Sub-kHz measurement of the 2 ^{3}S – 2 ^{1}S transition frequency in ^{4}He

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We have measured the transition frequency between the two metastable states of ^{4}He, 2 $^3S_1$ (lifetime 8 ks) and 2 $^1S_0$ (lifetime 20 ms), with 0.20 kHz accuracy (1.0×10^{-12} relative accuracy). Our result is almost a factor of ten more accurate than the previous result [1] and agrees within 2σ. The result connects orthohelium and parahelium tightly and constitutes the most accurate optical frequency measurement in the helium atom to date.

Our measurement is performed on a Bose-Einstein Condensate (BEC) of ^{4}He atoms in the 2 $^3S_1$ state, confined at a temperature of 0.2 μK in a crossed optical dipole trap (ODT). We have used an ODT near the 319.8-nm magic wavelength, minimizing AC Stark shifts in the transition. We measured this magic wavelength with 0.00015 nm accuracy and found very good agreement with calculations based on tabulated level energies and dipole matrix elements [2]. In the experiment we excite the 1557-nm transition with a telecom fiber laser, offset-locked to an ultrastable (~1 Hz) laser via a femtosecond frequency comb laser, realizing a 5 kHz laser linewidth over our 0.1 s interrogation time of the trapped atoms. We observe the transition (linewidth typically 10 kHz) counting the ions produced by Penning ionization of 2 ^{1}S atoms with 2 ^{3}S atoms in the trap. The excitation inside a BEC also causes a mean-field shift of the transition frequency, similar to the 1S–2S experiments in an atomic hydrogen BEC [3]. Varying the chemical potential we extract the *s*-wave singlet-triplet scattering length with 5% accuracy and find good agreement with a measurement of this scattering length performed in an ODT at 1.56 μm [4], however with much higher accuracy and now strongly disagreeing with a quantum chemistry calculation based on a complex potential of the 2 ^{1}S – 2 ^{3}S helium dimer.

Our new value of the transition frequency agrees very well with the most recent QED calculations, which have an accuracy of 0.8 MHz [5]. When we combine our new measurement with our earlier result on the same transition for ^{3}He, which ‘only’ has a 1.5 kHz accuracy [1], strong cancellation of QED terms in the isotope shift lead to a theoretical accuracy in the point-nucleus isotope shift of 0.19 kHz [5], which allows extraction of the difference in the squared nuclear charge radii for both isotopes, $\delta r^2 = r_3^2 - r_4^2$, with 0.007 fm^2 accuracy (6×10^{-3} relative accuracy). We hope to significantly improve on the isotope shift accuracy in the near future by measuring the ^{3}He transition in a magic-wavelength trap as well. Our present value for δr^2 still disagrees with δr^2 measurements from the isotope shift in the 2 ^{3}S – 2 ^{3}P transition, that also disagree among each other [6]. Comparison with δr^2 from μ-^{3,4}He$^+$ Lamb shift measurements at the Paul Scherrer Institute will reveal if there is also a helium nuclear size puzzle.

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