Precise Measurement of the Lamb Shift and Fine Structure of the 2S-2P Transition in Triplet Helium

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The Lamb shift and fine structure of the 2^3S-2^3P transition in helium has been precisely measured using laser excitation of an atomic beam. The Lamb shift is 5311.27(7) MHz, agreeing with the best previous measurement but a factor of 40 more precise. The 13 parts per 10^6 precision makes this Lamb shift one of the most precisely known in atomic physics. The results for the fine structure intervals have precisions equal to or exceeding the best previous rf measurements but are not in good agreement with them. Our results provide timely benchmarks for the testing of atomic theory and QED in helium.

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Helium is the simplest multielectron atom and yet its quantum description has no exact solutions even in the nonrelativistic limit. It has often served as a testing ground for approximation techniques in atomic physics and quantum mechanics [1]. While helium continues to play this role, recent theoretical advances allow the underlying theory, quantum electrodynamics, to be tested with accuracies approaching those obtained in hydrogenlike systems [2]. Significantly, the energies of the bound states of helium contain contributions which are not observed in hydrogen and which arise from the interactions between the electrons [3]. Precise measurements in helium thus complement those in one-electron systems. They provide extremely sensitive tests of quantum electrodynamics in the bound state as well as of approximation methods in atomic physics and quantum mechanics.

Surprisingly, there are few experiments on helium which can now confront the precision of theory. Previous discrepancies with measurements of gross energy level spacings [4-8] have been largely removed by techniques which improve the determination of Bethe logarithms for two-electron systems [9-11]. Even the precision of the landmark helium fine structure measurements of Pichanick and co-workers [12-15] is likely to soon be exceeded by theory. Thus an experiment which could contribute a new benchmark for testing the theoretical understanding of both the gross energy levels and the fine structure splittings would be timely. We report an experiment which we believe provides this new benchmark [16].

Our experiment measures the frequency of the $2S$ to $2P$ transition and its fine structure in triplet ($S=1$) helium (Fig. 1). The $1s2s\,^3S$ state has the largest Lamb shift in helium, with the exception of the ground state which is difficult to study [17]. The $1s2p\,^3P$ state has the largest fine structure splittings in helium. Thus the experiment is analogous to the classic $2S$ to $2P$ Lamb shift and fine structure measurements in hydrogen, but with the advantage of a larger Lamb shift (5 GHz compared to 1 GHz) and fine structure (30 GHz compared to 10 GHz), and a smaller natural linewidth (1.6 MHz compared to 100 MHz).

Our experimental approach is to use laser excitation of a polarized metastable helium beam with interferometric determination of the laser wavelengths. Atoms which absorb the laser photons return to the metastable state, though not necessarily with the same polarization. Transitions are thus detected by first polarizing the metastable beam using an inhomogeneous magnetic field produced by the "A" magnet, which selects the $2^3S(m=0)$ state (Fig. 2). A laser then induces transitions to the 2^3P states in the presence of a small uniform magnetic field produced by the "C" magnet. Spontaneous emission repopulates the $2^3S(m=\pm 1)$ states, which are then deflected by the B magnet into our detector. This method is essentially the Rabi molecular beam magnetic resonance method with the magnetic resonance replaced by a depolarizing laser resonance. The effusive helium source with electron excitation to the metastable state yields $\sim 4\times 10^4$ counts/sec in the channeltron detector when a transition is saturated. The transitions are driven with a home made LNA ($La_{1-x}Nd_xMgAl_{11}O_{19}$) ring laser [7] pumped with an argon ion laser. Starting from the $2^3S_1(m=0)$ initial state, all six allowed transitions to the 2^3P final state are measured: $J=0, m=0$; $J=1, m=\pm 1$;

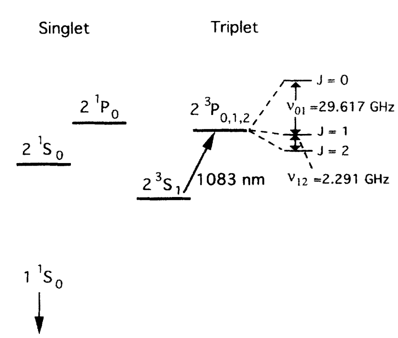

FIG. 1. The first few states of helium and the measured intervals.

