Status of the PRad Experiment
(E12-11-106)

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for the PRad collaboration

Outline

- PRad Physics goals
- ep-scattering and the proton radius
- PRad experiment
  - experimental setup
  - development of apparatus
  - current status
- Summary
The Proton Charge Radius Puzzle

- New high precision experiments are needed to solve this $7\sigma$ discrepancy
In the limit of first Born approximation the elastic \( ep \) scattering (one photon exchange):

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

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

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 \( G_M \) were extracted using Rosenbluth separation (or at extremely low \( Q^2 \) the \( G_M \) can be ignored, like in the PRad experiment)

The Taylor expansion at low \( Q^2 \):

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

\( \langle r^2 \rangle = -6 \left. \frac{dG_E^p(Q^2)}{dQ^2} \right|_{Q^2=0} \)

Defined as:

\[
\langle r^2 \rangle = \int \rho(r)r^2 dr
\]
An Example: Recent Mainz ep-Experiment (2010)

Three spectrometer facility of the A1 collaboration:

- $Q^2 = [0.004 – 1.0] \text{ (GeV/c)}^2$ range
- Large amount of overlapping data sets (~1400)
- Statistical error $\leq 0.2$
- Luminosity monitoring with spectrometer
- Additional beam current measurements

$r_p = 0.879(5)_{\text{stat}}(4)_{\text{sys}}(2)_{\text{mod}}(4)_{\text{group}}$

- Confirms the previous results from $ep \to ep$ scattering;
- Consistent with CODATA06 value: $(r_p = 0.8768(69) \text{ fm})$
The PRad Experiment (E12-11-106)

- Experimental goals:
  - reach very low $Q^2$ range ($\sim 10$ times less than the Mainz experiment)
  - reach sub-percent precision in $r_p$ extraction

- Suggested solutions:
  1) Non-magnetic-spectrometer method:
     - use high resolution high acceptance crystal calorimeter
     - reach smaller scattering angles: $(\Theta = 0.7^0 - 3.8^0)$
     - $(Q^2 = 2 \times 10^{-4} - 8 \times 10^{-2})$ GeV/c$^2$
     - essentially, model independent $r_p$ extraction
  2) Simultaneous detection of $ee \rightarrow ee$ Moller scattering
     - (best known control of systematics)
  3) Use high density windowless H2 gas flow target:
     - beam background fully under control with high quality CEBAF beam
     - minimize experimental background

- Two beam energies: $E_0 = 1.1$ GeV and 2.2 GeV to increase $Q^2$ range: $(2 \times 10^{-4} - 8 \times 10^{-2})$ GeV/c$^2$
- Will reach sub-percent precision in $r_p$ extraction (0.6% total)
- Approved by PAC39 (June, 2012) with high “A” scientific rating
Main detectors and elements:
- windowless $\text{H}_2$ gas flow target
- PrimEx HyCal calorimeter
- vacuum box with one thin window at HyCal end
- $X,Y$ – GEM detector on front of HyCal

Beam line equipment:
- standard beam line elements (0.1 – 10 nA)
- photon tagger for HyCal calibration
- collimator box (6.4 mm collimator for photon beam, 12.7 mm for $e^-$ beam halo “clean-up”)
- Harp 2H00
- pipe connecting Vacuum Window through HyCal
PRad Experimental Setup (3D view)
PRad Running Configuration in Hall B (suggested)

- Footprint of PRad setup: \( ~8.2 \times 1.7 \text{ m}^2 \)
- Installation in parallel with CLAS12 work/assembly in Hall B
- Engineering and Physics runs during evenings/nights and over weekends

**PRad Running Setup**

Facts about the installation:

- Distances within the setup:
  - Distance between the HPS Quads’ girder and the center of the Hall is \( ~10.5 \text{ m} \)
Windowless H$_2$ Gas Flow Target

- **Target proposal specs:**
  - 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$^3$
  - Cell pressure: 0.6 torr
  - Vacuum in target chamber: $\sim 5 \times 10^{-3}$ torr

- NSF MRI award in 2012 (#PHY-1229153) to develop and construct this target (~0.4M)
Target Status

- All parts and elements are at JLab:
  - Target system has been built
  - Chamber support stands are built
  - Assembled and tested in January 2015
  - Entire pumping system assembled and tested (at room T, with He, only 1 chamber turbo, not 2, no beam line turbos)
  - Achieved ~0.5 of goal thickness (with $^4$He)

- Full system test with He gas is underway (Oct. 2015)
- Target will be ready for installation in the Hall B beam line (estimated time: 8-10 days)
Electromagnetic Calorimeter (PrimEx HyCal)

- Combination of PbWO$_4$ and Pb-glass detectors (118x118 cm$^2$)
- 34 x 34 matrix of 2.05 x 2.05 x 18 cm$^3$ PbWO$_4$ shower detectors
- 576 Pb-glass shower detectors (3.82x3.82x45.0 cm$^3$)
- 2 x 2 PbWO$_4$ modules removed in middle for beam passage
- 5.5 m from H$_2$ target (~0.5 sr acceptance)

- Resolutions:
  - for PbWO$_4$ shower detectors:
    - energy: $\sigma/E = 2.6\%/\sqrt{E}$
    - position: $\sigma_{xy} = 2.5\ mm/\sqrt{E}$
  - for Pb-glass shower detectors factor of ~2.5 worse
HyCal Current Operational Status

- Moved back to Hall B in June, 2014:
  (thanks to Technical Group (D. Tilles and All))
  - Cabling system with infrastructure reassembled
  - Trigger, analog and HV electronics are reinstalled
  - Cooling system is operational
  - LMS checked and repaired
  - All individual detectors checked and repaired
  - DAQ is operational (HyCal readout part)
  - Transporter is reinstalled/repaired and operational

✓ HyCal is ready for experiment

HyCal in Hall B beam line (Nov., 2014)
HyCal Current Status

- HyCal is currently up in Transporter for cosmic ray tests

- HyCal is fully repaired and ready for the experiment.

