Elastic Electron and Muon Scattering Experiment Off the Proton at PSI

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While consistent results for the charge radius of the proton have been extracted from elastic electron-scattering data and through the spectroscopy of atomic hydrogen, recent high-precision studies of muonic hydrogen found notably smaller values for the charge radius. This so-called proton-radius puzzle raises questions ranging from experimental and methodological issues to physics beyond the Standard Model. The puzzle certainly calls for new measurements. The MUon Scattering Experiment (MUSE) at the Paul Scherrer Institute is being developed to provide elastic scattering data off the proton with electron and muon beams of positive and negative charge. Each of the four sets of data will allow the extraction of the proton charge radius; in combination, the data test possible differences of the electron and muon interactions and additionally two-photon exchange effects. The experiment will cover a four-momentum-transfer range from 0.002 to 0.07 GeV^2.

1 The Proton-Radius Puzzle

The electric and magnetic structure of the proton can be probed in electron-proton scattering experiments. In the one-photon exchange approximation, the experimental cross section depends on the electric and magnetic form factors, G_E and G_M, respectively. The form factors are functions of the four-momentum transfer squared, $-Q^2$, and can be determined in a Rosenbluth separation at fixed Q^2 in a series of measurements with varying electron scattering angles, θ. The slope of the electric form factor at $Q^2 = 0$ defines the proton charge radius, r_p,

$$r_p^2 = -6\hbar^2 \left. \frac{dG_E}{dQ^2} \right|_{Q^2=0} .$$

In a recent such measurement the A1 Collaboration in Mainz found a value of $r_p = 0.879 \pm 0.008$ fm [1]. The polarization transfer in electron-proton scattering experiments does not allow for a separation of the electric and magnetic form factors, but only depends on the form factor ratio, G_E/G_M. Polarization data, however, give independent constraints and a recent measurement and analysis of the LEDEX Collaboration at Jefferson Lab found a value of $r_p = 0.875 \pm 0.010$ fm [2]. An alternative method to determine the proton radius is the spectroscopy of atomic hydrogen. The electron wave function in the S states has overlap with the proton wave function and their interaction modifies the Lamb shift in hydrogen by an amount, which depends on the proton radius, $\Delta E \propto |\psi_S(0)|^2 r_p^2$. Radius extractions by CODATA from electronic hydrogen spectroscopy data give a value of $r_p = 0.8775 \pm 0.0051$ fm. Due to the larger muon mass, the overlap of the lepton wave function with the proton in muonic hydrogen is 8×10^6 times larger than in electronic hydrogen, making the spectroscopy of muonic hydrogen that much more sensitive. While the electronic data have been consistent, recent measurements of the Lamb shift in the muonic hydrogen atom obtained a significantly smaller value of the proton radius of 0.84087 ± 0.00039 fm [3, 4]. That these precise results differ by seven standard deviations from the combined results of all electronic data is the so called *proton radius puzzle*. Figure 1 shows this obvious disagreement.

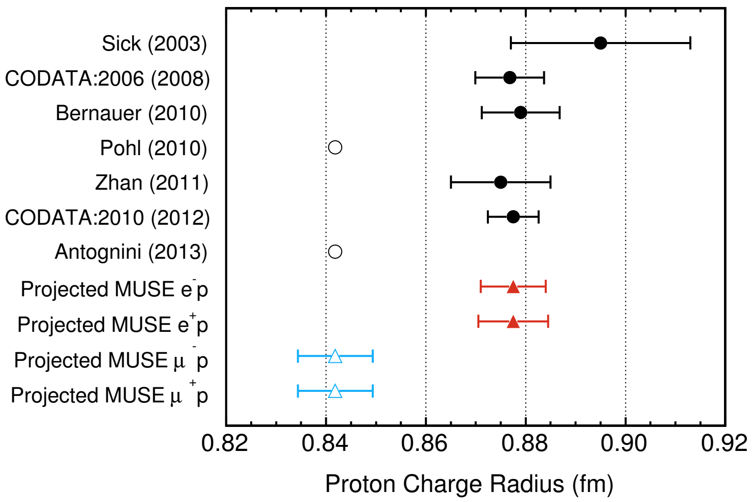

Figure 1: Previous results (circles) and projected MUSE results (triangles) of proton-radius measurements and extractions of electronic (full symbols) and muonic (open symbols) data [1, 2, 3, 4, 5, 6, 7].

This discrepancy has triggered a lively discussion. A recent review article [8] discusses many ideas, which were brought forward as possible solutions to the puzzle. The explanations can be grouped as follows. First, there may be problems with the experiment, including underestimation of uncertainties, difficulties in fitting the slope of the electric form factor for the radius extraction [9], or issues in QED calculations in the analysis of spectroscopy data. Second, novel hadronic physics may be important for μp but not for ep systems; suggested effects include proton polarizability effects proportional to m_ℓ^4 [10], off-shell corrections, and two-photon proton-structure corrections. Finally, the discrepancy may be an indication of the violation of μ/e universality and hint at physics beyond the standard model; *e.g.* [11]. Several ideas have been ruled out and none have gained universal acceptance.

Clearly, new data are needed. New spectroscopy measurements have been performed, including also experiments on deuterium and on helium [12]. New electron scattering experiments will try to improve on the precision of the form factor extraction and to reach lower values of Q^2 [12]. The proposed MUSE experiment [13] at the Paul Scherrer Institute (PSI), however, is unique. It is the only experiment, which will directly compare ep and μp in an elastic scattering experiment.

