Proton Charge Radius

7th Workshop on Hadron Physics in China and Opportunities Worldwide
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QCD: still unsolved in non-perturbative region

- 2004 Nobel prize for "asymptotic freedom"
- non-perturbative regime QCD ?????
- One of the top 10 challenges for physics!
- QCD: Important for discovering new physics beyond SM
- Nucleon structure is one of the most active areas
What is inside the proton/neutron?

1933: Proton’s magnetic moment

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

\[ g \neq 2 \]

1960: Elastic e-p scattering

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

Form factors → Charge distributions

1969: Deep inelastic e-p scattering

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

1974: QCD Asymptotic Freedom

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

Nobel Prize in Physics 1943
Otto Stern

Nobel Prize in Physics 1961
Robert Hofstadter

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

Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek
Lepton scattering: powerful microscope!

- Clean probe of hadron structure
- Electron (lepton) vertex is well-known from QED
- **Vary probe wave-length 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**

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

\[
Q^2 = -q^2
\]
Unpolarized electron-nucleon scattering

*(Rosenbluth Separation)*

- Elastic e-p cross section

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

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

- 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 $G_M$

\[
\tau = \frac{Q^2}{4M^2} \quad \varepsilon = (1 + 2(1 + \tau)\tan^2 \frac{\theta}{2})^{-1}
\]

super Rosenbluth Separation (JLab Hall A experiment)
Recoil proton polarization measurement from e-p elastic scattering

**Polarization Transfer**

\[
\frac{G^p_E}{G^p_M} = -\frac{P_t}{P_l} \frac{E + E'}{2M} \tan \frac{\theta}{2}
\]

- Recoil proton polarization
  - 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

\[ A_{\text{exp}} = P_b P_t \frac{-2 \tau v_{T'} \cos \theta^* G_p^p \cos^2 \theta^* \cos \phi^* G_M^p G_E^p + 2 \sqrt{2 \tau (1+\tau) v_{T_L'}} \sin \theta^* \cos \phi^* G_M^p G_E^p}{(1+\tau) v_L G_E^p \cos^2 \theta^* + 2 \tau v_T G_M^p \cos^2 \theta^*} \]

- 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 this technique, later also used in Jlab Hall A experiment
Tremendous advances in electron scattering

Unprecedented capabilities:

- High Intensity and duty factor
- High quality polarized beams
- Large acceptance detectors
- State-of-the-art polarimetry, polarized targets

\[ \frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell} \frac{(E_e + E_{e'})}{2M} \tan\left(\frac{\theta_e}{2}\right) \]

Polarized $^3$He target

Focal plane polarimeter – Jefferson Lab
Proton Charge Radius

- An important property of the nucleon
  - Important for understanding how QCD works
  - An important input to bound state QED calculations, affects muonic H Lamb shift \((2S_{1/2} - 2P_{1/2})\) by as much as 2%

- Electron-proton elastic scattering to determine electric form factor (Nuclear Physics)
  \[
  \sqrt{<r^2>} = \sqrt{-6 \left. \frac{dG(q^2)}{dq^2} \right|_{q^2=0}}
  \]

- Spectroscopy (Atomic Physics)
  - Hydrogen Lamb shift
  - Muonic Hydrogen Lamb shift
The absolute frequency of H energy levels has been measured with an accuracy of $1.4 \text{ part in } 10^{14}$ 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
Muonic hydrogen Lamb shift at PSI (2010, 2013)

*Nature* 466, 213-216 (8 July 2010)

2010: new value is $r_p = 0.84184(67)$ fm
New PSI results reported in Science 2013

A. Antognini et al., Science 339, 417 (2013)

\[ r_p = 0.84087(39) \text{ fm} \]
Recent ep Scattering Experiments

- Large amount of overlapping data sets
- Cross section measurement
- Statistical error \( \leq 0.2\% \)
- Luminosity monitoring with spectrometer
  - \( Q^2 = 0.004 - 1.0 \) (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 Experiment

**BigBite**

- Non-focusing Dipole
- Big acceptance.
  - $\Delta p$: 200-900 MeV
  - $\Delta \Omega$: 96 msr
- PS + Scint. + SH

**LHRS**

- $\frac{\Delta p}{p_0}$: ± 4.5%
- out-of-plane: ± 60 mrad
- in-plane: ± 30 mrad
- $\Delta \Omega$: 6.7 msr
- QQDQ
- Dipole bending angle 45°
- VDC+FPP
- $P_p$: 0.55 ~ 0.93 GeV/c

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

New pol. Target data soon from Hall A

C. Crawford et al. PRL98, 052301 (2007)
The proton radius puzzle intensified

\[ r_p = 0.879(11) \text{ fm} \] by Arrington and Sick (2015) from reanalysis of ep data
Charge Radius of Other Light Nuclei

Deuterium

- μD (2013)
- CODATA (2010)
- Sick (1998)
- e-D (1970)
- e-D (1973)
- e-D (1981)
- n-p scatt.

