EPJ Web of Conferences **113**, 05021 (2016)
DOI: 10.1051/epjconf/201611305021

The Proton Radius Puzzle

E. J. Downie[1,a]

[1] *Department of Physics, George Washington University, 725 21st Street NW, Washington DC 20052, USA.*

Abstract. The proton radius puzzle is the difference between the proton radius as measured with electron scattering and in the excitation spectrum of atomic hydrogen, and that measured with muonic hydrogen spectroscopy. Since the inception of the proton radius puzzle in 2010 by the measurement of Pohl et al.[1], many possible resolutions to the puzzle have been postulated, but, to date, none has been generally accepted. New data are therefore necessary to resolve the issue. We briefly review the puzzle, the proposed solutions, and the new electron scattering and spectroscopy experiments planned and underway. We then introduce the MUSE experiment, which seeks to resolve the puzzle by simultaneously measuring elastic electron and muon scattering on the proton, in both charge states, thereby providing new information to the puzzle. MUSE addresses issues of two-photon effects, lepton universality and, possibly, new physics, while providing simultaneous form factor, and therefore radius, measurements with both muons and electrons.

1 Introduction

The proton radius puzzle (PRP) concerns the difference between the radius of the proton as measured with electron scattering and atomic hydrogen spectroscopy, and that measured in muonic hydrogen. In 2010, the CREMA Collaboration published their measurement of the proton radius $R_p = 0.8409(4)$ fm, which was made by studying the Lamb shift in muonic hydrogen [1]. This result, although ten times more precise than, is completely incompatible with the CODATA value of $R_p = 0.8775(51)$ fm [2]. Until that point, the CODATA value was in good agreement with both scattering and spectroscopy results. Since 2010, various attempts have been made to resolve the PRP by looking closely at the experimental data and its interpretation: looking for errors in the theory of the radius extraction from the spectroscopy data, looking for errors in the data itself, and re-analyzing and refitting the electron scattering data, but all to no avail.

There were initially many suggestions as to what could theoretically cause this discrepancy in radius measurements, but, to date, none of the postulated solutions have been generally accepted as resolving the puzzle. Many have been ruled out. Remaining explanations include possible physics beyond the Standard Model (BSM), whereby the electron is measuring an electromagnetic radius, while the muon is measuring an electromagnetic radius modified by BSM effects. There are also suggestions that there might be a currently unconstrained correction in the proton polarizability. Neither is universally accepted but neither has been conclusively ruled out.

[a] On behalf of the MUSE Collaboration. e-mail: edownie@gwu.edu

The puzzle, if anything, has become more puzzling since its inception in 2010. Now the main focus for resolution of the PRP is on new measurements: atomic hydrogen spectroscopy measurements are being repeated; the CREMA collaboration is extending the range of muonic measurements to include D, ^{3}He and ^{4}He; new, lower Q^2, electron scattering measurements are planned and underway JLab and MAMI; and a simultaneous measurement of muon and electron scattering, of both charge states, will be performed at PSI by the MUSE collaboration. By measuring elastic scattering cross sections down to low Q^2, it is possible to test for the new particles postulated as part of the BSM explanation. By measuring in both charge states, MUSE can access two-photon exchange effects, postulated to be responsible for the breakdown of the Rosenbluth separation and which would be enhanced by the enhanced proton polarizability proposition.

2 Radius Measurements

2.1 Electron Scattering Measurements

The "radius" of the proton is defined as the slope of the electric form factor at $Q^2 = 0$. To date, the most comprehensive elastic electron scattering cross section measurement was performed at MAMI by Bernauer *et al.* [3]. They fit the data with a variety of functional forms and determined the proton electric radius to be $< r_E^2 >^{1/2} = 0.879(5)_{stat}(4)_{syst}(2)_{model}(4)_{group}$ fm. The data agree with the recent JLab polarized measurement [4] and the CODATA value. Other fits including the world data set, but deliberately excluding the Mainz data, [5], agree with the CODATA value, strengthening the puzzle. For a recent review, see Pohl *et al.* [6].

2.2 The Muonic Spectroscopy Measurements

The muonic hydrogen measurements [1, 7] were made as the knowledge of the proton radius limits precision in many electromagnetic physics measurements. Due to the finite size of the proton, the electron in atomic hydrogen actually has a finite probability to be found inside the proton, when occupying S-states. While inside the proton, some of its attractive potential is screened, thereby reducing the average attractive potential seen by the electron and perturbing the energy levels of the S-states. This perturbs the S-P transitions, so by measuring them very precisely, and applying some theoretical calculations, one can extract the radius of the proton.

