The P Rad experiment at JLab

The 6th Workshop on Hadron Physics in China and Opportunities in US

July 21-24, 2014
IMP, Lanzhou, China

Haiyan Gao
Duke University
Proton Radius Puzzle

SHRINKING THE PROTON
New value from exotic atom trims radius by four per cent

The Proton Problem
Could scientists be seeing signs of a whole new realm of physics?
Motivation for precise information on proton radius

• A fundamental static 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
  \((2S_{1/2} - 2P_{1/2})\) by as much as 2%

• Lamb Shift \((2S_{1/2} - 2P_{1/2})\) measurements are becoming more and more precise

• High precision tests of QED?
  – Needs inputs from electron scattering experiments on proton radius

• Turning things around one can determine proton radius using QED and Lamb shift measurements
Methods for measuring proton charge radius

- Electron-proton elastic scattering to determine electric form factor (Nuclear Physics)
  \[ \sqrt{\langle r^2 \rangle} = \sqrt{-6 \frac{dF(\vec{q})}{dq^2}} \bigg|_{q^2=0} \]

- Spectroscopy (Atomic physics)
  - Hydrogen Lamb shift
  - Muonic Hydrogen Lamb shift
Unpolarized electron-nucleon scattering

(Rosenbluth Separation)

- Elastic e-p cross section
  
  \[
  \frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2 \frac{\theta}{2} E'}{4E^2 \sin^4 \frac{\theta}{2} E} \left( \frac{G_E^p + \tau G_M^p}{1 + \tau} + 2\tau G_M^p \tan^2 \frac{\theta}{2} \right) 
  \]
  
  \[
  = \sigma_M f_{rec}^{-1} \left( A + B \tan^2 \frac{\theta}{2} \right) 
  \]

- 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 $G_M$

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

super Rosenbluth Separation
Recoil proton polarization measurement from e-p elastic scattering

**Polarization Transfer**

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

- Recoil proton polarization
  - recoil proton scatters off secondary $^{12}$C target
  - $P_t, P_l$ measured from $\phi$ distribution
  - $P_{b\gamma}$ and analyzing power cancel out in ratio

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

• Polarized beam-target asymmetry

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

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

BLAST pioneered the technique, later also used in Jlab Hall A experiment
Hydrogen Spectroscopy

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.
Muonic hydrogen Lamb shift experiment at PSI

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)
The proton radius puzzle intensified, more intrigued by muonic helium result

Maybe not (talks by Griffioen, Lorenz)
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>
</tr>
<tr>
<td>Källen–Sabry</td>
<td>1.5081</td>
<td></td>
</tr>
<tr>
<td>VP iteration</td>
<td>0.151</td>
<td></td>
</tr>
<tr>
<td>Mixed (\mu - e) VP</td>
<td>0.00007</td>
<td></td>
</tr>
<tr>
<td>Hadronic VP [21,23]</td>
<td>0.011</td>
<td></td>
</tr>
<tr>
<td>Sixth order VP [24]</td>
<td>0.00761</td>
<td></td>
</tr>
<tr>
<td>Whichmann–Kroll</td>
<td>-0.00103</td>
<td>20</td>
</tr>
<tr>
<td>Virtual Delbrück</td>
<td>0.00135</td>
<td></td>
</tr>
<tr>
<td>Light–by–light</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Muon self–energy and muonic VP (2(^{nd}) order)</td>
<td>-0.66788</td>
<td></td>
</tr>
<tr>
<td>Fourth order electron loops</td>
<td>-0.00169</td>
<td></td>
</tr>
<tr>
<td>VP insertion in self energy [17]</td>
<td>-0.0055</td>
<td>10</td>
</tr>
<tr>
<td>Proton self–energy [18]</td>
<td>-0.0099</td>
<td></td>
</tr>
<tr>
<td>Recoil [17,43]</td>
<td>0.0575</td>
<td></td>
</tr>
<tr>
<td>Recoil correction to VP (one–photon)</td>
<td>-0.0041</td>
<td></td>
</tr>
<tr>
<td>Recoil (two–photon) [19]</td>
<td>-0.04497</td>
<td></td>
</tr>
<tr>
<td>Recoil higher order [19]</td>
<td>-0.0096</td>
<td></td>
</tr>
<tr>
<td>Recoil finite size [32]</td>
<td>0.013</td>
<td>10</td>
</tr>
<tr>
<td>Finite size of order ((Z\alpha)^4) [32]</td>
<td>-5.1975(1) (r_p^2)</td>
<td>-3.979</td>
</tr>
<tr>
<td>Finite size of order ((Z\alpha)^5)</td>
<td>0.0347(30) (r_p^3)</td>
<td>0.0232</td>
</tr>
<tr>
<td>Finite size of order ((Z\alpha)^6)</td>
<td>-0.0005</td>
<td></td>
</tr>
<tr>
<td>Correction to VP</td>
<td>-0.0109 (r_p^2)</td>
<td>-0.0083</td>
</tr>
<tr>
<td>Additional size for VP [19]</td>
<td>-0.0164 (r_p^2)</td>
<td>-0.0128</td>
</tr>
<tr>
<td><strong>Proton polarizability</strong> [11,33]</td>
<td>0.015</td>
<td>40</td>
</tr>
<tr>
<td>Fine structure (\Delta E(2P_{3/2} - 2P_{1/2}))</td>
<td>8.352</td>
<td>10</td>
</tr>
<tr>
<td>(2P_{3/2}^{F=2}) hyperfine splitting</td>
<td>1.2724</td>
<td></td>
</tr>
<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
**Partial Summary**


- **Higher moments of the charge distribution and Zemach radii**, Distler, Bernauer and Walcher, PLB696, 343(2011),..