Helium

- μ⁴He (Prelim)
- Sick (2006)
- Sick (1998)
- McCarthy et al (1977)
- Ottermann et al. (1985)

Electron scattering consistent with μ-spectroscopy
Revisits of 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>
<td></td>
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<tr>
<td>Källen–Sabry</td>
<td>1.5081</td>
<td></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>
<td>20</td>
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<td>Sixth order VP [24]</td>
<td>0.00761</td>
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<tr>
<td>Whichmann–Kroll</td>
<td>-0.00103</td>
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<td>Virtual Delbrück</td>
<td>0.00135</td>
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<tr>
<td>Light–by–light</td>
<td>-</td>
<td>10</td>
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<tr>
<td>Muon self–energy and muonic VP (2nd 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>
<td>10</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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<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>
<td>-0.0096</td>
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<td>Recoil finite size [32]</td>
<td>0.013</td>
<td>10</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</td>
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<tr>
<td>Finite size of order $(Z\alpha)^5$</td>
<td>0.0347(30) $r_p^3$</td>
<td>0.0232</td>
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<tr>
<td>Finite size of order $(Z\alpha)^6$</td>
<td>-0.0005</td>
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<tr>
<td>Correction to VP [32]</td>
<td>-0.0109 $r_p^2$</td>
<td>-0.0083</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 [19, 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>
<td>10</td>
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<tr>
<td>$2P_{3/2}^F=2$ 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
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; 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,…..

• 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
High resolution, large acceptance calorimeter

Windowless $\text{H}_2$ gas flow target

Simultaneous detection of elastic and Moller electrons

GEM detectors

$Q^2$ range of $2 \times 10^{-4} - 0.14$ GeV$^2$

Future sub 1% measurements:
(1) $ep$ elastic scattering at Jlab (PRad)
(2) $\mu p$ elastic scattering at PSI - 16 U.S. institutions! (MUSE)
(3) ISR experiments at Mainz

Ongoing $H$ spectroscopy experiments
Distance: 2H00 wire harp to Solenoid support frame ~13.7 m
High Resolution Calorimeter

- HyCal is a PbWO$_4$ and Pb-glass calorimeter
- 2.05 x 2.05 cm$^2$ x 18 cm (20 rad. Length)
- 1152 modules arranged in 34x34 matrix
- ~5 m from the target,
- 0.5 sr acceptance
Vacuum Box and GEM

Two-cylinder design for vacuum box
GEM detector to replace veto counter to improve Q2 resolution (particularly with using lead blocks)

- GEM detector funded by DOE
Windowless $H_2$ Gas Flow Target

- **Target cell (original design):**
  - cell length: 4.0 cm
  - cell diameter: 8.0 mm
  - cell material: 30 µm Kapton
  - input gas temp.: 25 K
  - target thickness: $1 \times 10^{18}$ H/cm$^2$
  - average density: $2.5 \times 10^{17}$ H/cm$^3$
  - gas mass-flow rate: 6.3 Torr-l/s ≈ 430 sccm

- **Target components:**
  - pumping system
  - cryocooler
  - motorized Manipulator
  - chillers for pumps and cryocooler
  - Target and secondary chambers

- **Kapton cell**

Target supported by NSF - MRI grant and is complete
PRad Projected Result

- Sick et al
- Bernhauer et al
- Zhan et al
- CODATA

Proton Charge radius (fm)

- Pohl et al: 0.84184(67)
- Antognini et al: 0.84087(39)
The BEPCII electron-positron double storage rings

Beam energy: 1.0-2.3 GeV
Design Luminosity: $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$
Optimum energy: 1.89 GeV
Energy spread: $5.16 \times 10^{-4}$
No. of bunches: 93
No. $e^+$ or $e^-$/bunch: $4.5 \times 10^{12}$
Bunch length: 1.5 cm
Bunch distance: 2 m
Beam size $\sigma_x/\sigma_y$: 380/5.7 μm
Current/bunch: 9.8 mA
Total current: 0.91 A
Circumference: 237 m
Injection rate for $e^+$: 50 mA/s
Injection rate for $e^-$: 200 mA/s

Only running experiment: BESIII
Start data taking: 2009
Estimated end of BESIII life time: 2022
Can we do more experiments with BEPCII?

PRad at BEPCII?

2015-8-7
Beam energy measurement

- Reconstruction of the beam energy from an energy spectrum of laser photons backscattered on beam particles:

\[ E_{beam} = \frac{\omega_{max}}{2} \times \left(1 + \sqrt{1 + \frac{m_e^2}{\omega_0 \omega_{max}}} \right) \]

- Achieved accuracy is \( \Delta E/E \approx 4 \times 10^{-5} \)

- This allows us to tune the BEPCII operation regimes, to monitor the beam energy, and to apply corrections during data analysis.

![Beam Energy Measurement System Status](image1)

![Photon spectrum](image2)
Summary

• Proton charge radius puzzle still unresolved awaiting new results
• The PRad Experiment at Jefferson Lab will be ready to take data by the end of 2015
• Potential opportunities: Mainz, and BEPII?
• Stay tuned

Thanks to D. Dutta, A. Gasparian, R. Holt, M. Khandaker, H. Li, M. Meziane, Z.-E. C. Peng, J.W. Qiu, M. Vanderhaeghen ……..

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