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Measurement of the Lamb shifts in singlet levels of atomic helium

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We report laser spectroscopic results that extend the precision of earlier measurements substantially and provide tests of recent calculations on the singlet *S*, *P*, and *D* levels of atomic helium. We have determined the Lamb shift of the He $2\,^1S_0$, $3\,^1P_1$ states by unambiguously establishing the $2\,^1S_0$ absolute level position, by Doppler-free, two-photon transitions from $2\,^1S_0$ to $n\,^1D_2$ ($7 \le n \le 20$). The Lamb shift of 0.093761(5) cm^{-1} [2810.88(15) MHz] agrees with a less precise experiment of Sansonetti, Gillaspy, and Cromer [Phys. Rev. Lett. **65**, 2539 (1990)], but differs from theory by 98.36(15) MHz. In combination with the above-noted experimental result, the Lamb shift of the $3\,^1P_1$ level is 0.000522(45) cm^{-1}, in agreement with theory. Our relative spacings of the *D* levels is in disagreement with published theoretical calculations, but is in agreement with recent unpublished corrections of this work. This *D*-level agreement also confirms Casimir forces to the 2% level.

Recent advances in experimental laser spectroscopy and theoretical analysis of simple atomic systems have been spectacular. During the past two decades, the precision of optical measurements of the one-electron, atomic hydrogen spectrum has improved by 3 orders of magnitude. Current measurements of the Rydberg constant are now constrained by the realization of the meter in the optical domain at the 1.6×10^{-10} level. On the theoretical side, quantum electrodynamic (QED) calculations by Erickson [J. Phys. Chem. Ref. Data **6**, 831 (1977)] are still unchallenged by experiments on low-*Z* atoms.

Atomic helium, with its two electrons, is the prototypic many-body system. It (and the negative hydrogen ion) are the simplest systems that have the complexity of electron-electron (Coulomb and magnetic) interactions. Both experimental measurements of He spectra and the corresponding theoretical calculations are progressing at a very rapid rate today. Recently, laser spectroscopic measurements of the triplet spectrum by Hlousek, Lee, and Fairbank[1] and of the singlet spectrum by Sansonetti, Gillaspy, and Cromer[2] were to a precision of a few parts in 10^9. We report optical measurements with precision in the parts in 10^{11} level, which are timely tests of very recent calculations by Drake and Makowski.

The basic ideas of this experiment were suggested by Eyler and Lundeen.[3] The highly excited Rydberg states of helium, with large quantum number (n,l), are very close to hydrogenic, and are accurately treated by perturbation theory, which is checked precisely by rf spectroscopy. On the other hand, the low-lying *S* and *P* levels present a much more demanding test of theory and are only accessible by means of laser spectroscopy. Laser transitions between these two classes of states can be used to nail down the less accurately characterized, low-lying energy levels in terms of the better-understood Rydberg states.

For both sets of states, it appears that the calculation of the nonrelativistic part of the wave function has been solved to accuracies far beyond current experimental precision. The remaining, only partially solved, problem is to calculate the relativistic and QED corrections (Lamb shift) to a precision comparable to experiment for the lower levels.

Our experiment incorporates these ideas[3] by finding the absolute location of $2\,^1S_0$ by means of accurate wavelength measurement of two-photon transitions from the $2\,^1S_0$ to the relatively accurately placed $^1D_2$ energy levels for $7 \le n \le 20$ (Fig. 1). The specification of these energies starts with the theoretical treatment by Drachman[4] of highly excited states of helium ($n \approx 10$; $G, H, \ldots$ states), very precise rf measurements of the intervals *nI*-*nH*, *nH*-*nG*, *nG*-*nF* to a few kHz by Hessels *et al.*[5] and precise measurements to the *D* states by Farley, MacAdam, and Wing.[6] Drake[7] has published calculated positions of the ^1D levels for $3 \le n \le 10$ with uncalculated terms estimated to be of the order of 10 kHz (0.0000003 cm^{-1}) for $n=7$ and scaling as $1/n^3$.

Figure 2 shows the plan of the experiment. A beam of metastable He atoms, excited by electron bombardment, is crossed with a laser beam inside of a buildup cavity.

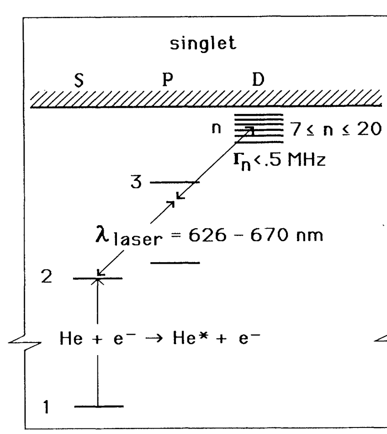

FIG. 1. Energy levels of He and two-photon transitions (level spacing not to scale).

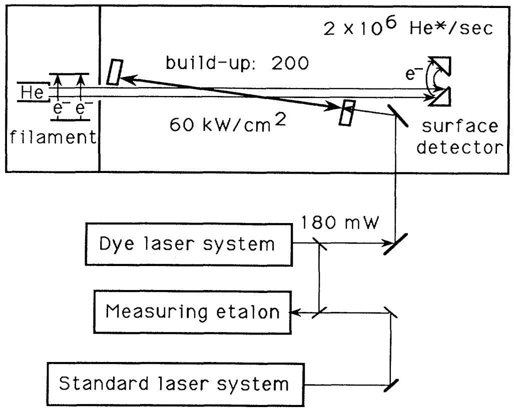

FIG. 2. Block diagram of the experiment with the lasers, metastable beam apparatus, and buildup cavity shown.

