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Quantum electrodynamics: A chink in the armour?

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A measurement of the size of the proton, obtained using spectroscopy of an exotic atomic system, yields a result of unprecedented accuracy — but in disagreement with values obtained by previous methods.

Richard Feynman quipped: “There's a reason physicists are so successful with what they do, and that is they study the hydrogen atom and the helium ion and then they stop.” On page 213 of this issue, Pohl and colleagues[1] revisit the hydrogen atom — or, more precisely, an exotic form of it — and come up with a surprise. They describe a measurement of the size of the proton that provides a rigorous test of quantum electrodynamics (QED), the quantum theory of how light and matter interact. QED boasts the most numerically accurate predictions of any physical theory, but is based on techniques that are still unproven more than 60 years since its foundation. The authors' measurement uses a novel method that is more sensitive than any of the earlier methods. But it gives a result that is significantly discrepant from that obtained by the next most accurate method, throwing doubt on the QED calculations that underlie both methods.

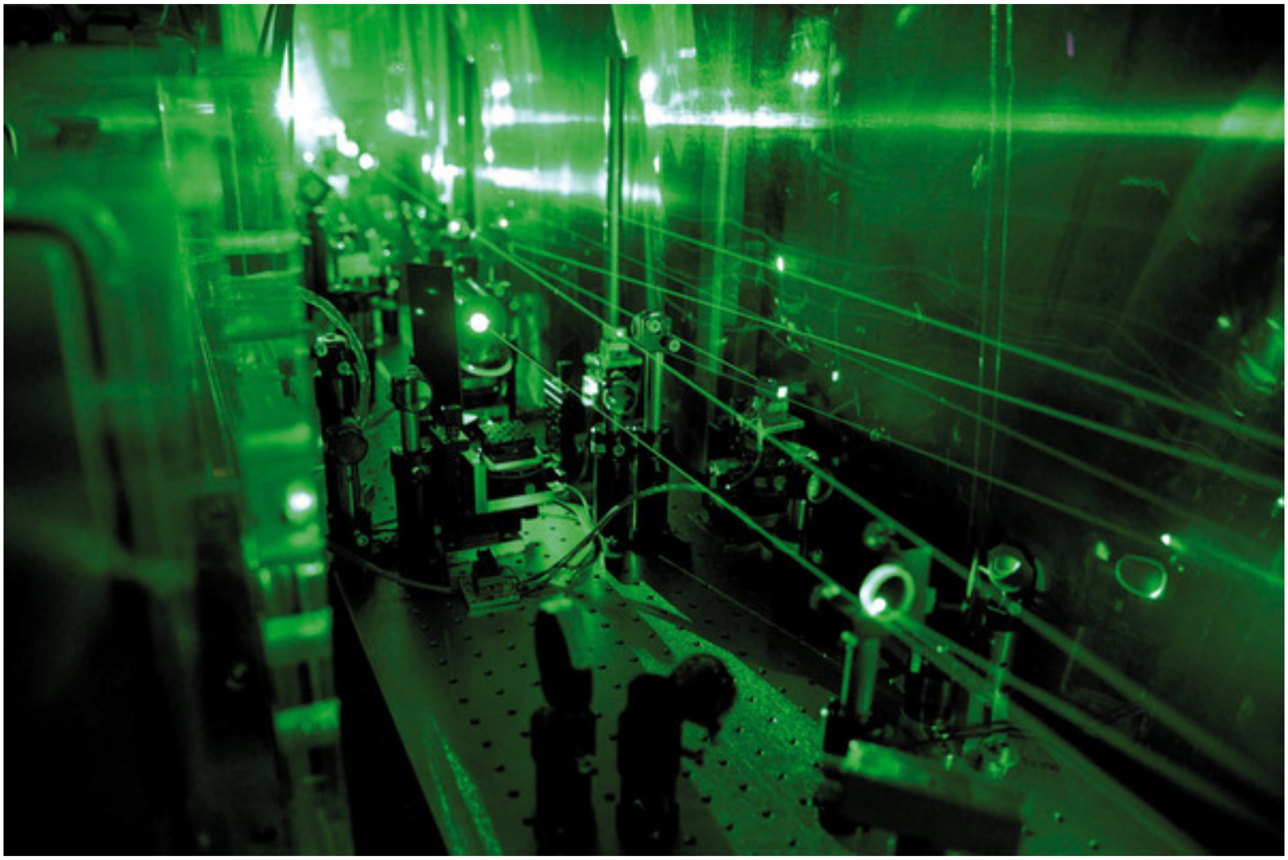
Much of quantum theory was developed as a result of attempts to explain the spectral lines of the elements, in particular atomic hydrogen[2] — the bound state of a proton and an electron. Being a simple two-body system, hydrogen has a structure that, although it took many decades of work to describe by theory, is still significantly simpler than any multi-electron atom. High-precision hydrogen spectroscopy performed by Lamb and Retherford[3] in 1947 showed that the existing theoretical description of the hydrogen atom was incomplete, and this led to the new theory of QED[4]. Among the predictions of this new theory was the existence of a small splitting between two of the atom's energy levels that were previously calculated to be the same as each other, and their energy difference measured in Lamb and Retherford's experiment is now known as the Lamb shift. QED has made predictions of remarkable precision and was the prototype of field theories that followed, but its mathematical foundation is not secure and experimental verification is still being actively pursued.

