High-precision Ramsey-comb spectroscopy in the XUV spectral range for tests of bound-state QED and the proton radius

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High-precision spectroscopy of simple atoms and molecules set the benchmark for tests of bound-state Quantum Electrodynamics (QED). Especially atomic hydrogen has served as a model system, and experimental efforts have lead to a measured 1S-2S transition frequency with a relative accuracy of 10^{-15} [1]. In order to improve the theoretical description of this system, the proton charge radius (r_p) was extracted from the measured Lamb shift in muonic hydrogen with a 10 times higher accuracy compared to previous determinations from electronic systems. This measurement, however, also shows a 5.6σ discrepancy with CODATA-2014 and this is now well known as the *proton radius puzzle* [2, 3]. Recent developments in this field have made matters even more confusing. The proton radius extracted from the measured 2S-4P transition frequency in electronic hydrogen agrees well with the muonic value [4], while a recent measurement of the 1S-3S transition frequency results in a value which coincides with CODATA-2014 [5]. Efforts are now being made to resolve this problem, using different systems. Therefore, our goal is to measure the 1S-2S transition in singly-ionized helium at 30 nm. This system is more sensitive to nuclear charge effects and the result can be compared directly with measurements conducted in muonic-He^+. Also, combining the expected more accurate determination of the nuclear charge-radius of the α-particle from the muonic-He^+ measurement with high accuracy spectroscopy of the 1S-2S transition in He^+, results in an even more stringent test of bound-state QED [6].
To pursue this goal we recently have developed the Ramsey-comb spectroscopy (RCS) method, which combines high-power amplified frequency comb laser pulses with high-precision frequency metrology. This enabled us to perform precision measurements in molecular hydrogen at deep ultra-violet wavelengths, demonstrating that RCS is very suitable for combining efficient frequency up-conversion with high-precision spectroscopy [7]. Moreover, systematic shifts due to the ac-Stark effect or chirp are greatly suppressed. We are currently extending this technique to the vacuum-UV and extreme-UV wavelength range using High-Harmonic Generation (HHG). A 3 meter long vacuum system was designed and constructed for this, and the latest results show that we have a refocused diffraction limited XUV beam ($\lambda < 50$ nm). We are currently testing RCS with HHG on the $5p^6 \rightarrow 5p^5 6d[1/2]_0$ transition in xenon at 113 nm (7th harmonic of 790 nm). With this measurement we can characterise the phase-shift induced by the HHG process and the quality of our XUV-beam, which is of great importance for the experiment in He^+.

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