Probing Nuclear Size Effects with Precision Spectroscopy of Quantum Degenerate Metastable Helium

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Precision measurements in simple, calculable systems can be used as sensitive tests for bound-state QED theory, and for a determination of fundamental constants. With this target in mind, we perform precision spectroscopy on the narrow, doubly forbidden $2^3S_1 \rightarrow 2^1S_0$ transition in helium at 1557 nm. To obtain sub-kHz accuracy, we use laser cooling and trapping of atoms in the metastable 2^3S state to prepare quantum degenerate samples. These are trapped in an optical dipole trap at the 320 nm magic wavelength for the transition, where the trap induces no systematic shift on the transition frequency measurement.

Our aim is to determine the squared nuclear charge radius difference between the fermionic ^{3}He, and bosonic ^{4}He isotope, based on a measurement of the isotope shift. For the isotope shift, complicating effects from electron correlations in the QED calculations largely cancel, so that the biggest unknown becomes the finite size of the nuclei. Since the two isotopes exhibit very different quantum-statistical behaviour, the measurements require a profound understanding of fundamental quantummechanical processes. As an example, in the ^{3}He degenerate Fermi gas, we reported a previously unobserved Pauli blockade effect in the excitation dynamics, causing an inherent sub-Doppler narrowing of the spectroscopic linewidths [2].

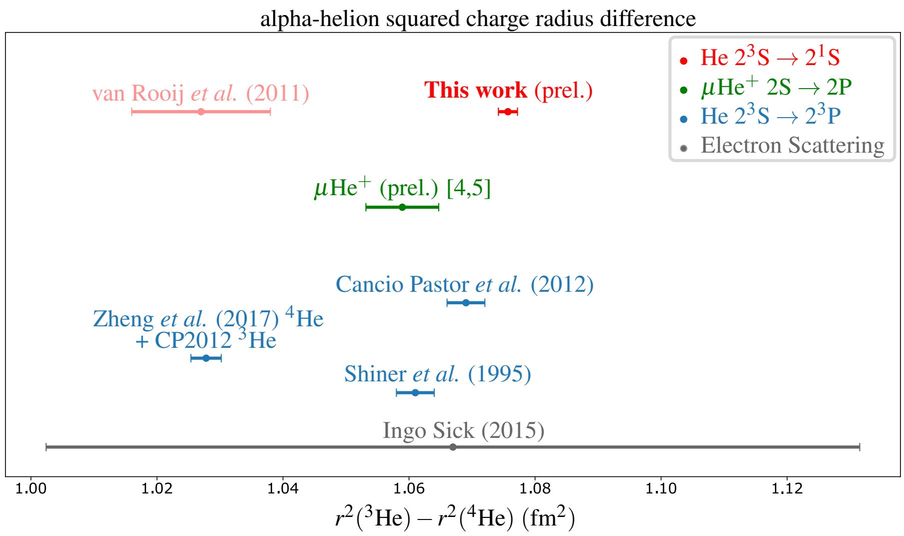

Figure 1: Determinations of the squared charge radius difference δr^2 between the alpha and helion particle. Our newest (preliminary) determination of δr^2 based on the $2^3S_1 \rightarrow 2^1S_0$ transition now gives the most accurate value of δr^2. There are significant discrepancies with other results, among which a (preliminary*) determination from muonic He$^+$ [4,5]. These deviations call for further experimental and theoretical investigation.

In both isotopes, the $2^3S_1 \rightarrow 2^1S_0$ transition has now been measured with a 10^{-12} relative accuracy [1,3], resulting in the most precise determination of the squared nuclear charge radius difference between the alpha and helion particle (see figure 1). Comparing with determinations based on a different transition in helium, as well as measurements of the absolute charge radii in muonic He$^+$ ions, we can check the consistency of the QED theory of helium atoms and test the equivalence between electrons and muons.

References

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* An updated determination of the helion charge radius from μ^3He^+ is expected soon based on improved theory.