The probability that the electron is found inside the proton is simply proportional to the volume of the proton relative to the volume of the atom. By replacing the electron with a muon, which is ~205 times as massive, one shrinks the size of the atom and thereby increases the strength of the perturbation, vastly improving the sensitivity of the measurement to the proton radius, and enabling a much more precise radius extraction.

The measurement by Pohl *et al.* of $r_p = 0.84184 \pm 0.00067$ fm [1] was highly unexpected. The result was confirmed in 2013 by the analysis of Antognini *et al.*, who measured the proton electric radius to be $r_p = 0.84087 \pm 0.00039$ fm. Interestingly, Antognini *et al.* produced a magnetic radius which agrees with that obtained from electron scattering, while still supporting the discrepant electric radius of Pohl *et al.*.

The CREMA collaboration has extended their measurements beyond hydrogen to deuterium, ^{3}He and ^{4}He. Preliminary results from muonic deuterium are consistent with the CODATA, electron-scattering and spectroscopy measured values for the deuterium radius. The ^{3}He measurements are also underway, and the ^{4}He data is under analysis.

3 New Measurements

It is commonly agreed that the only way to solve the proton radius puzzle is by new measurements. Some of these plan to confirm the old results with new, more precise measurements, some intend to extend their kinematic range, and some to measure completely new things, such as precise muon scattering or spectroscopy of new muonic ions.

3.1 Spectroscopy and Electron Scattering Measurements

There are current efforts underway to remeasure the proton radius via atomic hydrogen spectroscopy. In addition to this, as described above, the CREMA collaboration are extending their measurement series to a number of light nuclei. There are also new elastic electron scattering experiments, planned and underway, to extend the measurements at JLab and Mainz down to lower Q^2. To date, there have been experiments in spectroscopy involving electrons and muons and elastic scattering experiments involving electrons, but no elastic muon scattering experiment at a level of precision able to answer the proton radius puzzle. The MUSE experiment will change that.

3.2 The MUon proton Scattering Experiment (MUSE)

MUSE entails a simultaneous measurement of elastic scattering of muons and electrons on the proton, investigating both positive and negative charge states. The experiment will reach as low a Q^2 as the existing electron scattering measurements, with sub-percent precision. The experiment will use beam line Cherenkov, scintillating fiber and GEM detectors to determine the trajectory and species of each incoming beam particle. The scattered particles will be detected in Straw Tube Trackers and a double scintillator wall. This will allow a direct comparison of cross sections and form factors, and, ultimately, the proton radius, as extracted from muon and electron elastic scattering. The simultaneous measurement of electrons and muons allows very good systematic control and measurement of both charge states also allows a test of two-photon-exchange effects.

The MUSE experiment (see Fig. 1) will take place at the πM1 beam line of the Paul Scherrer Institute (PSI). The πM1 beam line is a secondary beam line and the beam consists of a mixture of pions, electrons and muons with a 50 MHz time structure. We will measure at three different beam momenta: $p_{in} \simeq 115$, 153 and 210 MeV/c^2. These momenta are chosen to allow good separation of the different particle types in time and give overlapping kinematic points for good systematic control while providing data in the range of kinematic interest for measurements sensitive to the proton radius.

Due to the large dispersion and the mixed particle nature of the beam, it is necessary to monitor beam timing and angle accurately. Precise timing will be achieved by tagging beam particles as they enter the experimental area at the two higher momenta using a Cherenkov detector, following the idea prototyped by Albrow *et al.* [8]. This will provide accurate timing of beam particles relative to the beam RF signals and time of flight. The Cherenkov detector will be the first detector in the beamline in the target area. At the lowest beam momentum (115 MeV), timing constraints are not as strict and multiple scattering is a much larger issue, so the Cherenkov will be replaced by a thin plastic scintillator.

