Determination of the Fine Structure Constant Using Helium Fine Structure

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We measure 31 908 131.25(30) kHz for the 2^3P $J = 0$ to 2 fine structure interval in helium. The difference between this and theory to order $m\alpha^7$ (20 Hz numerical uncertainty) implies 0.22(30) kHz for uncalculated terms. The measurement is performed by using atomic beam and electro-optic laser techniques. Various checks include a ^{3}He 2^3S hyperfine measurement. We can obtain an independent value for the fine structure constant α with a 5 ppb experimental uncertainty. However, dominant $m\alpha^8$ terms (potentially 1.2 kHz) limit the overall uncertainty to a less competitive 20 ppb in α.

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The recently published calculations for the 2^3P helium fine structure intervals by Pachucki and Yerokhin is a complete evaluation up to and including terms of order $m\alpha^7$ [1]. This theory is a culmination of significant contributions over many years, e.g., Douglas and Kroll [2], Lewis and Serafino [3], Zhang, Yan, and Drake [4], and Pachucki and Sapirstein [5], among others. With the new calculations, there is now good agreement between helium theory and the most precise experimental measurements of helium fine structure [6–9]. This provides an opportunity to use atomic fine structure as a means to determine a competitive value for α. Not since the 1964 paper by Schwartz [10] has this been feasible, when he originally suggested using helium fine structure, as opposed to hydrogen, to determine α. Shortly thereafter, the Josephson effect superseded atomic fine structure determinations [11]. Along with further improvements in theory, new measurements of 2^3P fine structure intervals in helium can either test the quantum electrodynamics of this simplest multielectron atom or be used to determine α. We report a measurement of the large 32 GHz $J = 0$ to $J = 2$ (J02) fine structure interval in helium with 10 ppb precision, which yields an experimental precision for α to 5 ppb. Now corresponding improvements in theory are required. See Fig. 1 for the intervals and notation used.

The precise measurement of helium fine structure intervals has been the goal of several groups employing a variety of experimental techniques. These include a direct microwave measurement with an atomic beam [6], laser absorption spectroscopy in a gas discharge [7], and a laser fluorescence technique with an atomic beam [8]. Our electro-optic laser technique uses modulated sidebands of a 1083 nm diode laser to induce transitions in a highly collimated (500 kHz Doppler width) metastable beam of atomic helium. Our initial states are the 2^3S $m_s = +1$ and $m_s = -1$ levels (illustrated in Fig. 1 along with all independent intervals we measure). After transitions, atoms that decay into the 2^3S $m_s = 0$ state are detected. We collect data on all the indicated intervals, usually during the same data run, thereby enabling valuable consistency checks in the process. Additionally, we use this setup and technique to measure the well-known 2^3S metastable hyperfine splitting in ^{3}He.

The optical setup for this experiment is very similar to our previous experiment [9], consisting of a frequency locked 1083 nm distributed-Bragg-reflector diode laser. Short term frequency stability is achieved by using an external optical feedback cavity, while long term stability (less than a few kilohertz over several hours) is derived from an iodine-stabilized HeNe laser by means of a 3 m resonant transfer cavity and locking electronics. A 0–20 GHz traveling wave electro-optic modulator and microwave synthesizer (using a GPS disciplined frequency reference) is used to phase modulate tunable sidebands on the laser. We operate with a modulation index of ~1.84 over the full bandwidth (microwave power ~300 mW). Various combinations of

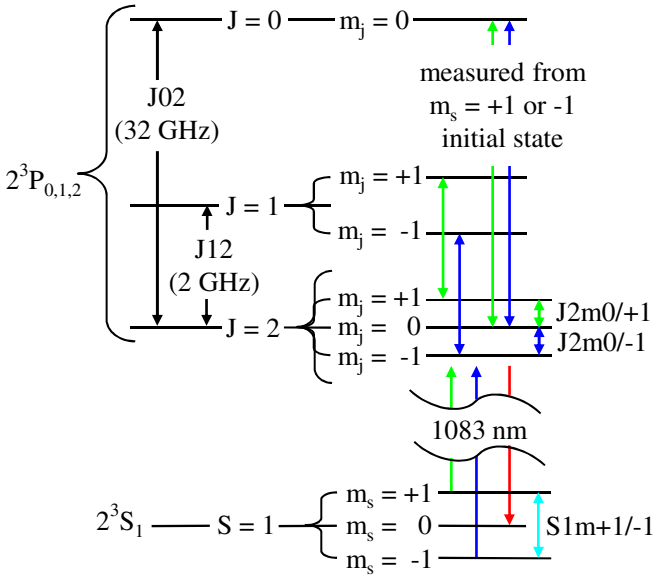

FIG. 1 (color online). Measured fine structure and Zeeman intervals (double arrows) in the $n = 2$ triplet states of helium. Shading (color) indicates the initial state used to measure the interval. $S1m + 1/-1$ uses both initial states.

