The proton charge radius

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Abstract

In 2010 and 2013, the Charge Radius Experiment with Muonic Atoms (CREMA) collaboration published the most precise results on the proton charge radius from muonic hydrogen spectroscopic measurements, and they are several standard deviations smaller than the CODATA recommended value at the time based on electron scattering and ordinary hydrogen spectroscopic measurements. This triggered the proton charge radius puzzle and motivated worldwide efforts to resolve this puzzle. In this paper, I discuss the current situation on the proton charge radius and present the latest status of the PRad-II experiment at Jefferson lab.

Keywords:

While the Standard Model (SM) of particle physics unifies the strong, electromagnetic and weak forces, and has been highly successful, the understanding of Quantum Chromodynamics (QCD), the theory of the strong force, remains rather limited. While QCD has been tested well at high energies where perturbative calculations can be carried out, in the non-perturbative region, our knowledge about how QCD works remains poor due to our inability to solve the QCD lagrangian analytically. The structure of the nucleon provides a rich window of opportunities not only to advance our understanding of how QCD works in the non-pQCD region, but also provide important foundation for stringent SM tests and search for new physics beyond the SM. The structure of the nucleon includes its electromagnetic and spin structure, spin and mass decomposition, partonic momentum and flavor structure, polarizabilities, and more

The proton charge radius (r_p), defined as the root-mean-squared charge radius, is one of the most fundamental quantities related to the structure of the proton. It is important not only for advancing our understanding of how QCD works in the non-perturbative region, but also for QED calculations of bound atomic energy levels. Experimentally it has been measured using both electron-proton elastic scattering, and atomic spectroscopy with ordinary (electronic) hydrogen. Consistent results had been achieved using these two approaches until 2010 with the first result from muonic hydrogen spectroscopy reported by the CREMA collaboration and their followup result in 2013. The most precise values came from these muonic H spectroscopy measurements which yielded $r_p = 0.84184 \pm 0.00067\ fm$ (1) and $r_p = 0.84087 \pm 0.00039\ fm$ (2). These results were 5.6 σ smaller than the 2014 CODATA recommended value (3), determined based on radius results from electron-proton (*e*-*p*) elastic scattering and ordinary H spectroscopic experiments prior to 2010. This triggered the "*proton charge radius puzzle*" and motivated experimental and theoretical efforts to resolve the puzzle worldwide. For a recent review, see Ref. (4).

In 2010 and 2011 two new electron scattering experiments reported their determination of the proton charge radius. The Mainz experiment (5) measured absolute differential cross sections from *ep* elastic scattering employing three magnetic spectrometers with one serving as a luminosity monitor and the other two with large amount of overlapping data sets. This experiment covered a Q^2 range from 0.004 to 1.0 $(GeV/c)^2$ and extracted both the proton electric and magnetic form factors. The extracted proton charge radius value is $r_p = 0.879(5)_{\text{stat}}(4)_{\text{sys}}(2)_{\text{mod}}(4)_{\text{group}}$ *fm*, consistent with CODATA recommended value at the time. The other experiment is the Jefferson Lab experiment (6) in which a longitudinally polarized electron beam, an unpolarized liquid hydrogen target, and a recoil proton polarimeter were employed to measure the recoil proton polarization from elastic *ep* scattering. This experiment obtained a value $r_p = 0.875 \pm 0.01$ (*fm*) by combining the extracted $\frac{G_E}{G_M}$ values in a Q^2 range of 0.3 to 0.7 $(GeV/c)^2$ with the world data on the differential cross sections excluding the 2010 Mainz data (5). The extracted r_p value is consistent with the Mainz result.

Following these two electron scattering experiments, two spectroscopic measurements from ordinary hydrogen reported results on the r_p in 2017 and 2018, respectively. Beyer *et al.* (7) measured the transition of $2S \rightarrow 4P$ and extracted a r_p value of 0.8335(95) *fm* and a Rydberg value of $R_\infty = 10973731.568076(96)\ m^{-1}$ combining with previously published results on the $1S \rightarrow 2S$ transition (8; 9). The other experiment by Fleurbaey *et al.* (10) measured the $1S \rightarrow 3S$ transition and again together with the results from

(8; 9) on the $1S \rightarrow 2S$ transition, they reported $r_p = 0.877(13)$ *fm*, and $R_\infty = 10973731.56853(14)\ m^{-1}$. While the result from (7) is consistent with the muonic hydrogen measurements, the result from (10) is not. In 2019, Bezginov *et al.* (11) measured the ordinary hydrogen Lamb shift $2S_{1/2} \rightarrow 2P_{1/2}$ transition directly and reported $r_p = 0.833(10)$ *fm*, which is consistent with results from muonic hydrogen.