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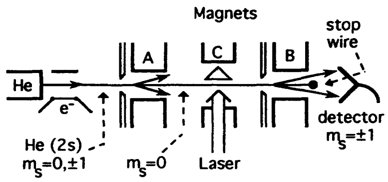

FIG. 2. Schematic of the atomic beam apparatus and method.

and $J=2, m=0, \pm 1$.

Our interferometric method for wavelength measurements is similar to that used in previous experiments in hydrogen [18,19] and helium [4]. A helium-neon laser is offset locked with a synthesized rf frequency to an iodine stabilized He-Ne laser at 633 nm [20]. The LNA laser is locked to a measuring etalon which is in turn locked to the offset He-Ne laser. The ratio of the unknown laser frequency to the known offset laser frequency is then given by the ratio of their respective order numbers in the measuring etalon. Corrections are made for the etalon mirror curvatures and phase shifts by measuring the transverse mode spacings of the interferometer and by changing the interferometer length. The frequencies of iodine stabilized He-Ne lasers have been newly calibrated with respect to the Cs standard with an accuracy of 2 parts in 10^{11} [21]. We use this new calibration but retain the previous uncertainty of 1.6 parts in 10^{10} [22] since our I_2 stabilized He-Ne laser has not been directly compared to a recalibrated standard. This is conservative since these standard lasers have been shown to have typical reproducibilities much smaller than this uncertainty [23].

The procedure used to determine the helium resonant frequencies is to equalize the transition signal at two laser frequencies separated by a transition full width at half maximum (2 MHz). The resonant frequency, given by the average of these two frequencies, is obtained to 3 kHz with a few minutes of counting. The laser power is typically set to produce about $\frac{1}{5}$ the saturated signal strength. By varying this power, we obtain a small correction (5 kHz) to apply to give the zero power resonant frequency. Doubling, tripling, and halving the laser frequency step size has no effect on the resonant frequency. This test of the line symmetry is sensitive to systematic effects such as a sloping background or a change in laser power versus frequency. A retroreflecting prism is used to make first order Doppler shifts negligible. This has been checked by cooling the beam to 77 K. The transitions take place in a small magnetic field (typically 30 G). Corrections for this are calculated with negligible error and have been experimentally verified at different magnetic field strengths. Corrections, for example, from the Stark effect, the ac Stark effect, and competing transitions are expected and experimentally confirmed to be negligible. During a run, an interesting experimental check is to average the frequencies for the $2^3S_1(m=0) \rightarrow 2^3P_2(m=\pm1)$ transitions. This result is found to equal, as it should, the $2^3S_1(m=0) \rightarrow 2^3P_2(m=0)$ frequency within statistical error (2–3 kHz) once quadratic Zeeman corrections are made ($\sim$300 kHz). A list of experimental uncertainties is given in Table I.

TABLE I. Uncertainty budget (kHz, 1 standard deviation).

Source	Lamb shift	Fine structure
Wavelength metrology	50	9 (5 for ν_{12})
I_2 He-Ne standard	44	...
First order Doppler	15	1.5
Laser power	3	1.5
Total (rms sum)	68	9 (5 for ν_{12})

The resonant frequencies are measured with two different interferometer lengths (1 and 3 m) using the same mirrors and alignment. The procedure is repeated several times. The wavelengths compared (633 and 1083 nm) are further apart than in other recent precision wavelengths measurements [4,18,19] and this tends to increase measurement uncertainties due to larger mirror phase shifts. The double stack dielectric mirrors used in the experiment have good finesse (700) and low loss but their phase shifts show some position dependence across the mirror. By repeating the experiment and changing mirrors, a conservative limit on the uncertainty from this effect has been determined. It is the dominant source of error in the experiment. A slightly better result can be obtained for the small (2 GHz) ν_{12} fine structure interval by using the larger (30 GHz) ν_{02} interval to calibrate the free spectral range of the interferometer. Recently, silvered mirrors have been used which suffer less from this problem, though their low finesse (60) makes them more difficult to use. Initial results with these mirrors confirm the previous results with the dielectric mirrors.