- **Dispersion relations**: Lorentz et al. arXiv:1205.6628

- …………..

- **New experiments**: Mainz (e-d, ISR, Jlab (PRad), PSI (Lamb shift, mu-p scattering), H Lamb shift, PRad …
How to resolve the proton charge radius puzzle?

Focus on experiments here

✧ Redo atomic hydrogen spectroscopy

✧ Muonic deuterium and helium (PSI)

✧ Muon-proton scattering (MUSE experiment)

✧ Electron scattering experiments (Jlab and Mainz) (preferably with completely different systematics)
- High resolution, large acceptance, hybrid HyCal calorimeter (PbWO$_4$ and Pb)
- Windowless H$_2$ gas flow target
- Simultaneous detection of elastic and Moller electrons
- $Q^2$ range of $2 \times 10^{-4} – 0.14$ GeV$^2$
- XY – veto counters replaced by GEM detector
- Vacuum box

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

Approved with A rating
Distance between the HPS Quads’ girder and the center of the Hall is ~10.5 m
High Resolution Calorimeter

- HyCal is a PbWO$_4$ and Pb-glass calorimeter
- 2.05 x 2.05 cm$^2$ x18 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)
Windowless $H_2$ Gas Flow Target

- **Target cell (original design):**
  - cell length 4.0 cm
  - cell diameter 8.0 mm
  - cell material 30 $\mu$m 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 $\approx$ 430 sccm

- **Target parts:**
  - pumping system (all parts at Jlab)
  - cryocooler (at Jlab)
  - motorized Manipulator (at Jlab)
  - chillers for pumps and cryocooler (at Jlab)
  - Target and secondary chambers (at JLab)

- **Kapton cell: work in progress**

Target supported by NSF - MRI grant
Background due to beam halo

- Beam halo is the main background source, it may hit the cell structure
- This background will be subtracted by empty target run
- The cell design is also changed to reduce the background level

Halo $\sigma_{x,y} = 0.38 - 0.95$ mm

6 GeV machine, by A. P. Freyberger

Target cell aperture diameter 4 mm
Background due to beam halo

- The aperture of cell is fixed at 4 mm, and the cell diameter increases.
- The new design maintains the target thickness, and reduces the background from halo.

<table>
<thead>
<tr>
<th>Aperture</th>
<th>Cell Diameter</th>
<th>H density ($10^{18} \text{ cm}^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 mm</td>
<td>12 mm</td>
<td>$2.295 \times 10^{18}$</td>
</tr>
<tr>
<td>4 mm</td>
<td>32 mm</td>
<td>$2.323 \times 10^{18}$</td>
</tr>
</tbody>
</table>
Normalization with Moller Scattering

Simultaneous detection of ep elastic and ee Moller events
Measurement Principle

3 methods to analyze the Möller electrons:

- **Single arm method:** one Möller electron detected:
  \[
  \left( \frac{d\sigma}{d\Omega} \right)_{ep} (Q_i^2) = \left[ \frac{N_{\text{yield}}^{ep} (ep \rightarrow ep \text{ in } \theta_i \pm \Delta \theta)}{N_{\text{exp}}^e (e^-e^- \rightarrow e^-e^-)} \right] \left( \frac{d\sigma}{d\Omega} \right)_{e^-e^-}
  \]
  Only detection efficiencies and relative acceptance are needed.

- **Double arm method:** both Möller electrons are detected
  \[
  \left( \frac{d\sigma}{d\Omega} \right)_{ep} (Q_i^2) = \left[ \frac{N_{\text{yield}}^e (ep \rightarrow ep \text{ in } \theta_i \pm \Delta \theta)}{N_{\text{exp}}^e (e^-e^- \rightarrow e^-e^-)} \cdot \frac{\varepsilon_{\text{geom}}^{e^-e^-}}{\varepsilon_{\text{geom}}^{\text{cp}}} \cdot \frac{\varepsilon_{\text{det}}^{e^-e^-}}{\varepsilon_{\text{det}}^{\text{cp}}} \right] \left( \frac{d\sigma}{d\Omega} \right)_{e^-e^-}
  \]

