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Towards Ramsey-Comb Spectroscopy of the 1S-2S Transition in He+

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Precision spectroscopy of the 1S-2S transition in singly-ionized hydrogen-like helium is a promising avenue to test bound-state quantum electrodynamics. Additionally, combined with measurements on μHe^+ [1], nuclear size effects and the nuclear polarizability can be probed [2]. He^+ can be confined in a Paul trap and sympathetically cooled by laser-cooled Be^+, which also serves as the readout ion. Due to the strong binding of the remaining electron of He^+, the 1S-2S transition lies in the extreme ultraviolet (XUV) spectral range. We aim to measure this transition with 1 kHz or better accuracy using Ramsey-comb spectroscopy (RCS) [3], combined with high-harmonic generation (HHG) [4].

In RCS, two pulses (near 790 nm) from a frequency comb (FC) pulse train are selectively amplified to the mJ-level, upconverted to the XUV via HHG, and then used to do a Ramsey-type measurement by slightly scanning the repetition frequency of the FC. This is repeated for different pairs of (amplified) pulses of the FC, at different macro-delays that are equal to an integer times the repetition time of the FC. By combining Ramsey fringes measured at different macro-delays, we restore most of the good properties of the FC, almost as if the whole pulse train was employed for the excitation. An important difference with direct FC spectroscopy is that phase shifts which are constant for all fringes drop out of the analysis [5]. This includes the phase shifts from amplification, HHG, and the ac-Stark shift of the transition. Moreover, for a trapped He^+ ion, it will enable us to cancel the first-order Doppler shift by synchronizing the repetition frequency of the comb to the secular frequency of the helium ion. As a result, Doppler-free excitation will become possible with unequal photons, one at 790 nm, and one at its 25^{th} harmonic (32 nm), which strongly enhances the excitation probability compared excitation with 2 times 60 nm.

We now demonstrate an important step towards this goal with the first laser excitation of the 1S-2S transition in He+, based on an atomic beam of helium. Within a single 150 fs laser pulse, helium atoms are first ionized to He^+, then excited from the 1S to the 2S state (in He^+), and finally the He^+ ions in the 2S state are ionized again to He^{2+}. By scanning the central wavelength of our frequency comb laser, we can observe the 1S-2S resonance with the He^{2+} signal. We can independently vary the XUV and 790 nm intensity, and show that the observed ac-Stark shifts are consistent with the expected values and are compatible with RCS. This paves the way to high-precision 1S-2S laser spectroscopy of He^+ in an ion trap with Ramsey-Comb spectroscopy.

[1] Krauth et al., Nature 589, 527–531 (2021)
[2] Krauth et al., PoS (FFK2019) 49, (2019)
[3] Morgenweg et al., Nat. Phys. 10, 30–33 (2014)
[4] Dreissen et al., Phys. Rev. Lett. 123, 143001 (2019)
[5] Morgenweg et al., Phys. Rev. A 89, 052510 (2014)

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