Precision Microwave Measurement of the 2^3P_1-2^3P_0 Interval in Atomic Helium: A Determination of the Fine-Structure Constant

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The 2^3P_1-to-2^3P_0 interval in atomic helium is measured using a thermal beam of metastable helium atoms excited to the 2^3P state using a 1.08-μm diode laser. The 2^3P_1-to-2^3P_0 transition is driven by 29.6-GHz microwaves in a rectangular waveguide cavity. Our result of 29 616 950.9 ± 0.9 kHz is the most precise measurement of helium 2^3P fine structure. When compared to precise theory for this interval, this measurement leads to a determination of the fine-structure constant of $1/137.035\,986\,4(31)$.

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It has long been recognized [1,2] that the long lifetime (98 ns) and large energy intervals (29.6 and 2.3 GHz) of the helium 2^3P fine-structure intervals make them ideal for measuring the fine-structure constant α and for testing QED in this simple two-electron system. Presented here is a 0.9-kHz measurement of the 29.6-GHz 2^3P_1-to-2^3P_0 interval. When combined with existing 1-kHz theoretical calculations for this interval [3–5], the present measurement leads to a 23 parts per 10^9 (ppb) determination of the fine-structure constant. With more precise calculations expected soon [5,6], the measurement presented here will lead to a 15-ppb determination of α, making it the second-most-precise determination of α. The most-precise determination of α (3.8 ppb) is obtained from comparison of experiment [7] and QED theory [8] for the anomalous magnetic moment (g-2) of the electron. Combining g-2 experiment [7] and g-2 theory [8] with a determination of α from sources other than g-2 provides the most-precise test of QED in any system. Thus, the current measurement can serve to test QED theory in this two-electron system; or, if the two-electron QED calculations are assumed to be correct, the current measurement can determine α and this determination of α could be used for the comparison of theory and experiment for g-2.

Figure 1 shows a schematic of the experiment. An intense thermal beam of 2^3S_1 metastable He atoms is created in a dc discharge source [9]. It enters a region with a small vertical dc magnetic field H_{0z}, which lifts the degeneracy of m substates. The metastable atoms are optically pumped into the $2^3S_1 m = +1$ state using a circularly polarized (σ^+) 1.08-μm diode laser (A in Fig. 1). To empty any residual $2^3S_1 m = 0$ population, a second diode laser (B in Fig. 1), this one linearly polarized in the z direction, drives $2^3S_1 m = 0$ atoms up to the $2^3P_0 m = 0$ state.

The $2^3S_1 m = +1$ population is driven up to the $2^3P_1 m = 0$ state using a third 1.08-μm laser (C in Fig. 1) which is σ^- and focused using a cylindrical lens to 25 μm at the atomic beam. 170 μm after passing through this laser beam (85 ns at the 2 km/s average speed of the atoms), before many of the $2^3P_1 m = 0$ atoms spontaneously decay, the atoms enter a resonant microwave cavity comprised of a 1.44-cm section of 0.711 × 0.356 cm rectangular waveguide between two inductive, copper irises (D in Fig. 1). Here, the $2^3P_1 m = 0$-to-$2^3P_0 m = 0$ magnetic-dipole transition is driven by a 29.6-GHz vertical microwave magnetic field $H_{1z}\cos(\omega t + \phi)$. One-third of the resulting $2^3P_0 m = 0$ atoms decay into the previously emptied $2^3S_1 m = 0$ state. Because of a selection rule, $2^3P_1 m = 0$ atoms are forbidden from decaying into the $2^3S_1 m = 0$ state, and thus any repopulation of the $2^3S_1 m = 0$ state is a direct indication that the 29.6-GHz transition has been driven. To detect these $2^3S_1 m = 0$ atoms, they are excited up to the 2^3P_0 state using a final laser (E in Fig. 1), linearly polarized in the z direction. The resulting 1.08-μm fluorescence is focused onto a LN_2-cooled InGaAs photodiode. The frequencies of all lasers are locked to saturated-absorption signals in rf-excited He cells.