Pohl and co-workers[1] at the Paul Scherrer Institute (PSI) in Switzerland have measured the Lamb shift in muonic hydrogen. In muonic hydrogen, the electron has been replaced by a negative muon — a similar particle of the same charge but 207 times heavier and unstable. The muon's larger mass gives muonic hydrogen a smaller atomic size and allows a much larger interaction with the proton, allowing the proton structure to be probed more accurately than by using hydrogen. This experiment has long been suggested as likely to give significant improvement in measurement uncertainty, but that has not been achieved until now because of considerable experimental difficulties.

At the PSI, an intense source of muons is available. Pulses of muons are stopped in hydrogen gas and some produce muonic hydrogen, a small proportion of which is in a relatively long-lived (metastable) state — with a lifetime of around one microsecond. Within this lifetime, the muonic hydrogen is subjected to an intense laser pulse (Fig. 1), and if correctly tuned, this pulse will induce a transition to an upper state separated in energy from the initial metastable state by the Lamb shift. This transition is detected through the emission of X-ray photons as the

upper state decays rapidly to the ground state. Detection in a narrow time window distinguishes these laser-induced X-rays from the background X-rays, from other unwanted states produced and from muon decays. Varying the tuning of the laser frequency over many repetitions of the muonic hydrogen and laser interaction allows highly accurate measurement of the transition energy, from which the proton size can be calculated.

Figure 1: Part of the laser system of the muonic-hydrogen apparatus used by Pohl and colleagues[1].



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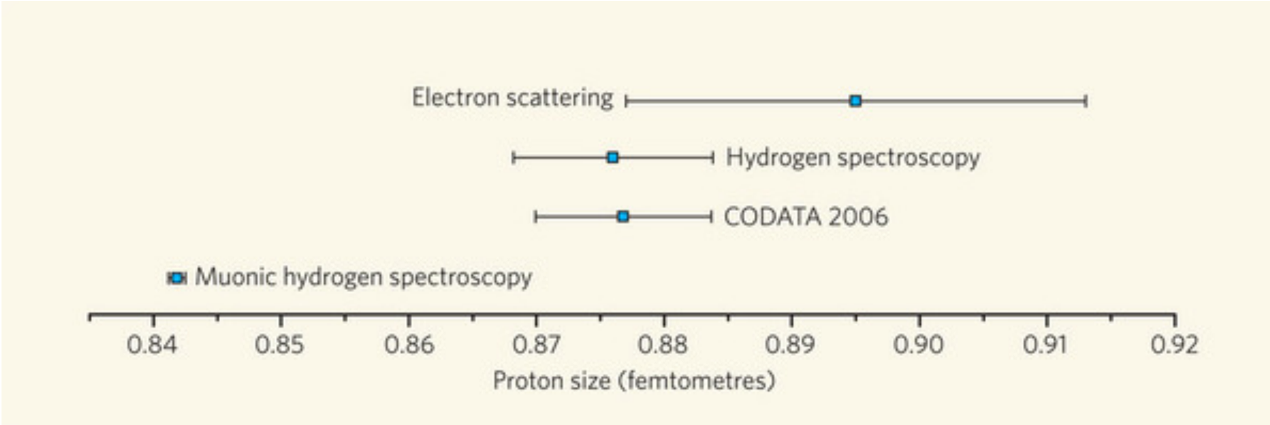
Previously, measurements of proton size have been made directly by scattering electrons from protons, and indirectly by spectroscopy of atomic hydrogen. Electron-scattering results are complex to analyse and the data are inconsistent. However, the available data have been analysed by Sick[5] to give a global result. Data from hydrogen spectroscopy have been compiled and combined with the electron-scattering data in the 2006 CODATA review[6]. Pohl and colleagues' new result[1] is significantly different, by five standard deviations, from the result of a combination of these previous methods (Fig. 2).

Figure 2: Size of the proton.



A comparison of the results of different methods used to measure the proton size is shown: electron scattering[5], hydrogen spectroscopy, the combination of these (both from the CODATA 2006 review[6]), and Pohl and colleagues' new measurement[1] derived from muonic hydrogen spectroscopy. The bars indicate an uncertainty of one standard deviation. The discrepancy of about five standard deviations between the muonic hydrogen result and the CODATA result, which summarizes all previous work, is clear.

The source of this discrepancy is currently unknown. The electron scattering is the most direct method, but the interpretation of the data is open to question. In both hydrogen and muonic hydrogen spectroscopy, long, detailed QED calculations are required to produce a proton size from the experimental data. Pohl *et al*. have detailed more than 30 terms in the derivation of the equation linking their transition-energy measurement to the proton size. In calculations of this complexity, the possibility of error always exists with a magnitude that is hard to determine. In hydrogen spectroscopy, different transitions have been measured to allow the proton size and the related Rydberg constant to be extracted. In hydrogen, unlike in the muonic hydrogen reported here, these require measurement to a small fraction of the experimental transition spectral linewidth, and so details of the transition must be modelled to a high degree of accuracy — again, a possible source of error.

The discrepancy is most likely to be resolved through future work on hydrogen, muonic hydrogen, muonic deuterium and similar 'simple atomic systems'[7] — that is, systems of two bound particles. The simplicity of these systems, and hence their accessibility to calculation, allows physics to be probed, with different systems emphasizing different aspects of the physics. The hydrogen atom is the best-known two-body system. Others under study — including muonium (a bound antimuon and an electron) and positronium (a positron and an electron) — probe the QED of systems without nuclei. The helium ion (an α-particle and an electron) and antihydrogen (an antiproton and an antielectron) offer further insight into fundamental physics.

If experimental discrepancies are confirmed rather than errors being found, high-accuracy work such as that by Pohl and colleagues, not the high-energy collisions of giant accelerators, may have seen beyond the standard model of particle physics.

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Comments

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