Invited talk

Alpha and helion particle charge radius difference determination with quantum-degenerate helium

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Precision spectroscopy of atoms and molecules is widely used for tests of the Standard Model and determinations of fundamental constants. Nuclear charge and magnetic radii also play a vital part in the comparison between theory and experiment and can be measured by spectroscopy as well. Both neutral helium[1] and singly-ionized helium[2] spectroscopy are an interesting target for such an enterprise. In this presentation we mainly focus on precision spectroscopy of neutral ^{3}He and ^{4}He. In both isotopes we measure the doubly-forbidden 2 $^3S_1$ – 2 $^1S_0$ transition at 1557 nm with single-photon excitation. The isotope shift derived from this measurement enables an accurate determination of the nuclear charge radius difference.

We cool the helium atoms to quantum degeneracy to minimize the Doppler effect and confine them in an optical dipole trap at the magic wavelength of 320 nm. The resulting ultra-cold Fermi gas (^{3}He) and Bose-Einstein condensate (^{4}He) show widely different quantum behavior and spectroscopy[3]. In 2018 we reached[4] an accuracy of 200 Hz for the 2 $^3S_1$ – 2 $^1S_0$ transition in ^{4}He, and recently we improved the same determination[1] in ^{3}He to 170 Hz. Based on the resulting isotope shift, and theoretical calculations, we initially determined a charge radius difference $\delta r^2 = r_h^2 - r_\alpha^2 = 1.0757(12)_{exp}(9)_{theo}$ fm^2 between the helion and alpha particle[1]. Interestingly, an evaluation by the CREMA collaboration of the same charge radius difference from muonic helium ion measurements[5] led to a value that deviates 3.6 combined sigma from ours. New theory evaluations of the hyperfine structure of ^{3}He by Qi et al.[6] and a full second-order calculation by Pachucki et al.[7] in 2024 has shown unexpectedly large contributions from higher-order effects that require a correction of the theoretical isotope shift (for point-like nuclei) by -1.77kHz. This leads to an updated δr^2 (based on our isotope measurement) of $1.0678(12)_{exp}(7)_{theo}$ fm^2, which now agrees with that of the CREMA collaboration within 1.2 combined sigma[1,5,7]. These measurements serve as an interesting test of a wide range of physics, and it presents a benchmark for nuclear structure calculations.

We recently completed new spectroscopic measurements for ^{4}He on the 2 $^3S_1$ – 2 $^1S_0$ transition to improve the accuracy of the experimental isotope shift further, and therefore the accuracy of δr^2. We investigated and improved many aspects, such as the influence of magnetic fields, motion of the BEC in the dipole trap observed through time-resolved detection, the laser linewidth, BEC mean-field interaction, and the spectroscopy laser Stark shift. Preliminary evaluations indicate we can expect a ^{4}He transition frequency accuracy of a few parts in 10^{13}. These aspects and the implications for improving δr^2 will be presented.

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[3] R. Jannin, Y. van der Werf, K. Steinebach, H.L. Bethlem, K.S.E. Eikema, *Nat. Comm.* **13**, 6479 (2022)

[4] R.J. Rengelink *et al., Nat. Phys.* **14**, 1132-1137 (2018)

[5] K. Schuhmann *et al.*, arXiv:2305.11679, accepted 2025 for publication in Science

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[7] K. Pachucki, V. Patkós, V.A. Yerokhin, *Phys. Rev. A* **110**, 062806 (2024)