The atoms pass into and out of the microwave cavity (D in Fig. 1) via 1.8-mm holes (in the 0.711-cm sides of the

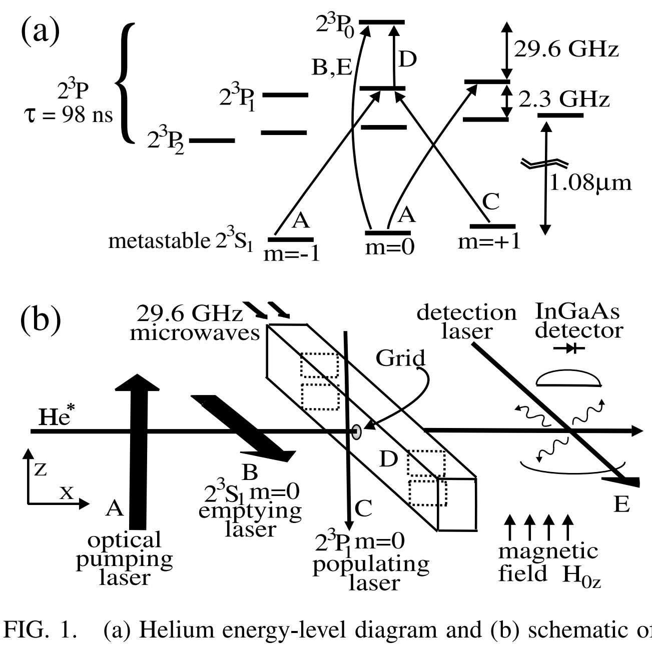

FIG. 1. (a) Helium energy-level diagram and (b) schematic of the experimental setup. Details are given in the text.

waveguide) covered by thin copper grids. Three different grids (7.5, 19, and 53 μm square holes) are attached using two different silver paints to cavities (Q factors from 10 to 55) constructed from four distinct waveguide sections and nine distinct sets of irises (thickness of 300 to 450 μm, slit height of 2.44 to 3.05 mm) in many separate data runs to test for possible systematic effects.

The microwave frequency is referenced to a Cs clock (via a Global Positioning System receiver) and the microwaves are 100% square-wave amplitude modulated, with a lock-in amplifier extracting the photodiode signal synchronous with this modulation. This signal is averaged for typically 10 s at each of 32 microwave frequencies near the atomic resonance. More than 5000 such scans are taken while varying a large variety of experimental parameters during several months of around-the-clock data collection. An average of data taken with typical experimental parameters is shown in Fig. 2. The expected [10] line shape for the resonance is Lorentzian:

$$\frac{\frac{2}{3}(\frac{\mu_B H_{1z}}{h})^2}{(f - f_0)^2 + (\frac{\Gamma}{2})^2 + \frac{2}{3}(\frac{\mu_B H_{1z}}{h})^2}, \qquad (1)$$

where $\frac{2}{3}(\frac{\mu_B H_{1z}}{h})^2$ is the square of the magnetic-dipole matrix element for the transition and $\Gamma = 3.252$ MHz [11] is the natural linewidth. Fits of the data yield power-broadened linewidths of 3.44 to 4.12 MHz, from which we deduce values H_{1z} of 0.49 to 1.11 G, which for each case agree with the field obtained using the Q factor determined from the cavity geometry and the 1 W power input into the cavity from the microwave amplifier.

H_{1z} depends on the difference between the applied microwave frequency f and the center frequency of the cavity resonance. By trimming the cavity length, the cavity resonance is tuned so that its center is very near the atomic resonance, and thus the variation of H_{1z} is small over the relatively narrow range of frequencies f used in the measurement. This small variation is well approximated by $H_{1z}^2 = H_1^2[1 + b(f - f_0) + c(f - f_0)^2]$, where f_0 is the center of the *atomic* resonance. The power as a function of frequency exiting the cavity is measured by coupling -20 dB of the power into a thermistor mount microwave power meter. Precision waveguide isolators and terminators are used to minimize microwave reflections which could lead to interferences and further variations of H_{1z} with frequency. From these measurements, c is deduced (values of 0.003 to 0.013%/MHz^2 for the various cavities), but, because b leads directly to a shift in the resonant line center, it must be known more accurately.

