Testing fundamental interactions on light atoms

Krzysztof Pachucki[a], Vladimir A. Yerokhin[b], Vojtěch Patkóš[c]
[a] *Faculty of Physics, Warsaw University, Pasteura 5, 02-093 Warsaw, Poland*
[b] *Center for Advanced Studies, Peter the Great St. Petersburg Polytechnic University, Polytekhnicheskaya 29, 195251 St. Petersburg, Russia*
[c] *Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, 121 16 Prague 2, Czech Republic*

We critically examine the current status of theoretical calculations of the energies and the isotope shift of the lowest-lying states of helium, searching for unresolved discrepancies with experiments. Calculations are performed within the nonrelativistic quantum electrodynamics expansion in powers of the fine structure constant α and the electron-to-nucleus mass ratio m/M. For energies, theoretical results are complete through orders $\alpha^6 m$ and $\alpha^6 m^2/M$, with the resulting accuracy ranging from 0.5 to 2 MHz for the $n = 2$ states. The isotope shift between ^{3}He and ^{4}He is treated theoretically with a sub-kHz accuracy, which allows for a high-precision determination of the differences of the nuclear charge radii δr^2. Several such determinations, however, yield results that are in a 4σ disagreement with each other. Apart from this, we find no significant discrepancies between theory and experiment for the helium atom.

Further, we present the complete relativistic $O(\alpha^2)$ nuclear structure correction to the energy levels of ordinary (electronic) and muonic hydrogen-like atoms. The elastic part of the nuclear structure correction is derived analytically. The analytical result is verified by high-precision numerical calculations. The inelastic $O(\alpha^2)$ nuclear structure correction is derived for the electronic and muonic deuterium atoms. The correction comes from a three-photon exchange between the nucleus and the bound lepton and has not been considered in the literature so far. In the case of deuterium, the inelastic three-photon exchange contribution is of a similar size and of the opposite sign as the corresponding elastic part and, moreover, cancels exactly the model dependence of the elastic part. The obtained results affect the determination of nuclear charge radii from the Lamb shift in ordinary and muonic atoms.

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