The position and timing of beam particles for trigger purposes will then be measured using a scintillating fiber (SciFi) detector in the target area. This consists of four layers of forty fibres each, with double-ended maPMT readout. The SciFi detector is followed by a stack of three Gas Electron Multiplier (GEM) chambers, repurposed from OLYMPUS at DESY [9]. These provide accurate tracking for offline scattering angle reconstruction, but the faster SciFi signal is necessary for trigger-purposes. While all the other equipment will be custom-made for the experiment, the GEM chambers already

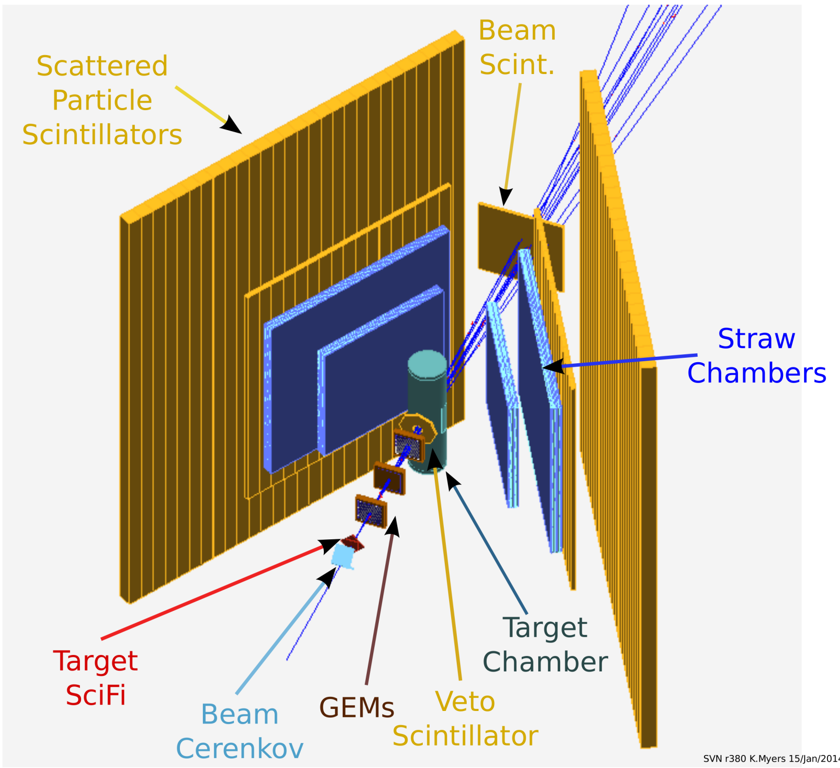

Figure 1. The MUSE setup: showing Cherenkov detector, SciFi, and GEM beamline detectors, and the scattered particle detector arms, with STTs and triggering scintillator walls.

exist, are already present in PSI and have been used for test beam times. The GEM chambers are, however, being reconfigured to shorten their stack length in order to minimize their impact on multiple scattering in the experiment. The SciFi and GEM chambers will be used in the offline analysis to determine the exact angle of the particles entering the target to enable accurate scattering angle definition.

In order to compensate for the low beam flux of the πM1 beam line, the scattered particle detector system employed by the MUSE experiment will take the form of a non-magnetic, large-acceptance tracking detector. There will be two identical sectors, one on each side of the beamline. Each side will consist of two ten-layer straw tube tracking chambers (STTs) with 1425 straws per side followed by two layers of fast scintillators (92 bars in total) for triggering and timing.

The STTs will be based on the PANDA design and will be read out for timing only using PADIWA discriminators and TRB3 boards which provide timing, scalars and trigger logic [10]. The scintillation counter signals will be sent into PADIWA discriminators and TRB3 boards for timing etc., but also into QDCs in order to allow for offline pulse-height timing corrections.

The experimental trigger will be based on the requirement of a particle firing the Cherenkov / beam line scintillation detector, the SciFi detector and a scattered particle with appropriate timing and position reaching the scattered particle scintillators. The trigger algorithm will be processed in the specially programmed FPGAs (Field-Programmable Gate Arrays) of the TRB3 boards used to