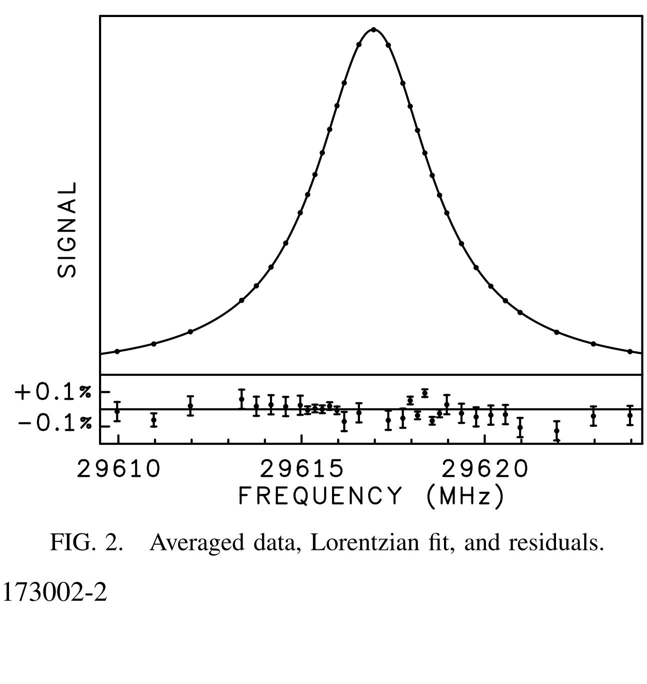

FIG. 2. Averaged data, Lorentzian fit, and residuals.

A direct measurement of b is obtained by tuning laser C of Fig. 1 to the 2^3S_1-to-2^3P_0 transition and reorienting the dc magnetic field into the direction of the atomic beam, thus allowing H_{1z} to drive the $2^3P_0 m = 0$-to-$2^3P_1 m = \pm 1$ transitions. By tuning the dc H field to 6, 9, and 12 G, the center frequency of the $m = \pm 1$ resonances are shifted by ± 12, ± 18, and ± 24 MHz. The ratio of the heights of the $m = +1$ and $m = -1$ resonances divided by the separation in frequency between the two resonances is a direct measure of b. Since the magnetic-dipole matrix elements for the $2^3P_0 m = 0$-to-$2^3P_1 m = \pm 1$ transitions and the $2^3P_1 m = \pm 1$-to-$2^3S_1 m = 0$ branching ratios vary [10] slightly with the applied dc magnetic field, a small correction must be applied to the measured ratios. Using this method, b is determined to an accuracy of $\sim$0.04%/MHz and varies from -0.3 to $+0.3$%/MHz for the various cavities used, with $|b|$ less than 0.1%/MHz for most cavities. In a previous measurement [12], the accuracy of this method for determining b was directly verified (at the 0.02%/MHz level) by comparing to precision calorimeter measurements.

To extract the line center, the observed resonances are fit to the line shape of Eq. (1). Table I lists (in column 2) the average centers obtained from these least-squares fits of data taken with the experimental parameters listed in column 1. The net statistical uncertainty of all data taken in the experiment is 100 Hz. The final uncertainty in the measurement is entirely dominated by systematic effects. The excellent signal-to-noise ratio in this measurement is used to test extensively these systematic effects.

To examine the effect of the variations b and c of H_{1z}, the data are refit to Eq. (1), this time including b and c (fixed at their measured values). Such a fit is shown in Fig. 2. The residuals from the fit are also shown and are small (<0.05% rms), showing that the data are consistent with this line shape. Column 3 of Table I lists the shifts of the line centers as obtained from these fits. The excellent agreement between rows 1, 2, and 3 of the Table, for which corrections of 7.2, -0.9, and -5.7 kHz are applied, directly confirms the corrections of column 3. The uncertainties in this column are primarily due to the uncertainties in the determinations of b.

The largest systematic shift is the small 0.198 kHz/G^2 quadratic Zeeman shift [1,13] of the $2^3P_1 m = 0$-to-$2^3P_0 m = 0$ interval. The small magnetic fields applied in this experiment are measured to a precision of 2% using a Hall-effect gaussmeter. The resulting Zeeman

TABLE I. Summary of systematic effects and measured centers. All values are in kHz, with 1 standard deviation uncertainties in the last digits in parentheses.

Experimental parameter	Fit center	Power slope	Zeeman shift	Laser C position	Light shift	Doppler shift	Grid effects	Total
Power slope $b \gg 0$	29 616 942.8(6)	7.2(14)	1.5(1)	0.0(7)	−0.1(1)	0.0(2)	0.0(6)	29 616 951.4(18)
Power slope $b \approx 0$	29 616 949.9(4)	−0.9(4)	1.8(2)	0.0(5)	−0.1(1)	0.0(2)	0.0(4)	29 616 950.6(9)
Power slope $b \ll 0$	29 616 956.1(6)	−5.7(10)	1.7(2)	0.0(4)	−0.1(1)	0.0(3)	0.0(5)	29 616 952.0(14)
dc field $H_{0z} = 2.9$ G	29 616 950.8(4)	−1.5(4)	1.7(2)	0.0(5)	−0.1(1)	0.0(2)	0.0(4)	29 616 951.0(9)
dc field $H_{0z} = 5.8$ G	29 616 946.4(5)	−1.7(5)	6.6(4)	0.0(5)	−0.1(1)	0.0(2)	0.0(4)	29 616 951.1(10)
Final measured result	29 616 950.4(3)	−1.6(4)	2.2(2)	0.0(5)	−0.1(1)	0.0(2)	0.0(4)	**29 616 950.9(9)**