We first discuss the result for the $2S \rightarrow 2P$ transition frequency. The statistically weighted average $(2J+1)$ of the $2S$ to $2P$ frequencies is given in Table II. It agrees with the best previous measurement [7], but is a factor of 40 more precise. We can obtain from this result the experimental Lamb shift by using the following equation to define the total energy of a transition:

TABLE II. Comparison with previous work (MHz).

Interval	This work	Previous	Diff.
$(2S\text{-}2P)_{\text{mean}}$	276 736 495.58(7)	276 736 494.0(3.0)[a]	1.6(3.0)
$2^3P_0\text{-}2^3P_1$	29 616.961(9)	29 616.864(36)[b]	0.097(37)
		29 616.904(43)[c]	0.057(44)
$2^3P_0\text{-}2^3P_2$	31 908.135(9)	31 908.040(20)[d]	0.095(22)
$2^3P_1\text{-}2^3P_2$	2291.174(5)	2291.196(5)[e]	−0.022(7)
^{3}He 2^3S_1 hfs	6739.699(3)	6739.701 177(16)[f]	−0.002(3)

[a]Reference [7].
[b]Reference [14].
[c]Reference [30].
[d]Reference [15].
[e]Reference [13].
[f]Reference [29].

$$\Delta E_{\rm tot} = \Delta E_{\rm nonrel} + \Delta E_{\rm nuc} + \Delta E_{\rm rel} + \Delta E_{\rm QED}\,.$$

In this equation, $\Delta E_{\rm nonrel}$ is the nonrelativistic contribution to the energy, $\Delta E_{\rm re}$ is the relativistic (Breit) contribution of $O(\alpha^2)$ and $O(\alpha^2\mu/M)$, $\Delta E_{\rm nuc}$ is the nuclear size correction, and $\Delta E_{\rm QED}$ is the sum of all quantum electrodynamic energy shifts and relativistic corrections of $O(\alpha^3)$ and higher. In multielectron systems it is natural to take $\Delta E_{\rm QED}$ as defining the Lamb shift of the transition. In our case, since all terms other than $\Delta E_{\rm QED}$ are known far more accurately than our experimental error, we can deduce the Lamb shift of the $2S \rightarrow 2P$ transition to be 5311.27(7) MHz, which has a 13 parts per 10^6 fractional uncertainty. This result is the most precise Lamb shift measurement in a multielectron system. In fact, its precision is comparable to the most precise Lamb shift determinations in atomic physics, such as the 10 parts per 10^6 result for hydrogen ground state [24], the 9 parts per 10^6 result for the hydrogen $2S$ state [25], and the 10 parts per 10^6 result for the helium ion $2S$ state [26]. The hydrogen Lamb shifts have somewhat larger errors if the nuclear size discrepancies contained in $\Delta E_{\rm nuc}$ (17 parts per 10^6) are included.

The largest current uncertainty in the theoretical prediction of the $2^3S \rightarrow 2^3P$ Lamb shift comes from the evaluation of the Bethe logarithm in helium. Using a $1/Z$ expansion, the theoretical prediction for the Lamb shift is 5301.66 MHz [2], which differs from our measurement by 9.61(7) MHz. This difference is not unexpected given the uncertainties in the $1/Z$ expansion of the Bethe logarithm. In a review of experiments in helium, it was recently concluded [2] that the value for the 2^3S state using this method is low by 12.7(2.4) MHz, consistent with our result. The 2^3P state itself has an additional uncertainty of about 1.8 MHz. Recently, precise methods for the evaluation of Bethe logarithms in helium have been developed [9,10], and a preliminary result for the 2^3S state greatly reduces the uncertainty from this source [11]. However, obtaining a theoretical result comparable to the new experimental precision of 70 kHz will be a substantial challenge. It is likely to require refinements in both method and computation for the Bethe logarithm of the 2^3S and the 2^3P states [27]. Moreover, the $\alpha^6 mc^2$ terms in the electron-electron interaction can no longer be ignored, their expected size being a few MHz. The complete determination of these terms, only an order of α^2 beyond the fine structure interactions, is a basic problem in atomic physics that needs to be addressed. Our result can help to provide a stimulus and test of such a determination [28].