- **Integrated Möller cross section method** over all the HyCal acceptance
  \[
  \left( \frac{d\sigma}{d\Omega} \right)_{ep} (Q_i^2) = \left[ \frac{N_{\text{yield}}^e (ep, \theta_i \pm \Delta \theta)}{N_{\text{exp}}^e (e^-e^-, \text{ on PbWO}_4)} \right] \frac{\varepsilon_{\text{geom}}^{e^-e^-} (\text{all PbWO}_4)}{\varepsilon_{\text{geom}}^{\text{cp}} (\theta_i \pm \Delta \theta)} \frac{\varepsilon_{\text{det}}^{e^-e^-} (\text{all PbWO}_4)}{\varepsilon_{\text{det}}^{\text{cp}} (\theta_i \pm \Delta \theta)} \left( \frac{d\sigma}{d\Omega} \right)_{e^-e^-}
  \]
Radiative Corrections at low $Q^2$ for the PRad Experiment

Updated ep radiative corrections code MASCARAD

Updated Møller radiative corrections code MERA

Two studies within PRad collaboration:
(1) Akushevich, Gao, Ilyichev and Meziane
(2) Gasparian and Gramolin

Solid line: 1.1 GeV
Dashed line: 2.2 GeV
Inelasticity cut: 0.05 GeV$^2$ for ep and 10$^{-5}$ GeV$^2$ for Moller
Both latest Arrington (solid lines) and Bernauer et al. (color lines) give Coulomb corrections significantly less than 0.1% to the unpolarized cross section for $\varepsilon \rightarrow 1$.

Largest $\varepsilon$ of this experiment: 0.998

Coulomb corrections

$Q^2 = 0.3 \text{ (GeV/c)}^2$

$Q^2 = 1 \text{ (GeV/c)}^2$


TPE: M. Gorshteyn
Full Simulation of the Experiment

A Geant4 based simulation of the entire experiment has been developed

A detailed study of backgrounds and background subtraction has been performed using this simulation (need 20% beam time for empty target runs)

Empty target

Full target

Simulations by C. Peng (Duke)
Full Simulation and projection of the Experiment

$Q^2$ range using full HyCal, and adding GEM position detector, statistical and sys. uncertainties included

$r_p = 0.8768 \text{ fm (input)}$  \hspace{1cm}  $r_p = 0.8758(58) \text{ fm (extracted)}$

Simulations by
C. Peng
Projected Result

Proton Charge radius (fm)

- Sick et al
- Bernauer et al
- Zhan et al
- CODATA
- (This exp.)
- Pohl et al
- Antognini et al

Pohl et al: 0.84184(67)
Antognini et al: 0.84087(39)
# JLab Three-Year Run Plan

## Jefferson Lab Three-Year Schedule

<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calendar Year</td>
<td>2014</td>
<td>2015</td>
<td>2016</td>
</tr>
<tr>
<td><strong>CEBAF</strong></td>
<td>Activity Beam</td>
<td>Commissioning</td>
<td>Comm.</td>
</tr>
<tr>
<td><strong>Hall B</strong></td>
<td>Activity Beam</td>
<td>CLAS12 Construction/Installation</td>
<td>Non-CLAS12 Ops</td>
</tr>
<tr>
<td><strong>Hall C</strong></td>
<td>Activity Beam</td>
<td>SHMS Construction/Installation</td>
<td>Comm.</td>
</tr>
</tbody>
</table>

Legend:
- Green: Beam for Commissioning
- Blue: Beam for Physics
- Purple: Non-CLAS12 Ops

*Dec 2013*
PRad Collaboration Institutional List

- Currently 16 collaborating universities and institutions
  - Jefferson Laboratory
  - NC A&T State University
  - Duke University
  - Idaho State University
  - Mississippi State University
  - Norfolk State University
  - Argonne National Laboratory
  - University of North Carolina at Wilmington
  - University of Kentucky
  - Hampton University
  - College of William & Mary
  - University of Virginia
  - Tsinghua University, China
  - Old Dominion University
  - ITEP, Moscow, Russia
  - Budker Institute of Nuclear Physics, Novosibirsk, Russia

- Welcome new collaborators and institutional groups
Summary and outlook

• Proton charge radius: fundamental quantity important to atomic, nuclear, and particle physics
• Proton charge radius puzzle triggered by muonic hydrogen atom Lamb shift measurements motivated extensive theoretical and experimental activities
• New precision measurement from electron scattering is a MUST
• PRad: new experiment on e-p elastic scattering will use novel experimental techniques
• Stay tuned for more news about proton charge radius

Acknowledgement: the PRad Collaboration
Supported in part by U.S. Department of Energy under contract number DE-FG02-03ER41231, NSF MRI PHY-1229153
The 21st INTERNATIONAL SYMPOSIUM on Spin Physics (SPIN2014), Beijing, China

**Dates:** October 20-24, 2014  
**Place:** Peking University  
Beijing, China  
**Conference co-chairs:**  
Bo-Qiang Ma and Haiyan Gao

Symposium website  

Poster competition with prizes  

**Deadline:** August 30, 2014
11th European Research conference on “Electromagnetic interactions with nucleons and nuclei

• Scientific program will include:
  • Nucleon form factors and low-energy hadron structure
  • Partonic structure of nucleons and nuclei
  • Precision electroweak physics with searches for dark photons
  • Meson spectroscopy and structure
  • Baryon and light-meson spectroscopy
  • Nuclear effects and few-body physics