shift is listed in column 4. Data are taken at dc fields of $H_{0z} = 2.9$ and 5.8 G, and the consistency of the centers obtained at these two fields (rows 4 and 5 of Table I) is a direct confirmation of the Zeeman corrections.

In previous measurements [9,12] a very small fraction of the microwave power was found to radiate through the grid, and, since the radiated field was out of phase with the main microwave field, the line shape was distorted and the line center shifted due to a separated-oscillatory-field effect. The size of the shift was proportional to the separation between laser C of Fig. 1 and the grid. In the present experiment, the line centers at different separations (170 to 390 μm) are consistent. To test for the possible presence of this effect at even smaller separations, some cavities are constructed out of a modified waveguide in which the side near laser C is curved to allow the waist of the laser beam closer to the grid. The centers obtained with this type of cavity are consistent with those obtained with cavities constructed of standard rectangular waveguides. The uncertainties in column 5 are the maximum shifts that could be present given the consistency of the observed centers at different separations.

Light shifts could result if laser power is present at the location of the microwave excitation. The grid acts to separate the microwave and laser fields. To test for light shifts, some data are taken with the 1-mW power of laser C increased to 10 mW. The 10-mW data are shifted by 1.06 ± 0.52 kHz from data at 1 mW, indicating a shift of 0.12 ± 0.06 kHz/mW as shown in column 6.

The Doppler shift is small since the microwave cavity is oriented perpendicular (always within 25 mrad) to the atomic beam and the powers traveling in the two directions in the cavity are approximately equal. The typical vacuum pressure in the experiment is 2×10^{-6} Torr. Some data are taken at 7 times higher pressure and, as expected, no shift of the line center is seen. The power shift (including the Bloch-Siegert shift) caused by the microwave magnetic field is calculated to be <0.01 kHz.

The microwave fields in the cavity are slightly distorted by the holes in the Cu grid over the entrance hole. The size of this distortion and possible shifts of the atomic line center depend on the size of the grid holes. The centers obtained with the three different grids are very consistent. This consistency for 7.5 to 53-μm grid-hole sizes restricts possible extrapolations to zero grid-hole size to <0.04 kHz per μm of hole size. The grid is displaced ~ 10 μm from the inner surface of the waveguide. This displacement is measured to an accuracy of 2 μm by measuring the capacitive pickup of a probe which is scanned over its surface. The possible effect of the distortion of microwave field due to this grid displacement is studied by varying the displacement from 0 to 250 μm. The observed centers are consistent with no shift and limit possible shifts to <0.03 kHz per μm of displacement. The uncertainties in column 8 include the possible effects due to grid-hole size and grid displacement.

Line centers obtained with two different paints used to attach the grids ($29\,616\,950.7 \pm 1.0$ and $29\,616\,951.3 \pm 1.0$ kHz), with positive and negative dc field H_{0z} ($29\,616\,951.1 \pm 0.9$ and $29\,616\,951.0 \pm 0.9$ kHz), with σ^+ and σ^- polarization of laser C ($29\,616\,951.2 \pm 0.9$ and $29\,616\,950.8 \pm 0.9$ kHz), with gold-plated and copper cavities ($29\,616\,949.5 \pm 1.9$ and $29\,616\,951.2 \pm 0.9$ kHz), and with low and high Q cavities ($29\,616\,950.9 \pm 0.9$ and $29\,616\,951.6 \pm 1.6$ kHz) show excellent consistency. The final measured value for the 2^3P_1-to-2^3P_0 interval is $29\,616\,950.9 \pm 0.9$ kHz.

This is the most precise measurement of 2^3P fine structure (see Table II). It shows good agreement with the next-most-precise measurement of Minardi *et al.* [14] (who studies 2^3S-to-2^3P laser transitions to measure the interval) and with our previous measurement [9]. Table II also shows the measurements of Shiner *et al.* [15] and of Wen

TABLE II. Previous measurements and theory of the 2^3P intervals. Values are in kHz with 1 standard deviation uncertainties in the last digits in parentheses.

