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Precision metrology on the hydrogen atom in search for new physics

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The Hydrogen atom has been the benchmark system throughout the history of atomic physics. This year we celebrate the centennial of the Bohr model [1], proposing the first quantum description of an atom and the rationale behind the Rydberg formula. This explanation of the spectrum of the H-atom ignited the quantum revolution. With the invention of the laser and the development of laser spectroscopic techniques the accuracy of spectroscopic measurements of the 1S-2S transition of hydrogen atom (natural linewidth 1.3 Hz) has improved by many orders of magnitude as shown in Figure 1, culminating now at an impressive 10 Hz or a relative accuracy of 4×10^{-15} [2].

Precision metrology of the H-atom is aimed towards testing fundamental theories in physics, in particular quantum electrodynamics (QED). At the basic level there are three ingredients involved in these tests: QED calculations for the H-atom, a value for the Rydberg constant R_∞ , and a value for the rms proton charge radius $\langle r_p \rangle_{\text{rms}}$ [3]. The effect of the proton radius is small, only contributing some 1.2 MHz on the binding energy of the 1S ground state [3], but with respect to the present-day 10-Hz experimental accuracy, this contribution is significant. The uncertainties are however intertwined, e.g. the present uncertainty in the proton charge radius from electron scattering propagates

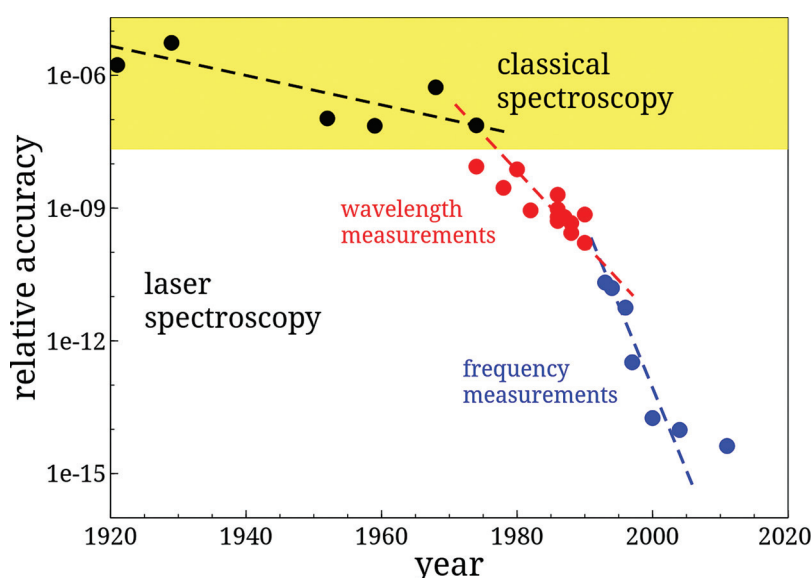


Figure 1 Display of improvement of the relative accuracy achieved in spectroscopic studies of the 1S-2S transition in atomic hydrogen. (adapted and extended from Hänsch, Rev. Mod. Phys. **78**, 1297 (2006)).

to an uncertainty contribution of 50 kHz into the *ab initio* calculation of the 1S Lamb shift and currently limits the test for bound-state QED involving this state. Turning the problem on its head by assuming that QED is correct, a more accurate value of $\langle r_p \rangle_{\text{rms}}$ can be extracted from the accurate measurements of H-atom transitions. For this derivation of the proton charge radius, an accurate value of the Rydberg constant is needed. Traditionally, the most accurate value for R_∞ is determined from measurements on the metastable 2S

state to (nS/D) Rydberg states where QED shifts are much smaller [3]. Indeed, the $\langle r_p \rangle_{\text{rms}}$ value obtained from this procedure is in agreement with measurements from electron-proton scattering experiments. However, a major problem arose when the value of the proton charge radius determined in analogous fashion from spectroscopy of the muonic hydrogen atom turned out to differ by 7 standard deviations from that obtained from (electronic) hydrogen spectroscopy and electron scattering [4,5,6]: a major discrepancy, now referred to as

the *proton size puzzle*. Numerous theoretical investigations have been undertaken both to reevaluate and confirm previous calculations as well as to introduce new effects, however, all theoretical efforts to date have left the conundrum unresolved. On the experimental front, several efforts have been started both in the H-atom and in other light atoms where QED theory is sufficiently good, e.g. in deuterium, the helium ion and the helium atom (both ^3He and ^4He). For these atoms, experiments are also planned or are underway for their muonic hydrogenic counterpart: muonic deuterium [6], the muonic ^4He ion [7] and the muonic ^3He ion [7]. Comparison of the nuclear charge radii (of the deuteron, the helium, and the α -particle) determined from these *muonic* atoms with those determined from *electronic* atoms are expected to shed light on possible frequency shifts due to the substitution of a muon in place of an electron. Of particular interest are the isotope shifts between equivalent transitions in hydrogen and deuterium [8,9] or in ^3He and ^4He [10,11] since QED inaccuracies are much smaller for the isotope shifts compared to that of the transition frequencies.