Our results for the fine structure splittings of the $2^3P(J=0,1,2)$ states are given in Table II. The splittings are not in good agreement with the best previous measurements [13–15], which are of similar precision (Fig. 3). Having no explanation for this, another measurement was performed as a test for the presence of unaccounted for or underestimated systematic uncertainties. The $2^3S_1(F=1/2) \rightarrow 2^3P_0(F=1/2)$ and the $2^3S_1(F=3/2) \rightarrow 2^3P_0(F=1/2)$ transitions in ^{3}He were measured. Our result for their frequency difference is also given in Table II, with only random errors assigned. The agreement with the very precisely known hyperfine interval of the ^{3}He 2^3S state [29] suggests that our systematic uncertainties may actually be overestimated. We are in the process of repeating the measurements with silvered mirrors to see if this is the case.

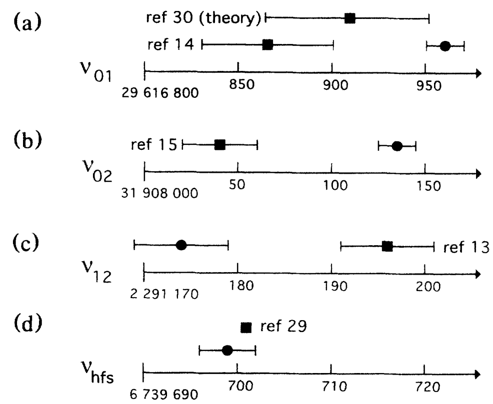

FIG. 3. Comparison of our results (circles) with previous values (squares). The first three graphs show results for the fine structure intervals of the 2^3P state of ^{4}He; the last shows results for the hyperfine interval of the ^{3}He 2^3S state. Units are kHz.

The best theoretical prediction for the fine structure splittings is for the value of the $J=1$ to $J=0$ interval [30], shown in Fig. 3(b). Recently, Drake and Yan have improved the precision of substantial parts of the fine structure calculations, with uncertainties less than 1 kHz [31,32]. We look forward to the completion of their work on the remaining parts, which will then provide a very interesting comparison of theory and experiment. In fact, a precise value of the fine structure constant α could be derived from theory and experiment on the large interval ν_{02}. The smaller interval, ν_{12}, could then be used as an experimental check on the size of uncalculated terms.

In conclusion, we have determined the Lamb shift of the $2^3S \rightarrow 2^3P$ transition in helium with a precision of 13 parts per 10^6, giving one of the most accurately determined Lamb shifts in atomic physics and a timely challenge to atomic theory. New results for the fine structure intervals of the 2^3P state have been obtained; they are not in good agreement with the best previous values. In the future, improvements in these fine structure results are desirable to both clarify the experimental situation and make possible a test of the theoretical results, which are likely to attain uncertainties below the 1 kHz level. With 1 kHz precision, a 16 parts per 10^9 determination of the fine structure constant α becomes possible. The best current determinations of α are from the electron g factor, 7 parts per 10^9, and the quantum Hall effect, 24 parts per 10^9 [33]. We are investigating a more direct frequency calibration of our fine structure measurements to enable these possibilities to be realized.