upper and lower 1st- and 2nd-order sidebands drive the transitions. Our redesigned atomic beam apparatus (Fig. 2) incorporates many improvements, in particular, a metastable source with 3 times the signal, less maintenance, and higher reliability. Previously, we prepared the atoms in the $m_s = 0$ state and detected the atoms in the $m_s = \pm 1$ states. Using instead the ± 1's as initial states and detecting the 0's, we can increase the number of available transitions, thereby adding useful consistency checks. Also, small alignment sensitivities occurred when detecting the deflected ± 1's around a stopwire in our previous setup. We eliminate this sensitivity by having a single undeflected detection state for all transitions. A metastable atomic beam from a 300 K effusive source is created by using electron bombardment and then pumped by a custom-built 1083 nm Yb-doped fiber laser to transfer the 0's into the ± 1 states (99.9%). This also increases our available signal by 50%, yielding 3×10^5 counts per second per initial state. The collimation of the atomic beam is provided by a 0.15×1.5 mm source and detector slits separated by 0.5 m. During the interaction, a mirror may be used to retroreflect the laser for Doppler cancellation. The interaction takes place in a uniform magnet field ranging from 0.2 to 8 mT. The singlet state atoms in the metastable beam are quenched (99.9%) by using a 350 kV/cm electric field [12]. Stern-Gerlach deflecting magnets are used to remove the ± 1 states. In order to reduce the photon background, the atoms eject electrons off of a polished metal surface at grazing incidence, which are then detected as pulses in a channel-electron multiplier.

A typical line shape for one of the transitions used to measure the J02 interval is shown in Fig. 3. The fit is a saturated Lorentzian distribution with various broadening mechanisms incorporated with their associated parameters, i.e., Doppler broadening due to beam collimation and velocity distribution, as well as Gaussian broadening due to finite interaction time. The data for the fit were collected for about 1 h to minimize laser carrier drifts and at a typical low laser intensity (2 μW and $\omega_0 = 2.4$ mm) to minimize saturation effects. The statistical uncertainty in the line center is determined to better than 200 Hz. All error bars are 1 standard deviation and obtained from only square root of N counting noise. Determining the line centers in this way is an inefficient way to obtain frequency intervals between transitions since drifts, for instance, from Doppler alignment and small magnetic field changes, are not averaged over quickly. Also, these fits use parameters that are not important to determining the line center. As an alternative, our normal data runs are performed by sampling one pair of frequencies on either side of the transition. The usual step size from the center is 0.8 MHz (the transition HWHM) to maximize the slopes and achieve the best statistics for determining the line centers. The frequency synthesizer for the electro-optic modulator steps through each of the frequencies for all the selected transitions in a forward and reverse fashion so as to average out any carrier drifts. When analyzing the data, the transition centers are calculated and differences in the modulator frequency are taken to determine the intervals. Line-shape-related effects that could shift the transition intervals can be evaluated by varying the step size.

The uncertainties of important known systematic effects are evaluated for the J02 interval as follows. Shifts caused by collecting data at high laser intensities (Fig. 4) are corrected by extrapolating to zero intensity. The extrapolations are shown to be linear up to very high intensity where saturation effects are large. The shifts for the retroreflected laser are significantly larger than the nonreflected laser due to laser cooling effects. Data are typically collected at intensities where the final extrapolation is much less than 1 kHz. Magnetic field corrections for the well-known Zeeman level shifts [13] are tested up to 8 mT [Fig. 5(a)]. Because of transition overlaps, results obtained at 0.2 mT show shifts larger than our quoted uncertainty. Relative symmetry of the transitions used to measure the J02 interval is tested by varying the frequency step size [Fig. 5(b)]. Although consistent with no step size dependence, a linear fit to the data shifts the extrapolated result 200 Hz. Alignment sensitivity in the data is tested by

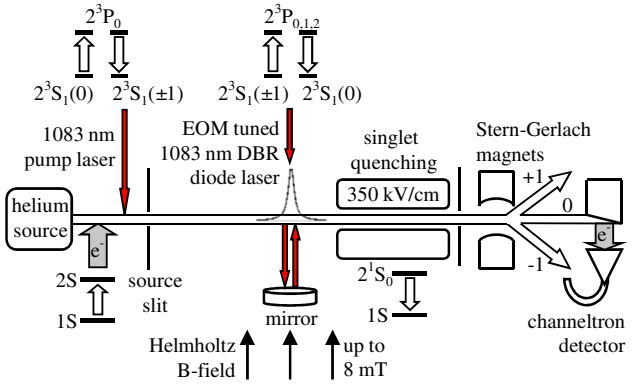

FIG. 2 (color online). Schematic of the atomic beam apparatus.