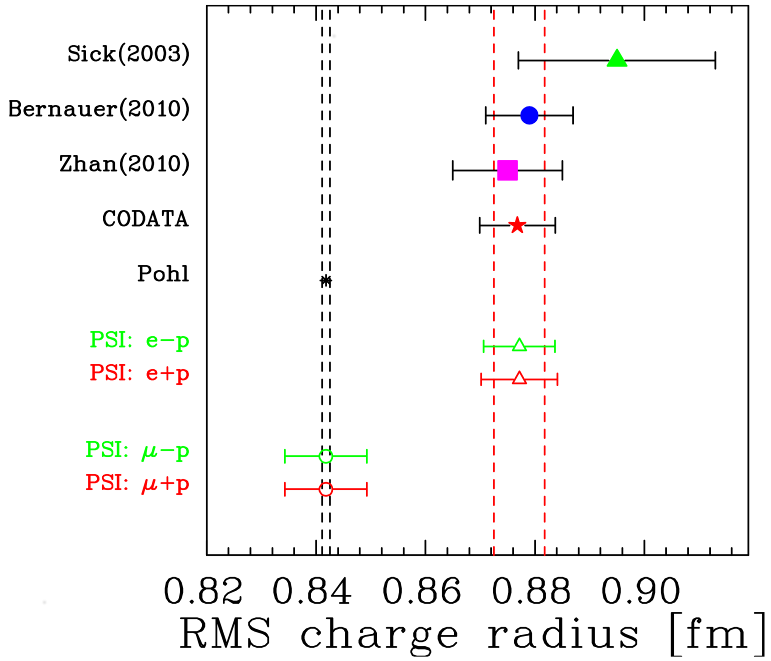

Figure 2. Current proton radius values and the anticipated MUSE measurement precision.

provide timing and scalar information for each chanel, with one TRB3 trigger master which will make the final trigger decision and distribute the trigger and trigger number to the TRB3s and non-TRB3 parts of the detector system.

In order to suppress backgrounds caused by muon decays in-flight, and scattering in the beamline, there will be an annular veto detector, comprising of eight scintillators, surrounding the entrance to the liquid hydrogen target scattering chamber. The signals from these detectors will be incorporated in the trigger system as a veto. These backgrounds will be further reduced in the offline analysis by studying the time of flight from the initial target Cherenkov or, at low energy, plastic scintillation detector to the scattered particle scintillator wall. In order to monitor the beam and ensure stability throughout the experiment, there will be twelve beam-monitor scintillators which will be used to monitor beam flux and position.

It is expected that MUSE will produce cross section measurements for the elastic scattering of $\mu^{+/-}$ and $e^{+/-}$ with sub-1% relative precision over a Q^2 range from 0.002 to 0.07 GeV^2. Using these data, form factors will be extracted and the resulting radii from muon and electron scattering, and from both charge states, will be compared. See Fig. 2 for the anticipated precision.

4 Conclusion

After five years of effort, the proton radius puzzle remains puzzling. There are multiple experimental efforts underway to find a solution to this very interesting, and challenging, conundrum. These include renewed hydrogen spectroscopy measurements, an extended study of muonic ^{2}H, ^{3}He and ^{4}He, and new, lower Q^2 elastic electron scattering measurements at JLab and MAMI. Complementary to these efforts, covering the one clear gap in the proton radius puzzle experimental information: MUSE will measure elastic muon scattering on the proton, simultaneously with elastic electron scattering in order to have a very firm grasp on possible systematic uncertainties. By measuring in both charge states, MUSE will also be able to access two-photon effects. In so doing, MUSE can access the signatures of the main postulated explanations for the proton radius puzzle. New particles would modify the scattering cross sections at low Q^2, and a correction to the polarizability would be clearly visible in enhanced two-photon-effects. Thus, with the new data from scattering and spectroscopy experiments, we hope to resolve the proton radius puzzle and identify any possible signatures of new physics.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. PHY-1309130 and the U.S. Department of Energy, Office of Science, Office of Nuclear Physics program under contract number DE-SC0012485.

References

[1] R. Pohl, A. Antognini, F. Nez, F.D. Amaro, F. Biraben et al., Nature **466**, 213 (2010)

[2] P.J. Mohr, B.N. Taylor, D.B. Newell, Rev.Mod.Phys. **80**, 633 (2008), 0801.0028

[3] J. Bernauer et al. (A1 Collaboration), Phys. Rev. Lett. **105**, 242001 (2010), arXiv: [nucl-ex]1007.5076

[4] X. Zhan et al., Phys. Lett. **B705**, 59 (2011), arXiv: [nucl-ex]1102.0318

[5] I. Sick, Phys.Lett. **B576**, 62 (2003), nucl-ex/0310008

[6] R. Pohl, R. Gilman, G.A. Miller, K. Pachucki, Ann.Rev.Nucl.Part.Sci. **63**, 175 (2013), arXiv: [atom-ph]1301.0905

[7] A. Antognini et al., Science **339**, 417 (2013)

[8] M. Albrow, H. Kim, S. Los, E. Ramberg, A. Ronzhin et al., JINST **7**, P10027 (2012), arXiv: [ins-det]1207.7248

[9] R. Milner et al., Nuclear Inst. and Methods in Physics Research A **741**, 1 (2014), arXiv: [ins-det]1312.1730

[10] TRB homepage containing full specification and documentation: trb.gsi.de