The ionization energy of metastable ^{3}He and ^{4}He ($2\,^3S_1$) and the alpha- and helion-particle charge-radius difference from precision spectroscopy of the np Rydberg series

Gloria Clausen[1] **and Frédéric Merkt**[1, †],

[1] *Institute of Molecular Physical Science, ETH Zurich*
†corresponding author's email: frederic.merkt@phys.chem.ethz.ch

The comparison of calculated and experimental energy intervals in He represents an attractive route to test the fundamental theory of two-electron systems and to determine physical constants and particle properties such as the charge radii of the helion ($^3He^{2+}$) and alpha ($^4He^{2+}$) particles. This route is, however, currently blocked by discrepancies between experimental and theoretical results in this fundamental atomic system. In particular, calculated and measured values of the transition frequencies from the $2\,^3S_1$ metastable and the $2\,^3P_0$ states of ^{4}He to the $3\,^3D_1$ state differ by more than 10σ [1, 2, 3] and experimental and theoretical values of the ionization frequency of the $2\,^3S_1$ and $2\,^1S_0$ metastable states of ^{4}He differ by 9σ [1, 4, 5]. Moreover, recently reported $^3He^{2+}$ and $^4He^{2+}$ squared-charge-radii differences obtained by combining theory and precision spectroscopy for $2\,^2P \leftarrow 2\,^2S$ transitions in muonic He^+ ions [6] and for the isotopic shift of the $2\,^3S_1 \leftarrow 2\,^1S_0$ transition [7] in He deviate by 3.6σ. Recent progress in the theoretical treatment of singlet-triplet mixing in ^{3}He might resolve this discrepancy [8, 9].
In this talk, we present an improved experimental method for the determination of the ionization energy of the $2\,^3S_1$ state of ^{4}He via the measurement of transitions from the $2\,^3S_1$ state to np Rydberg states. The upgrades to our experiment include (i) the preparation of a cold, supersonic expansion of helium atoms in the $2\,^3S_1$ state, (ii) the development of a laser system with SI-traceable frequency calibration for driving the transitions to np Rydberg states, (iii) the implementation of a sub-Doppler, background-free detection method [10], and (iv) an interferometric alignment procedure for counter-propagating laser beams to cancel the 1st-order Doppler shifts [5]. We illustrate the power of this method with a new determination of the ionization energy of $2\,^3S_1$ metastable ^{4}He [$E_I(^4He)/h = 1\,152\,842\,742.7082(55)_{stat}(25)_{sys}$ MHz] with a fractional uncertainty of $4 \cdot 10^{-12}$ by extrapolation of the np series.
These measurements were recently extended to precision measurements of hyperfine-resolved transitions from the $2\,^3S_1$ metastable state of ^{3}He to high np Rydberg states converging on the $F^+ = 0, 1$ hyperfine levels of the $^3He^+$ $1s\,^2S_{1/2}$ ground state. Rydberg-series extrapolation using multichannel quantum-defect theory (MQDT) enabled the determination of the ionization energy of the $2\,^3S_1$ state of ^{3}He [$E_I(^3He)/h = 1\,152\,788\,844.6154(77)_{stat}(25)_{sys}$ MHz] and of the corresponding isotopic shift [$(E_I(^4He) - E_I(^3He))/h = 53\,898.093(9)$ MHz]. The MQDT analysis also permitted the quantification of singlet-triplet mixing in the np series induced by the hyperfine interaction. From the isotopic shift of the ionization energy of He, the difference δr^2 between the squared charge-radii of the helion and alpha particles was determined to be 1.060(10) fm^2.

References

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