events on 1µm Carbon foil target
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)
Background Subtraction

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

![Graphs showing background subtraction for $ep$ and $ee$ channels with $Q^2$ and scattered electron polar angle, $\theta_{e_1}$ vs. $N_{\text{background}}/N_{\text{total}}$.](image)
Elastic cut and inelastic contribution

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

M.E. Christy and P.E. Bosted. PRC 81, 055213 (2010)