The PRad collaboration proposed an innovative new way of conducting *ep* elastic scattering measurement that is magnetic spectrometer-free (12) in 2011. The experiment utilized a lead-tungstate ($PbWO_4$) high resolution and large acceptance hybrid calorimeter (HyCal) with lead blocks on the outer edge and a hole in the middle to allow the electron beam to pass through along with a plane of two large area Gas Electron Multipliers (GEMs) to measure the energy and the position of *ep* scattered electrons and Möller electrons with the latter being a QED reference process. With 1.1 and 2.2 GeV incident electron beam energies, and a windowless cryo-cooled gas-flow hydrogen target (13), the experiment reached the lowest Q^2 value ever, covering a Q^2 range of $2 \times 10^{-4} - 0.06\ (GeV/c)^2$. This experiment was conducted successfully during May and June of 2016 in Hall B at JLab. The PRad collaboration reported in 2019 (14), $r_p = 0.831 \pm 0.007_{stat.} \pm 0.012_{syst}$ *fm* that, within experimental uncertainties, is consistent with the results from the muonic H spectroscopy, and also consistent with the results from two recent ordinary H spectroscopy measurements (7; 11). The most precise lattice result of r_p (15) is also consistent with the PRad result. These new results (11; 14) motivated the inclusion of the muonic hydrogen results (1; 2) into the CODATA (16) evaluation for the first time. The 2018 CODADA recommended value is dominated by the contribution from the mounic hydrogen measurements due to their high precision, and the Rydberg constant is also shifted.

Grinin *et al.* (17) carried out a high-precision measurement of the $1S \rightarrow 3S$ transition frequency. Again using the previously published measurements of the $1S \rightarrow 2S$ transition frequency, they reported $r_p = 0.8482(38)$ *fm*, and $R_\infty = 10973731.568226(38)\ m^{-1}$ in 2020. This is the most precise determination of the r_p from ordinary hydrogen spectroscopic measurements supporting a smaller value of the radius. Most recently, Brandt *et al.* (18) measured the transition between $2S_{1/2} \rightarrow 8D_{5/2}$ from ordinary hydrogen. Combining with the aforementioned $1S \rightarrow 2S$ transition, they extracted $r_p = 0.8584(51)$ *fm*, and $R_\infty = 10973731.568332(52)\ m^{-1}$, representing a 3.1 σ deviation from the CODATA 2018 (16) recommended value. Table 1 summarizes all published

Experiment	Type	Transition(s)	r_p (fm)	R_∞ (m^{-1})
Pohl 2010	μH	$2S_{1/2}^{F=1} - 2P_{3/2}^{F=2}$	0.84184(67)	
Antognini 2013	μH	$2S_{1/2}^{F=1} - 2P_{3/2}^{F=2}$	0.84087(39)	
		$2S_{1/2}^{F=0} - 2P_{3/2}^{F=1}$		
Beyer 2017	H	$2S - 4P$	0.8335(95)	10973731.568076(96)
		with $(1S - 2S)$		
Fleurbaey 2018	H	$1S - 3S$	0.877(13)	10973731.56853(14)
		with $(1S - 2S)$		
Bezginov 2019	H	$2S_{1/2} - 2P_{1/2}$	0.833(10)	
Grinin 2020	H	$1S - 3S$	0.8482(38)	10973731.568226(38)
		with $(1S - 2S)$		
Brandt 2022	H	$2S - 8D$	0.8584(51)	10973731.568332(52)
		with $(1S - 2S)$		

Table 1: Summary of proton charge radius results from muonic and ordinary hydrogen spectroscopic measurements published since 2010.

results from both ordinary and muonic hydrogen spectroscopic measurements since 2010. While great progress has been made on the proton charge radius, the puzzle is not resolved. Below I discuss several ongoing and new lepton scattering experiments.

The ongoing MUon proton Scattering Experiment (MUSE) (19) at PSI measures lepton-proton elastic scattering cross sections, and compare the results between muons beams and the e^-/e^+ beams to extract the proton charge radius and test lepton universality. The MUSE experiment uses the PSI $\pi M1$ beam line with $e^\pm$, and $\mu^\pm$ beams at incident momentum values of 115, 153 and 210 MeV/c to allow for simultaneous measurements of the $\mu^\pm p$ and $e^\pm p$ elastic scattering cross sections. The Q^2 range of the MUSE experiment is 0.0016 to 0.08 $(GeV/c)^2$. The lowest Q^2 value reached by MUSE is comparable to that of the Mainz experiment (5), but much higher than that of the PRad experiment (14), 0.0002 $(GeV/c)^2$. The uncertainties from the MUSE experiment in the r_p separately determined with μ^+p, μ^-p, e^+p, and e^-p are expected to be nearly the same, around 0.01 *fm*. More details about the MUSE experiment can be found in (20).

Another lepton scattering experiment utilizing muons is the AMBER experiment (21) measuring elastic μp scattering at high energy and low Q^2 with the M2 beam-line at CERN. This experiment will extract the proton electric form factor in a Q^2 range of 0.001 to 0.04 $(GeV/c)^2$ with relative point-to-point precision better than 0.001. The projected precision in the determination of the proton charge radius is expected to be better than 0.01 *fm*. The experiment is currently ongoing.

