Pushing QED to the limit in the helium atom

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QED theory remains one of the most well-tested theories in physics to date. Both theorists and experimentalists keep pushing the limits to which QED continues to accurately predict the electron anomalous magnetic moment, the fine-structure constant α, and electronic energy levels in atoms and ions. At the LaserLaB in Amsterdam we test QED by measuring (doubly) forbidden transitions in helium. We are able to observe such weak transitions because we perform spectroscopy in ultracold quantum degenerate metastable helium ($T \approx 1\ \mu$K) confined in an optical dipole trap. Apart from the significantly reduced Doppler broadening in this system, the ultracold trapped gas can also be very well characterized. This is essential for controlling the systematic effects typically limiting the error budget in high-precision spectroscopy.

We have recently determined the ionization energy of the $2\ ^1P_1$ state of ^{4}He to 6.7×10^{-10} relative accuracy by directly measuring the forbidden $2\ ^3S_1 \rightarrow 2\ ^1P_1$ transition at 887 nm [1]. This determination agrees with results obtained by a different group [2] but disagrees by over 3σ with the most accurate QED calculations to date [3]. As the QED calculations agree with all other low-lying electronic states in helium, these results indicate that there might be a particular issue with the $2\ ^1P_1$ state. In addition to the determined ionization energy, the measured lineshape of the transition provides the most accurate determination of the lifetime of the $2\ ^1P_1$ state to date, which is in excellent agreement with theory and other experiments.

Pushing towards even higher accuracy, measurements exceeding the accuracy of QED theory allow extraction of the nuclear charge radius from the QED calculations. This has recently been used in hydrogen and muonic hydrogen spectroscopy, where an over 7σ discrepancy was found in the determined charge radius of the proton. This discrepancy is also known as the *proton radius puzzle* [4]. Apart from ongoing work to perform similar measurements in muonic helium ions [5], our group has previously measured the doubly forbidden $2\ ^3S \rightarrow 2\ ^1S$ transition at 1557 nm (natural linewidth $2\pi \times 8$ Hz) to a few kHz precision in both ^{3}He and ^{4}He. The results were combined with QED calculations to determine the ^{3}He-^{4}He nuclear charge radius difference with 1.1% accuracy [6]. A similar recent determination based on the measurement of the $2\ ^3S \rightarrow 2\ ^3P$ transition shows a disagreement of 4σ with our result [7].

We are currently working on a new measurement of the $2\ ^3S \rightarrow 2\ ^1S$ transition with sub-kHz precision as this can shed more light on the 4σ discrepancy. Furthermore this will provide a more accurate nuclear charge radius difference for comparison with the muonic helium ion measurements of which the first results are expected soon. We have made several improvements on the previous experiment. First the previously measured linewidth of the transition (~ 100 kHz) is reduced by improving the stability of the spectroscopy laser. Second the Zeeman shift is measured with better precision than before or even eliminated using atoms in the $M_J = 0$ state. Third we implement a magic wavelength optical dipole trap operating at 319.8 nm to significantly reduce the ac Stark shift [8], and we are currently able to produce the required UV light at a CW power of 2 Watts which is more than sufficient for our purposes.

References

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