	2^3P_1-to-2^3P_0	2^3P_1-to-2^3P_2
This work	29 616 950.9(9)	
Previous measurements		
Inguscio *et al.* [14]	29 616 949.7(2)	2 291 174(15)
Shiner *et al.* [15]	29 616 959(3)	2 291 175.9(10)
Wen and Gabrielse [16]	29 616 936(8)	2 291 198(8)
Hughes *et al.* [1]	29 616 864(36)	2 291 196(5)
Hessels *et al.* [9,12]	29 616 966(13)	2 291 174.0(14)
Theory		
Pachucki and Sapirstein [4,5]	29 616 949.6(10)	2 291 173.6(11)
Zhang and Drake [3]	29 616 974(20)	2 291 180(20)

TABLE III. Determinations of the fine-structure constant from compilation in Ref. [18] with 1 standard deviation uncertainties in the last digits in parentheses. In square brackets the precision in parts per 10^9 is given, along with the number of standard deviations that the determination differs from the g-2 determination.

Method	$1/\alpha$	
Electron g-2	137.035 999 6(5)	[3.8 ppb]
Present He 2^3P	137.035 986 4(31)	[23 ppb; -4.2σ]
Quantum-Hall effect	137.036 003 0(27)	[20 ppb; $+1.3\sigma$]
Neutron de Broglie λ	137.036 008 4(33)	[24 ppb; $+2.7\sigma$]
Josephson effect	137.035 987 1(43)	[32 ppb; -2.9σ]
Muonium hyperfine	137.035 995 2(79)	[57 ppb; -0.6σ]

and Gabrielse [16] who both use laser techniques, and earlier microwave measurements of Hughes *et al.* [1].

Theoretical calculations for the interval have been done by Drake [3], who includes all terms up to and including $\alpha^7 mc^2 ln\alpha$ and by Pachucki and Sapirstein [4], who have calculated the most important $\alpha^7 mc^2$ terms. The higher-order terms are similar in size for the 2.3 and 29.6 GHz intervals. Pachucki and Sapirstein give [5] an uncertainty for uncalculated terms for both intervals of less than 1 kHz. Both groups intend to complete the calculation of all order $\alpha^7 mc^2$ terms [5,6], which will yield sub-kHz calculated values for the intervals. One group [6] intends to publish a result to this order very soon. The values shown in the final row of Table II are the lower-order terms calculated by Drake plus the $\alpha^7 mc^2$ terms calculated by Pachucki and Sapirstein. The uncertainties listed for these values include the uncertainty in the calculated terms [4], as well as a 1-kHz uncertainty for uncalculated terms [5]. The accuracy of these calculations is confirmed by their agreement with our earlier [12] 1.4-kHz measurement of the 2.3-GHz 2^3P_1-to-2^3P_2 interval.

The present measurement, when compared to the calculated value for the 29.6-GHz interval gives [17] a new determination for the fine-structure constant: $\alpha = 1/137.035\,986\,4 \pm 15$ ppb (experiment) $\pm$ 17 ppb (theory). This 23-ppb determination of α is compared to other determinations of α recently reviewed by Mohr [18] in Table III. The determinations are not in good agreement. Of particular note is the 4.2 standard deviation (96 ppb) difference between the present determination and the very precise (3.8 ppb) electron g-2 determination. This discrepancy could result from unanticipated contributions to the theory of 2^3P helium fine structure, but this scenario is made somewhat unlikely by the good agreement between theory and experiment for the 2.3-GHz interval. A second possible explanation for the discrepancy is that our determination of α is correct and that the theory needed to predict g-2 (which involves a much higher energy scale than helium fine structure) is not completely understood. This second possibility seems intriguing given the discrepancy between theory and experiment for the recent muon g-2 measurement [19]. The determinations of α obtained from the quantum-Hall effect and the neutron de Broglie wavelength do not, however, support this scenario. Thus, the reason for the 4.2 standard deviation discrepancy is presently unknown. This situation may become clarified as more precise theory for these helium fine-structure intervals becomes available and as precise determinations of α are made in other systems. The next generations of our experiment will use separated oscillatory fields to narrow the microwave resonance, allowing for 200 Hz measurements of the 2^3P intervals and a 3-ppb determination of α.

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