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The size of the proton

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A measurement of the Lamb shift (2S–2P energy difference) in muonic hydrogen (μp, the exotic hydrogen atom made from a proton and a negative muon μ^-) has been on the physicists' wish list for more than 40 years. Due to its 200 times larger mass, the muon's Bohr radius in μp is only 1/200 of the electron's Bohr radius in regular hydrogen (H). This enhances finite size effects by about 200^3 in μp, compared to H. The proton's finite size r_p affects the 2S Lamb shift in μp by as much as 2%, making μp a unique, clean, atomic system to study r_p using laser spectroscopy. We have recently observed the first transitions in muonic hydrogen [1] and muonic deuterium [2]. The $2S_{1/2}^{F=1}$ to $2P_{3/2}^{F=2}$ transition in μp was found at 49881.88(76) GHz [1]. Even with this - by laser spectroscopy standards - very moderate accuracy of 760 MHz (4% of the natural line width) we can deduce r_p 10 times more accurately than the CODATA world average [3]. We obtain $r_p = 0.84184(67)$ fm [1]. The accuracy of r_p is limited by the uncertainty of the proton polarizability which is enters the theory relating the measured frequency to r_p. We have also measured a second transition in μp ($2S_{1/2}^{F=0}$ to $2P_{3/2}^{F=1}$) [2]. It confirms our value [1] of r_p, and provides the first determination of the 2S hyperfine splitting (HFS) in μp. The HFS reveals the Zemach radius, i.e. the radius of the magnetization distribution inside the proton. Now there is a "proton size puzzle." We found the resonance [1] 75 GHz (i.e. 4 natural line widths) away from the expected position. Our r_p is 10 times more accurate, but 4% (5σ) smaller than the CODATA value [3]. There are still surprises in physics.

[1] R. Pohl et al. (CREMA collaboration), Nature 466, 213 (July 2010).
[2] CREMA collaboration, to be published.
[3] P.J. Mohr, B.N. Taylor and D.B. Newell, Rev. Mod. Phys. 80, 633 (2008).