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The Lamb shift in muonic hydrogen

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The charge radius r_p of the proton has so far been known from electron-proton scattering with an astonishingly low precision of about 2%. The CODATA value of r_p with an uncertainty of 1% is mainly determined from hydrogen (H) spectroscopy data and bound-state QED calculations. The less accurate H-independent value from e-p-scattering limits the test of bound-state QED in hydrogen, as well as the accuracy in the determination of the Rydberg constant R.

Muonic hydrogen (mu-p, i.e. a proton orbited by a negative muon) provides an elegant way to improve the uncertainty of r_p: The 2S Lamb shift is altered by as much as 2% due to the finite size of the proton.

We have recently measured the Lamb shift in mu-p by laser spectroscopy of the $2S_{1/2}^{F=1}$ - $2P_{3/2}^{F=2}$ transition. Using present QED calculations for mu-p we determine r_p with a relative uncertainty of 8 10^{-4}. This new limit is imposed by theory (mainly the proton's polarizability) - the experimental data could provide a twice better uncertainty on r_p.

The new value of r_p is 10 times more precise, but it deviates by 5.2 sigma from the present CODATA value, and 3.1 sigma from the value obtained by electron-proton scattering. The origin of this uncertainty is yet unknown. If it comes from QED calculations in mu-p, a term as large as 1.6 10^{-3} of the total Lamb shift must be missing. This is to be contrasted to the claimed accuracy of the calculations of 2.4 10^{-5}. Alternatively, the problem could come from hydrogen spectroscopy or from the calculation of the Lamb shift in hydrogen.

Assuming for now the correctness of the calculations we can use the very accurately determined 1S-2S transition frequency in H, and our new r_p, to determine the Rydberg constant R with 4.6 times smaller uncertainty [1.5 ppt], but 5 sigma away from the CODATA value.

We have also recorded a second resonance line in muonic hydrogen. The data is still being analyzed, but a preliminary analysis confirms the value of r_p deduced by the first resonance in mu-p. From this seconds resonance we will deduce the 2S hyperfine splitting in mu-p. We will be able to determine the Zemach radius (radius of the magnetic moment distribution) of the proton with a few per cent accuracy.

In addition, we have observed three resonances in muonic deuterium. We will be able to give a deuteron charge radius and/or the deuteron polarizability, complementing isotope shift measurements in ordinary hydrogen and deuterium.

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