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CLAS col. meeting, Oct. 2015
Tasks for GEM:
- factor of >10 improvements in coordinate resolutions
- similar improvements in $Q^2$ resolution (very important)
- unbiased coordinate reconstruction (including transition region)
- increase $Q^2$ range by including Pb-glass part

Designed at UVa
- All components are built at CERN/RESARM and received at UVa
- 1st GEM chamber is completed in Sep. 2015, cosmic tests are underway (UVa)
- 2nd chamber is planned for Nov. 2015 (UVa)
- GEM DAQ is ported into CODA (MSU/UVa)
- Delivery to JLab: Jan. 2016

GEM will be ready for installation in Feb. 2016 (estimated installation time: 3 days)
Conceptual design is done by Duke/Jlab

Remaining work:

- engineering design in progress
- construction (in local shop)
Vacuum Box

- Engineering design is done by Duke/Jlab
- Construction is done (March 2015)
- Tested with window by vendor (March 2015)
- Delivered to JLab (March 2015)

- Remaining work:
  - stands for vacuum box:
    - conceptual design done;
    - engineering design in progress

- ready for installation:
  (estimated time: 2 days)
Vacuum Window

- Thin Al-window on Vacuum Box at the HyCal end
  - thickness: ~2 mm
  - diameter: 1.7 m
  - connected to the beam vacuum pipe in center

- Design and construction done

- Vacuum tests are done

- Remaining work:
  - connection to the vacuum pipe
  - design in progress

- Vacuum Window will be ready for installation: Feb. 2016
  (estimated time: 2 days)
PRad Beam Line

tagger
collimator box
harp
target chamber
vacuum box
HyCal with GEM
Remaining work on Beam Line:

- vacuum box stands (design in progress)
- beam line from Vacuum Window through HyCal (design in progress)
- collimator box (installation)
- Harp 2H00 (installation)

Beam line ready for installation: Jan 2016

Beam line change from HPS to PRad: ~ 20 days (including target)
- PrimEx FASTBUS-based electronics and UVa linear sum modules for trigger
- Ready, taking cosmic data
Currently 16 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
University of Kentucky
Hampton University
College of William & Mary
Tsinghua University, China
Old Dominion University
ITEP, Moscow, Russia
Budker Institute of Nuclear Physics, Novosibirsk, Russia

Open for new collaborators and institutional groups !!!
Summary

- "Proton radius puzzle" is still unsolved after 5 years.
- PRad is uniquely designed to address this puzzle.

- PRad experimental setup, in most part, is ready for the experiment.
  - few remaining work on beam line elements
- The experimental setup will be ready for installation in Feb. 2016.

- Readiness Review is scheduled for Nov. 12, 2015.

- PRad will be ready for any "opportunistic" run for this spring.
  - open for new collaborators and institutional groups !!!

- PRad is supported in part by NSF MRI award #PHY-1229153
- my research work is supported in part by NSF awards: PHY-1506388 and PHY-0855543
Buck up slides
Estimated Errors

- Extraction of proton charge radius was always limited by systematics and fitting uncertainties

- High rates will provide good statistical errors (~0.2% for all $Q^2$ bins)

- Simultaneous detection of two processes:
  - $ep \rightarrow ep$
  - $ee \rightarrow ee$ Moller scattering

- and windowless H$_2$ gas target

  - will significantly reduce major systematic errors typical for all previous $ep$-scattering experiments

<table>
<thead>
<tr>
<th>Contributions</th>
<th>Estimated Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical error</td>
<td>0.2</td>
</tr>
<tr>
<td>Acceptance (including $Q^2$ determination)</td>
<td>0.4</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>0.1</td>
</tr>
<tr>
<td>Radiative corrections</td>
<td>0.3</td>
</tr>
<tr>
<td>Background and PID</td>
<td>0.1</td>
</tr>
<tr>
<td>Fitting error</td>
<td>0.2</td>
</tr>
<tr>
<td>Total Error</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

- Estimated error budget (added quadratically)
Beam Quality Requirements

<table>
<thead>
<tr>
<th>Quality</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>1.1 and 2.2 GeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>0.1 – 10 nA</td>
</tr>
<tr>
<td>Luminosity</td>
<td>~ $10^{28}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>$\sigma_x, \sigma_y$</td>
<td>~ 100 μm</td>
</tr>
<tr>
<td>Position stability</td>
<td>~ 100 μm</td>
</tr>
<tr>
<td>Beam halo</td>
<td>&lt; (1x10$^{-7}$)*</td>
</tr>
<tr>
<td>Divergence</td>
<td>&lt; mrad</td>
</tr>
<tr>
<td>Emittance ($\varepsilon_x, \varepsilon_y$)</td>
<td>8x10$^{-10}$ m-rad</td>
</tr>
</tbody>
</table>

* for $R > 3$ mm from the beam center
New Results from Muonic Hydrogen Experiments (2010, 2013)

- $r_p = 0.84184(67)$ fm  \[\rightarrow\] Unprecedented less than 0.1% precision

- Different from most of previous experimental results and analyses
Proton Radius Extracted From e-p Scattering Experiments

- More different analysis results than actual experiments
- Started with: \( r_p \approx 0.81 \text{ fm} \) in 1963
- Reached to: \( r_p \approx 0.88 \text{ fm} \) by 2011
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