New MAMI proton radius experiment using ISR

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for the A1-Collaboration
The proton radius puzzle

- What is the size of the proton?
- Many different measurements (scattering exp., Lamb shift) done through the years.
- Consistent results.
- New $\mu$-p Lamb measurement, $7\sigma$ away.
- Further investigations necessary.
Elastic Cross-Section measurement

Radius can be obtained by measuring cross section of $H(e,e')p$:

$$\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{Mott} \frac{1}{1 + \tau} \left[ \tilde{r}_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2) \right]$$

$$\varepsilon = \left[ 1 + 2(1 + \tau) \tan^2 \frac{\vartheta_e}{2} \right]^{-1} \quad \tau = \frac{Q^2}{4m_p^2},$$

Extraction of FF via Rosenbluth, Super-Rosenbluth Separation:

$$G_E(Q^2) \approx G^{Dipole}(Q^2) = \left( 1 + \frac{Q^2}{0.71} \right)^{-2}$$

Best estimate for radius:

$$\langle r_E^2 \rangle = -6\hbar^2 \frac{d}{dQ^2} G_E(Q^2) \bigg|_{Q^2=0}$$

$$\rho_{Dipole}(r) = \frac{1}{8\pi} \left( \frac{12}{r_E^2} \right)^{3/2} \exp \left( -r \sqrt{\frac{12}{\langle r_E^2 \rangle}} \right)$$

No data at lowest $Q^2$. Determination of proton radius depends on the slope of FF ($Q^2\to0$).
Exploiting the radiative tail

- To test the behavior of FFs at $Q^2 \sim 0$, elastic cross-section measurements at lower $Q^2$ would be needed.

- Lowest $Q^2$ is constrained by the limitations of experimental apparatus (Beam Energy, Scattering angle ...).

WAY AROUND: Use information stored in the radiative tail.
Initial state radiation

- Radiative tail dominated by coherent sum of two Bethe-Heitler diagrams.

- In data ISR can not be distinguished from FSR.
- Combining data to the Simulation, ISR information can be reached.
- Idea behind new MAMI experiment to extract $G_{e^p}$ at $Q^2 \sim 10^{-4} \text{ (GeV/c)}^2$
- Redundancy measurements at higher $Q^2$ for testing this approach in a region, where FFs are well known.
- In the experiment the $G_{e^p}$ will not be directly extracted from data.

- FF are camouflaged by effects that accompany FSR and ISR diagrams (Born diagrams, vertex corrections).

- Approach analogous to Bernauer et al. will be used, where simulated distributions are directly compared to measured data.

- Simulate $e^p \rightarrow e^p \gamma$ with a sophisticated Monte-Carlo simulation Simul++.

- Simulation will be run with various values of $G_{E^p}$. Contribution of $G_{M^p}$ is neglected @ $Q^2 \sim 0$.

- Final values of FFs will be determined by a $\chi^2$-minimization.
Going beyond simple approximation

- Simul++ employs an advanced event generator, which exactly calculates amplitudes for four leading order diagrams.

- Next order terms considered via effective correction to the cross-section.

- Precise spectrometer acceptances, particle energy-losses and rescatterings are also implemented.
First experiment

- First measurements done in 2010. Three weeks of data taking. (2 weeks with full target, 1 week with empty target)

- **Purpose:** Is the experiment feasible? Discover potential problems.

**Electron Beam:**
- Energy: 195, 330, 495 MeV
- Current: 10nA – 1 µA
- Rastered beam

**Spectrometer A:**
- Luminosity monitor (const. setting)
- Momentum: 150, 300, 370 MeV/c
- Angle: 37.9deg

**Spectrometer B:**
- Data taking
- Angle: 15.3deg
- Momentum:
  - 62-178 MeV/c (35 setups)
  - 167-313 MeV/c (9 setups)
  - 236-468 MeV/c (16 setups)

**Spectrometer C:**
- Not used

**Luminosity monitors:**
- pA-meter
- Förster probe
Improvements for the full experiment

**To minimize the thickness of cryogens:**
- Ensured **better vacuum** in target chamber ($10^{-4} \rightarrow 10^{-6} \text{ mbar}$).
- New target windows.
- Additional Aramid windows.
- Fixing Spectrometer A to elastic settings to see effects of snow gathering more clearly.

**Spectrometer optics:**
- Ensured that NMR signal is present for all kinematic points.
- Dedicated 2-week beam time for the optics calibration.
- Detailed analysis of detector efficiencies.
- For each kin. setting solid-state target data were collected.
Full experiment

- Full experiment done in August 2013. Four weeks of data taking.

Electron Beam:
- Energy: 195, 330, 495 MeV
- Current: 10nA – 1µA
- Rastered beam

Luminosity monitors:
- pA-meter
- Förster probe
- SEM

Spectrometer A:
- Luminosity monitor (const. setting)
- Momentum: 180, 305, 386 MeV/c
- Angles: 50, 60 deg

Spectrometer B:
- Data taking
- Angle: 15.3deg
- Momentum:
  - 48 - 194 MeV/c (35 setups)
  - 156 - 326 MeV/c (12 setups)
  - 289 - 486 MeV/c (9 setups)

Spectrometer C:
- Not used

Beam control module:
- Communicates with MAMI and ensures very stable beam.
- BPM and pA meter measurements performed automatically every 3min.
Kinematic settings of the full experiment

- Measured kinematic points and corresponding $Q^2$ at vertex.
- Three kinematic regions overlap to verify ISR approach.
First Results

- First findings of online analysis.

- Data are normalized to 0.1mC using Forster probe & Spek-A.

- Only acceptance and Vertex-z cuts considered.

- Pion production processes contribute ~10% at smallest momenta.

- Coarse structure on top of distributions caused by changing detection efficiency.

- Visible effects of finite resolution. (wall contributions still present)

- Agreement between data and simulation justifies use of Simul++.
- Proton radius puzzle is an important open question of nuclear physics.

- A new experiment is underway at MAMI to measure $G_E^p$ at very low $Q^2$.

- A new technique is being used based on ISR, which exploits information from radiative tail to determine FF at lowest $Q^2$.

- First test measurements in 2010 revealed problems with cryogens covering the target cell and spectrometer optics.

- All diagnosed obstacles were addressed.

- Full experiment was successfully run in August 2013.

- Data analysis is now underway.
Thank you!
Handicaps of the pilot measurement

- For many momentum settings **no NMR** available. Spectrometer momentum determined using **Hall probes**, which not absolutely calibrated.

- Optics matrix needs adjustments to improve resolution.

- Due to **poor vacuum and low beam intensities**, layer of **cryogens covered the target cell**.

+ Cryogenic depositions consist of residual Nitrogen, Oxygen and H$_2$O.
+ Disturbs Luminosity determination.
+ Amount of snow changes irregularly with time.