At Mainz there are efforts to address the proton charge radius puzzle. The A1@MAMI is an ongoing experiment (22) in the A1 experimental hall with the MAMI accelerator using a hydrogen gas jet target to provide better control of a few systematic uncertainties associated with the original A1 experiment (5), and also to investigate the systematic difference in the G_E^p results between the PRad (14) and the A1 experiment. The MAGIX experiment (Mainz Gas-Internal Target Experiment) at MESA is a future experiment centered around the Mainz Superconducting Energy Recovery Linac (MESA). MESA, as a recirculating superconducting linear accelerator, provides an external beam with a high degree of polarization and an internal beam with high current for high precision experiments like MAGIX. The MAGIX experiment will employ compactly designed spectrometers allowing for a relative momentum resolution of order 10^{-4}, and a windowless internal gas-jet target (23) to suppress background.

The Ultra-Low Q^2 (ULQ^2) (24) experiment completed data taking on an electron scattering experiment at the Research Center for Electron-Photon Science at Tohoku University using its 60 MeV electron linac. This experiment covers a Q^2 range of 0.0003 to 0.008 $(GeV/c)^2$ for ep elastic scattering. This experiment aims at an absolute cross section measurement with a precision of 0.1 %, and a precision of $\sim 1\%$ (relative.) in determining the r_p.

At Jefferson Lab, the PRad Collaboration is working on its follow-up experiment, PRad-II. While the PRad experiment has demonstrated the advantages of the calorimetric method to measure r_p with precision, it did not reach the ultimate precision allowed for by this technique. The PRad collaboration proposed a follow-up experiment – PRad-II (25) which was approved by the Program Advisory Committee. In PRad-II, there are several improvements compared to the original the PRad apparatus, which will lead to the reduction of the total uncertainty in r_p measurement by a factor of ~ 3 compared to PRad. PRad-II will employ two planes of GEM tracking detectors for better z-vertex determination and tracking capability to suppress the background, better Q^2 determination, and better GEM efficiency determination. The latter allows for PRad-II to use the integrated Möller method for the entire kinematic coverage and turn the Q^2 dependent systematic uncertainty into a normalization factor to reduce a major systematic uncertainty due to GEM efficiency correction observed in PRad. PRad-II

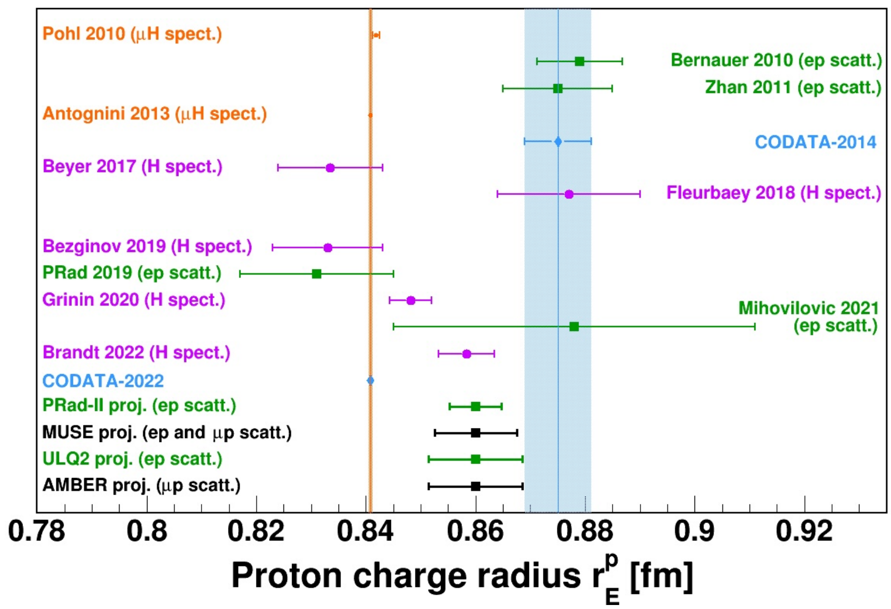

Figure 1: Results on the proton charge radius measurements published since 2010 together with anticipated results from ongoing and future experiments shown with their projected total uncertainties only. Also shown are the CODATA-2014 and 2022 recommended values.

will use all flash ADC-based readout system to enhance the data acquisition (DAQ) rate, and combining with more beam time to reduce the statistical uncertainty by a factor of ~ 4. PRad-II will suppress beamline-associated background further beyond the implementation of two planes of GEM trackers by improving vacuum and adding a second beam halo blocker upstream of the tagger. Another major improvement for PRad-II will be in calculating the Radiative Correction (RC) effect by going to the next-to-next-leading order (NNLO). Currently, the PRad-II experiment is being installed in Hall B at Jefferson Lab and data taking is expected to start in spring 2026. Figure 1 shows all published results on r_p since 2010, projected measurements from lepton scattering experiments and 2014 and 2022 CODATA (26) recommended values.

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