The metastable beam intensity is diminished when two-photon transitions occur. The results, shown in Table I, differ from Drake's calculations[7] of the relative spacing of the D levels by more than a MHz (0.000 03 cm^{-1}), an order of magnitude larger than typical experimental errors. The reason for this discrepancy lies in an incorrect treatment of the two-electron Bethe logarithm in the calculation of the Lamb shift and also in the relativistic mass polarization terms.[7]

Table I presents corrected theoretical results, based on Drake's revised calculations[7] for $7 \leq n \leq 10$ and Hessels' unpublished extrapolation to $n > 10$. The reduced χ^2 value for the data is 0.80, which now shows good agreement within the errors of ~0.000 001–0.000 007 cm^{-1} (30–200 kHz).

On the basis of this consistency among the D energy levels, we used the ideas of Eyler and Lundeen[3] to make an accurate determination of the Lamb shift of the $2\,^1S_0$ state, by means of our transitions to the $n\,^1D_2$ levels. The data indicates an error in the mean $2\,^1S_0$ binding energy of 0.8×10^{-6} cm^{-1}. However, the final error of 5×10^{-6} cm^{-1} is entirely due to the realization of the meter.

After we completed this set of measurements, we learned that Sansonetti, Gillaspy, and Cromer[2] had measured the $2\,^1S_0$ to $3\,^1P_1$ transition in He to a precision of 0.000 045 cm^{-1}. However, because the energy of the upper level was found by means of a lengthy and imprecise chain of measurements, they were only able to specify the location of it to a precision of 0.000 170 cm^{-1} and the lower level to 0.000 180 cm^{-1}. Our data give the location of $2\,^1S_0$ with a factor of 30 higher precision and, by combining our results with theirs, the $3\,^1P_1$ level to a factor of 4 higher precision.

TABLE I. Binding energies of the helium singlet D states. Units are cm^{-1}. The helium singlet $2S$ binding energy is 32 033.228 830 3 cm^{-1}.

n	Experiment	Theory[a]	Expt.-theor. difference (10^{-6} cm^{-1})
7	2 240.540 587 3(40)	2 240.540 593 2	−5.9(40)
8	1 715.294 923 0(23)	1 715.294 924 2	−1.2(23)
9	1 355.220 227 4(36)	1 355.220 226 2	1.2(36)
10	1 097.679 442 7(33)	1 097.679 446 0	−3.3(33)
11	907.139 688 2(35)	907.139 689 5	−1.3(35)
12	762.225 764 2(35)	762.225 764 3	−0.1(35)
13	649.453 397 1(23)	649.453 396 7	0.4(23)
14	559.975 198 4(35)	559.975 203 1	−4.7(35)
15	487.791 017 9(47)	487.791 020 2	−2.3(47)
16	428.715 174 8(14)	428.715 172 4	2.4(14)
17	379.755 738 6(36)	379.755 736 9	1.7(36)
18	338.728 138 4(56)	338.728 133 4	5.0(56)
19	304.007 137 7(66)	304.007 139 9	−2.2(66)
20	274.363 425 3(72)	274.363 429 9	−4.6(72)

[a]Drake (Ref. 7) for $7 \leq n \leq 10$ and Hessels' unpublished extrapolation of these calculations for $n > 10$.

The comparison of the various experimental and theoretical determinations of the energy levels and Lamb shifts for these levels is shown in Table II. The result for the $2\,^1S_0$ Lamb shift is in somewhat surprising disagreement with theory. However, uncalculated terms could account for this discrepancy.[7] The combined value from our work and Ref. 2 for the $3\,^1P_1$ level is in agreement with theory. However, because the Lamb shift for the P state is much smaller and the experimental error is larger (see Table II), the percent discrepancy between experiment and calculation could be just as large as for the S state.

While the low-lying S and P states have the highest QED shifts, higher-lying states of He show significant effects of Casimir forces, which arise from retardation. In fact, helium has been considered the best system for

TABLE II. Lamb shift of He $2\,^1S_0$ and $3\,^1P_1$ (cm^{-1}).

	Binding Energy		Lamb Shift	
State	Experiment	Theory (non-QED)[a]	Experiment[b]	Expt.-theor. difference
$2\,^1S_0$	32 033.228 830(5)[c]	32 033.322 591	0.093 761(5)[c]	0.003 281(5)
			0.093 780(180)[d]	0.003 300(180)
$3\,^1P_1$	12 101.304 036(45)[c,d]	12 101.304 558	0.000 522(45)[c,d]	0.000 015(45)
			0.000 670(170)[d]	0.000 163(170)

[a]Drake (Ref. 7), and (private communication).
[b]Difference between experiment and theoretical non-QED binding energies.
[c]This work.
[d]Ref. 2.

high-precision tests of these forces in several theoretical studies.[8–10] It is just the relative insensitivity of the high-lying states to other QED and relativistic effects that makes them such ideal test cases for Casimir forces.

It should be noted that Drake's calculations automatically include retardation effects under the orbit-orbit term of the Breit interaction[11] (H_2) and in what he calls the two-electron Lamb-shift corrections. The agreement between our measurements and his calculations for the nD levels checks the retardation terms in He to the 2% level. We take this as confirmation of the recently reported microwave measurements ($n=10$: $F\rightarrow G$, $G\rightarrow H$ transitions) in helium by Hessels *et al.*,[5] who found agreement at the 1% level. Currently omitted are higher-order terms in the electron-electron interaction, which involve crossed Coulomb and transverse photon exchange as well as two-transverse photon exchange.[12] Such terms give rise to interesting Casimir long-range behavior, but are smaller than experimental error.

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