The paper by Peters *et al.* is an important contribution to approach the proton size puzzle from another point of view: the reevaluation of the Rydberg constant. It is still possible that the measurements of the accepted value of the Rydberg constant had an unexpected systematic error. Independent measurements on atomic hydrogen will clarify this issue. It is therefore very important that two groups put an effort to measure the Hydrogen 1S-3S/D transitions, using different techniques. In Paris, the required 205 nm light is generated with continuous-wave lasers. Their most recent measure-

ment constitutes a relative accuracy of 4.5×10^{-12} [12], not yet accurate enough to improve the determination of the Rydberg constant but new experiments are underway. Peters *et al.* have now demonstrated that frequency comb spectroscopy is feasible to perform high-precision two-photon spectroscopy at 205 nm. As the authors indicate, there are still a lot of experimental problems to be solved, but we look forward to their combination of the 1S-2S and 1S-3S/D measurements to obtain a competitive value of the Rydberg constant.

Precision measurements of the H-atom not only can be used to test QED and determine nuclear charge radii and fundamental constants, but these accurate measurements can also be used to probe new physics. The extreme precision frequency measurement of the 1S-2S transition can be used in investigations of drifting fundamental constants, where similar measurements are performed over a certain

time span [13]. Fundamental tests of Lorentz invariance are also possible as well as stringent tests of CPT invariance by comparing these transition frequencies with the same ones in anti-hydrogen. Here we would like to add another test from measurement of the 1S-2S transition frequency: It is possible to extract bounds on a fifth force between leptons and hadrons, in a similar way as a bound to a fifth force between hadrons at a sub-Angstrom scale [14].

The occurrence of fifth forces beyond the Standard Model can be phenomenologically parameterized by a Yukawa-type potential of the form $V_5(r) = \beta e^{-r/\lambda}/r$, where β is a coupling strength and λ represents the range of the force and therefore with the mass of the force carrying particle ($\lambda = \hbar/m_Y c$) [15]. The effect of such a fifth force on the 1S-2S transition in hydrogen can be calculated by taking the difference between expectation values $\langle V_5 \rangle_{1S}$ and $\langle V_5 \rangle_{2S}$ and keeping

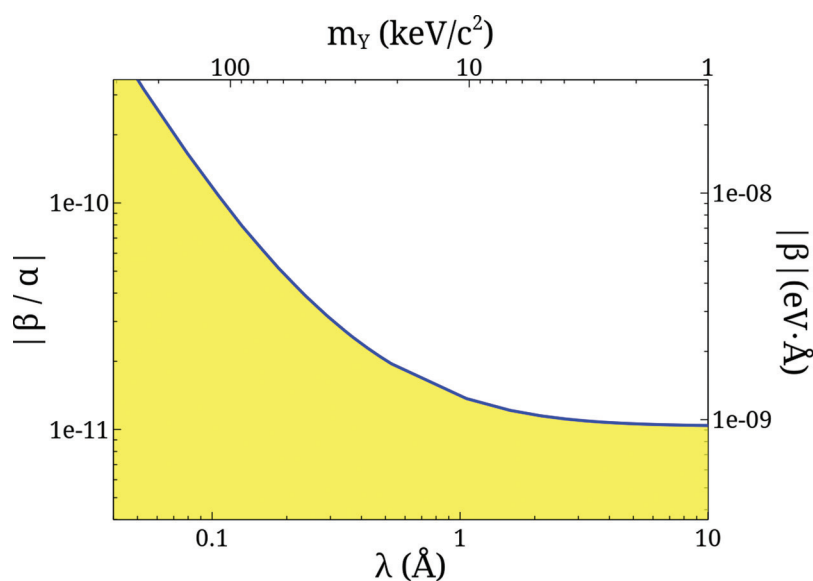


Figure 2 Limits on the strength of the coupling constant β relative to the electromagnetic fine structure constant α as a function of the interaction range λ for a fifth force between leptons and hadrons represented by a Yukawa potential. Note that the white region is ruled out by the experiment on atomic hydrogen.

λ as a parameter [13]. The intrinsic sensitivity to a fifth force of 1S- n S transitions increases with n , so the 1S-3S transition can potentially yield tighter constraints than the 1S-2S transition. By assuming that the QED description of the hydrogen atom is accurate to within 50 kHz, a bound on the coupling strength β can be obtained for a certain value of the λ -parameter probed by the 1S-2S transition in the hydrogen atom, i.e. for Å-scale separations. Results for bounds on the coupling strength β , are plotted in Fig. 2 in terms of units eV Å , as well as in terms of scaling with respect to the fine structure constant α .

Hence at the atomic scale a possible fifth force between leptons and hadrons is more than 10 orders of magnitude weaker than the electromagnetic interaction. This bound can be lowered if an improved value of the Rydberg constant can be

established and the proton-size puzzle resolved. The current accuracy of QED theory of 4 kHz [3] would then yield an order of magnitude lower bound. Further constraining bounds will depend on future refined QED calculations. Atomic hydrogen continues to be relevant in testing physical theories and provides a search ground for new physics.

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