Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter
PRISMA

Mainz Institute for Theoretical Physics

Precision Measurements and Fundamental Physics: The Proton Radius Puzzle and Beyond

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The 2010 measurement of the Lamb shift (2S-2P energy difference) in the muonic hydrogen atom has created the "proton radius puzzle": The proton charge radius R_p determined by the muonic hydrogen Lamb shift differs by 4% or 6 standard deviations from the 2014 CODATA value of R_p which has been obtained from elastic electron-proton scattering and spectroscopy of electronic hydrogen and deuterium. The puzzle is both difficult and fascinating because it impacts and requires expertise from diverse areas of particle, nuclear and atomic physics. Several new experiments have been motivated by the puzzle and are starting to produce results. Correspondingly, there is a great deal of theory effort aimed at all aspects of the puzzle.

The topical workshop summarized new experimental results in atomic spectroscopy and lepton scattering, discussed new theoretical tools and ideas impacting structure effects in scattering and bound state problems; and explored new physics discovery potential with precision tests in muonic and electronic systems.

This is the fourth workshop in a series of workshops dedicated to the proton radius puzzle. The previous editions were in 2012 at ECT* (European Centre for Theoretical Studies in Nuclear Physics and Related Areas), in 2014 at MITP (Mainz Institute for Theoretical Physics), and in 2016 at ECT*. Each day of the topical workshop had a general theme. The talks were clustered in three daily sessions supplemented by a two-hour afternoon discussion.

Several new unpublished experimental results were presented at the workshop: (i) New measurement of the proton charge radius from Lamb shift in hydrogen from York University in Canada. (ii) New measurement of the proton charge radius from 1S−3Sin hydrogen from Max-Planck-Institute for Quantum Optics (MPQ) in Germany. (iii) New measurement of the proton electric form factor at the lowest Q^2 ever $\sim 10^{-4}$ GeV^2 by the PRad experiment at the Jefferson Lab in the USA.

The new 2S−2P measurement from York U. is of particular significance, as it allows for a direct comparison with the 2S−2P transitions in muonic hydrogen, which created the proton radius puzzle. Moreover, in contrast to all other transition frequencies in atomic hydrogen used to determine the proton charge radius, the interpretation of the 2S−2P transition does not depend on the exact value of the Rydberg constant because the measurement takes place between two atomic states with the same principal quantum number n. The York measurement uses a novel technique called "frequency offset separated oscillatory fields"(FOSOF) which is a major improvement compared with the well-known Ramsey method of separated oscillatory fields. The FOSOF technique yields much reduced sensitivity to systematics related to line-shape distortions because the excitation frequency does not have to be scanned. The new measurement presented a preliminary value in agreement with the muonic hydrogen result. Since then, the uncertainty has been further improved and the paper is soon to be published in the journal "Science".

The new 1S−3S measurement from MPQ has similar precision to the published 1S−3S measurement from Paris, but it leads to a smaller radius consistent with the muonic hydrogen extraction. We now have two measurements of the same transition in hydrogen with similar error bars that leads to different values of the proton charge radius. Further insight is expected from ongoing measurements of the hydrogen 1S-4S transition in Paris and Garching, and from 2S-nP (n≥6) in Garching. The 1S-3S transition in atomic deuterium has been measured in Garching and yields the smaller deuteron radius that has been reported from the 2S-2P measurements in muonic deuterium. The PRad experiment at Jefferson Lab in the USA reported a measurement of elastic electron-proton scattering at the lowest Q^2 ever $\sim 10^{-4}$. It used a very forward detector at scattering angles between $0.7^\circ$and 7.0°. Moreover, a windowless hydrogen target and the simultaneous measurement of Moller scattering (which is a calculable QED process) allow for a very good normalization of the elastic scattering cross section. At the low Q^2 of the PRad experiment, the fit of the form factor data can be performed with significantly reduced model dependence.

As in previous workshops, various methods for extrapolation of the proton form factors to $Q^2=0$ were discussed. There was no agreement on how it should be done. With the publication of the PRad results this issue will become even more prominent. Further low-Q^2 electron-proton scattering measurements are planned at Tohoku University, by ProRad in Orsay, and at MAMI and the future MESA facility in Mainz. New targets such as windowless gas-jet solid hydrogen jets or active-target TPC promise reduced systematic uncertainties from backgrounds and access to very low Q^2 .

Substantial progress has been made in calculations of muonic hydrogen energy levels. In general, an agreement between ab initio calculations and dispersion fits of scattering data yields trustworthy nuclear structure contributions to the Lamb shift. The notable exception is muonic helium-4, where a preliminary result from dispersion fits seems to disagree significantly with the ab initio calculations using NN and 3N forces. This disagreement must be solved to obtain trustworthy charge radii from the muonic Lamb shift measurements. Similarly, the two-photon exchange contributions to the hyperfine splitting in muonic H, D and ^{3}He have recently been significantly improved. Three-photon results are now known for muonic deuterium. Further improvements are required in light of three on-going experiments at J-Parc, RAL and PSI which aim at a measurement of the ground state (1S) hyperfine splitting in muonic hydrogen (and muonic ^{3}He at PSI). The current spread of results would lead to a prohibitively long measurement time of at least half a year for the PSI experiment. An accuracy of 25 ppm for the line position predicted is required for these experiments to become feasible.

Muon-proton scattering is pursued by the MUSE Collaboration at PSI, and first production data will be acquired in 2 beam times in 2019 and 2020. Recently, the COMPASS collaboration at CERN has performed a pathfinder experiment for a high-energy, low-Q^2 measurement of muon-proton scattering. Preliminary results were shown. Both experiments are very important, also in view of obtaining more accurate TPE results which would be required for a possible improved muonic hydrogen Lamb shift measurement at PSI.

On the atomic physics side there are also many new projects with relation to the proton radius puzzle. The advanced laser system is currently developed by the CREMA Collaboration. Their muonic hyperfine measurements could lead to a much more accurate new measurement of the Lamb shift in muonic hydrogen and deuterium. Better charge radii would, however, require similarly improved calculations of the nuclear polarizabilities.

Spectroscopy of He and He^+, underway in Amsterdam, Garching, and elsewhere may soon be compared with results from muonic helium. Similar to the hydrogen case, combining the muonic and electronic measurements yields a very accurate value of the Rydberg constant. Laser spectroscopy of muonic Li and Be ions would allow a hundredfold improved measurement of the corresponding charge radii of Li and Be. In reality, such measurements would be limited to a tenfold improvement by the current calculations of the respective nuclear polarizabilities, but progress seems possible. These light nuclei will become of great interest when spectroscopy of e.g. He-like Li^+ becomes available. Such an experiment is under consideration at MPQ.

Laser spectroscopy of other exotic atoms, such as muonium ($e^-\mu^+$) and positronium (e^+e^-) are underway and may eventually yield values of the Rydberg constant that are free from finite size effects. Ultimately, comparison of Rydberg values from several experiments may be used as a probe for physics beyond the SM, such as Z-dependent deviations or differences between muonic and electronic probes.