2 The MUSE Experiment at PSI

The MUSE experiment will measure $e^{\pm}p$ and $\mu^{\pm}p$ elastic scattering cross sections for lepton scattering angles between $\theta = 20^\circ$ and 100° and beam momenta of $p = 115, 153$, and 210 MeV with a low beam flux of up to 5 MHz. The experiment will cover a range in Q^2 between 0.002 and 0.07 GeV^2. Measurements with both charges for the lepton allow for studies of possible two-photon exchange mechanisms. The use of both e and μ beams allows for a direct test of lepton-type dependent effects.

The experiment will be set up at PSI's πM1 secondary beam line. A schematic diagram of the proposed large-acceptance setup is shown in Fig. 2. In the absence of inelastic reactions off the proton, the determination of the lepton scattering angle at a given beam momentum completely determines the kinematics of the reaction. A magnetic spectrometer to determine the scattered particle momentum is not needed. The beam Čerenkov detector measures the beam particle time relative to the radio-frequency of the accelerator. Test measurements have shown that the particle types (e, μ, and π) can be well separated by their time-of-flight. The quite large emittance of the incident beam requires to track each incoming particle in a scintillator fiber detector and a set of three gas-electron multiplier (GEM) chambers. The scattered particles are tracked in a series of straw chambers and are detected in the fast scintillators, which are

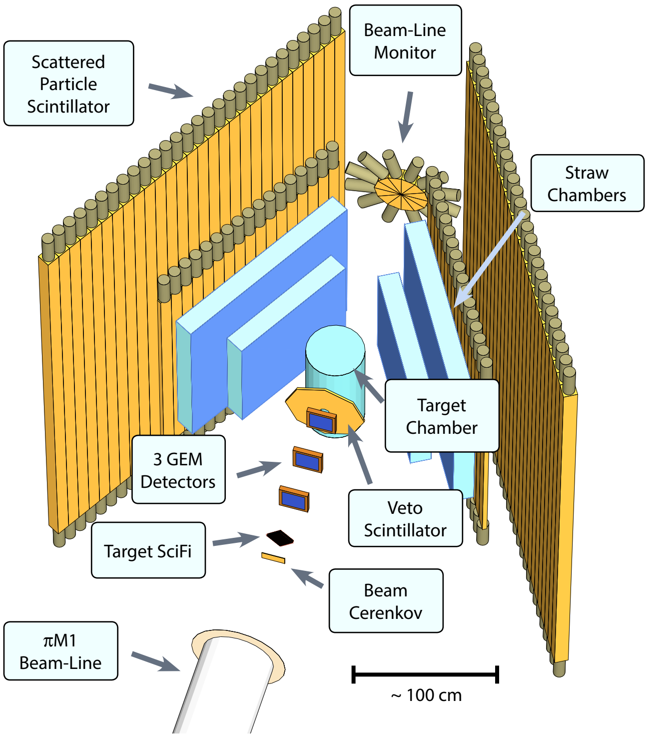

Figure 2: Schematic view of the planned detector setup for the MUSE experiment.

included in the trigger for the experiment. The veto scintillator, just upstream of the scattering chamber, allows a reduction of the trigger rate due to background tracks. The stability of the beam properties will be monitored with a downstream beam-line monitor. That detector also serves as an efficient veto for Møller scattering events.

Detailed Geant4 [14] based Monte-Carlo simulations of the experiment are underway to help optimize the detector setup and to study the parameters of the experiment. Items being studied include the resolution of the scattering-angle and vertex reconstructions, the muon decay-in-flight background, which is a source of electron tracks, and the Møller scattering background. Beam- and scattered-particle momentum distributions including radiative tails are necessary ingredients for radiative corrections of the experimental cross sections. These distributions are determined in full simulations of the experiment. The simulation results are being validated to the extent possible with experimental data.

Preliminary estimates of the total relative cross-section uncertainties for muon and electrons are 0.4% and 0.6%, respectively. The sensitivity of the experiment to differences in the extracted proton radius from e and μ scattering data is expected to be ±0.009 fm.

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References

[1] J.C. Bernauer *et al.*, Phys. Rev. Lett. **105**, 242001 (2010).

[2] X. Zhan *et al.*, Phys. Lett. **B705**, 59–64 (2011).

[3] R. Pohl *et al.* Nature **466**, 213–216 (2010).

[4] A. Antognini *et al.*, Science **339**, 417–420 (2013).

[5] I. Sick, Phys. Lett. **B576**, 62–67, (2003).

[6] P.J. Mohr, B.N. Taylor, and D.B. Newell, Rev. Mod. Phys. **84**, 1527–1605 (2012).

[7] P.J. Mohr, B.N. Taylor, and D.B. Newell, Rev. Mod. Phys. **80**, 633–730 (2008).

[8] R. Pohl, R. Gilman, G.A. Miller, and K. Pachucki, Ann. Rev. Nucl. Part. Sci. **63**, 175–204 (2013).

[9] E. Kraus, K.E. Mesick, A. White, R. Gilman, and S. Strauch, arXiv:1405.4735 [nucl-ex] (2014).

[10] G.A. Miller, Phys. Lett. **B718**, 1078–1082, (2013).

[11] C.E. Carlson and B.C. Rislow, Phys. Rev. **D86**, 035013 (2012).

[12] Mainz Institute for Theoretical Physics. Proton Radius Puzzle Workshop, (2014). `https://indico.mitp.uni-mainz.de/conferenceDisplay.py?ovw=True&confId=14`.

[13] R. Gilman *et al.*, arXiv:1303.2160 [nucl-ex] (2013).

[14] S. Agostinelli *et al.*, Nucl. Instrum. Meth. **A506**, 250–303 (2003).