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[1] See, for example, H. A. Bethe and E. E. Salpeter, *Quantum Mechanics of One- and Two-Electron Atoms* (Springer-Verlag, Berlin, 1957).
[2] A recent review of theory and experiment in helium is given by G. W. F. Drake, Adv. At. Mol. Opt. Phys. **31**, 1 (1993).
[3] An evaluation of some terms in helium similar to those found in positronium is given by G. W. F. Drake, I. B. Khriplovich, A. I. Milstein, and A. S. Yelkhovsky, Phys. Rev. A **48**, R15 (1993).
[4] W. Lichten, D. Shiner, and Zhi-Xiang Zhou, Phys. Rev. A **43**, 1663 (1991).
[5] C. J. Sansonetti and J. D. Gillaspy, Phys. Rev. A **45**, R1 (1992).
[6] C. S. Adams, E. Riis, A. I. Ferguson, and W. R. C. Rowley, Phys. Rev. A **45**, R2667 (1992).
[7] Ping Zhao, J. R. Lawall, A. W. Kam, M. D. Lindsay, F. M. Pipkin, and W. Lichten, Phys. Rev. Lett. **63**, 1593 (1989).
[8] L. Hlousek, S. A. Lee, and W. M. Fairbank, Jr., Phys. Rev. Lett. **50**, 328 (1983).
[9] J. D. Baker, R. C. Forrey, J. D. Morgan III, R. N. Hill, M. Jeziorska, and J. Shertzer, Bull. Am. Phys. Soc. **38**, 1127 (1993).
[10] S. P. Goldman and G. W. F. Drake, Phys. Rev. Lett. **68**, 1683 (1992).
[11] J. D. Baker and J. D. Morgan III (private communication).
[12] A review of these measurements is given by F. M. J. Pichanick and V. W. Hughes, in *Quantum Electrodynamics*, edited by T. Kinoshita (World Scientific, Singapore, 1990).
[13] F. M. J. Pichanick, R. D. Swift, C. E. Johnson, and V. W. Hughes, Phys. Rev. **169**, 55 (1968); S. A. Lewis, F. M. J. Pichanick, and V. W. Hughes, Phys. Rev. A **2**, 86 (1970).
[14] A. Kponou, V. W. Hughes, C. E. Johnson, S. A. Lewis, and F. M. J. Pichanick, Phys. Rev. A **24**, 264 (1981).
[15] W. Frieze, E. A. Hinds, V. W. Hughes, and F. M. J. Pichanick, Phys. Rev. A **24**, 279 (1981).
[16] The interesting and complementary work on heliumlike high Z ions is not discussed here. Theoretical approaches using $1/Z$ expansions become viable in ions. Experiments in both helium and heliumlike ions are sensitive to uncalculated terms of order $(Z\alpha)^4$ a.u. See, for example, H. G. Berry, R. W. Dunford, and A. E. Livingston, Phys. Rev. A **47**, 698 (1993).
[17] K. S. E. Eikema, W. Ubachs, W. Vassen, and W. Hogervorst, Phys. Rev. Lett. **71**, 1690 (1993).
[18] P. Zhao, W. Lichten, H. P. Layer, and J. C. Berquist, Phys. Rev. Lett. **58**, 1293 (1987).
[19] J. C. Garreau, M. Allegrini, L. Julien, and F. Biraben, J. Phys. (Paris) **51**, 2293 (1990).
[20] H. P. Layer, IEEE Trans. Instrum. Meas. **29**, 358 (1980).
[21] F. Nez *et al.*, Phys. Rev. Lett. **69**, 2326 (1992).
[22] D. A. Jennings, C. R. Pollock, F. R. Petersen, R. E. Drullinger, K. M. Evenson, J. S. Wells, J. L. Hall, and H. P. Layer, Opt. Lett. **8**, 136 (1983).
[23] J.-M. Chartier *et al.*, Metrologia **28**, 19 (1991).
[24] M. Weitz, F. Schmidt-Kaler, and T. W. Hänsch, Phys. Rev. Lett. **68**, 1120 (1992).
[25] S. R. Lundeen and F. M. Pipkin, Phys. Rev. Lett. **46**, 232 (1981).
[26] A. van Wijngaarden, J. Kwela, and G. W. F. Drake, Phys. Rev. A **43**, 3325 (1991).
[27] Recent work along these lines is discussed by R. C. Forrey and R. N. Hill, Ann. Phys. (N.Y.) **226**, 88 (1993).
[28] J. Saperstein (private communication).
[29] S. D. Rosner and F. M. Pipkin, Phys. Rev. A **1**, 571 (1970).
[30] M. L. Lewis and P. H. Serafino, Phys. Rev. A **18**, 867 (1978).
[31] G. W. F. Drake and Z.-C. Yan, Phys. Rev. A **46**, 2378 (1992).
[32] Zong-Chao Yan and G. W. F. Drake, Bull. Am. Phys. Soc. **38**, 1127 (1993).
[33] Recent determinations of α are reviewed by B. N. Taylor, in *Units and Fundamental Constants in Physics and Chemistry*, Landolt-Bornstein Numerical Data and Functional Relationship Series, edited by O. Madelung (Springer-Verlag, Berlin, 1993).