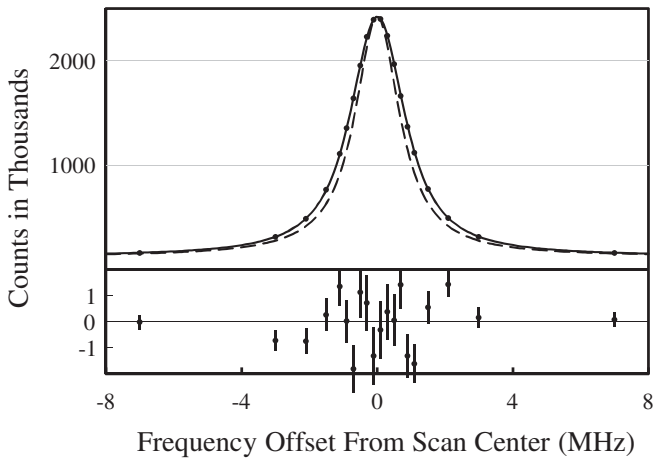

FIG. 3. Data collected on the transition from 2^3S_1 ($m_s = +1$) to 2^3P_2 ($m_j = 0$). Also shown is a simple Lorentzian with the natural 1.6 MHz linewidth (dashed line) and a saturated and Doppler-broadened Lorentzian fit to the data (solid line) with residuals below.

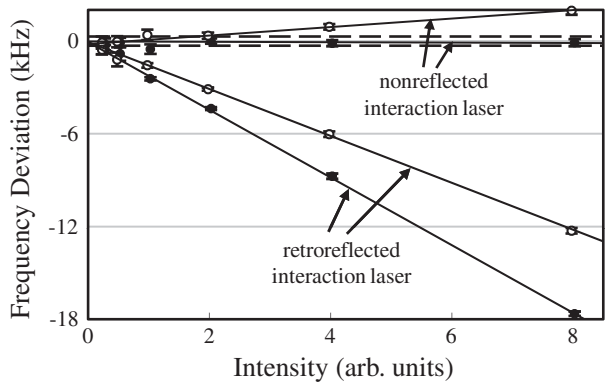

FIG. 4. Power extrapolated values for the J02 interval measured from the initial states $m_s = +1$ (filled circles) and $m_s = -1$ (empty circles).

misaligning the interaction laser to induce large Doppler shifts [Fig. 5(c)] with negligible effect. Searching for other potential systematics has been conducted by varying numerous other experimental parameters, e.g., polarization, B-field orientation and homogeneity, pressure, atomic beam alignment, singlet quenching electric field, carrier position, modulation power, etc. No systematic effects on the J02 interval are observed with these tests. The uncertainty budget for the J02 interval is shown in Table I.

Additional consistency checks (Fig. 6) have been performed by using a number of helium transitions (see Fig. 1 for notation). The fine structure intervals for both the J02 and J12 are very consistent when measured from either ± 1 initial state. However, when comparing the frequency interval between the $m_s = \pm 1$ initial states ($S1m + 1/-1$) using a common upper level, a systematic effect of several kilohertz is observed. This is due to the ± 1 initial states not

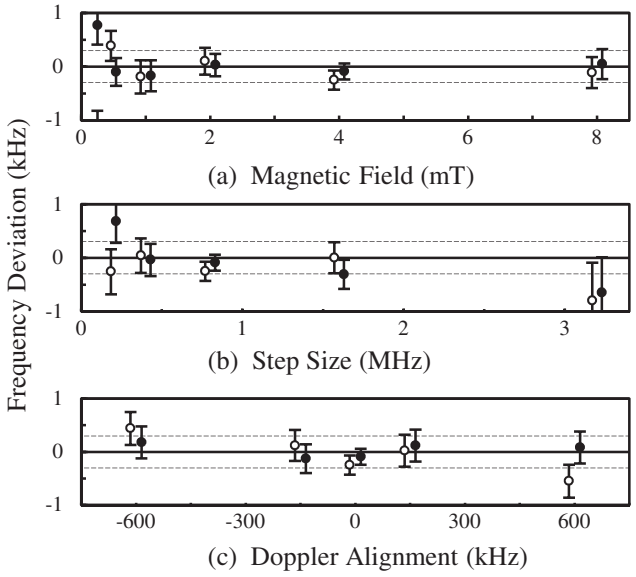

FIG. 5. Systematic checks for the J02 interval measured from the initial states $m_s = +1$ (filled circles) and $m_s = -1$ (empty circles).

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

Source	J02 fine structure interval
Laser power	<0.1
1st-order Doppler	<0.1
B field	<0.1
Line shape	0.2
Other	0.1
Total (quadrature sum)	0.3

having the same average direction causing a differential Doppler shift. Retroreflecting the laser cancels this shift. Another systematic effect due to laser polarization uniformity is observed when comparing the Zeeman levels in the 2^3P $J = 2$ state. The $m_j = 0$ and $m_j = \pm 1$ levels require different laser polarizations to drive the transitions. However, stress-induced birefringence on the apparatus laser window causes the average direction of the orthogonal polarization states sampled by the atoms to be different. This effect can be averaged out by rotating the magnetic field 90° and thereby rotating the atomic quantization axis so that laser polarization effects are switched. While the systematics observed in these two consistency checks are understood and can be corrected for, it is important to note that these effects do not (nor would they be expected to) alter the J02 fine structure interval.

A calibration to our overall experimental technique is performed by measuring the 6.7 GHz hyperfine interval in the metastable 2^3S state of ^{3}He. A direct microwave measurement gives 6 739 701.177(16) kHz as reported by Rosner and Pipkin [14]. Using our optical technique, we measure the hyperfine interval with respect to a common unstable upper level in the 2^3P state ($J = 0$, $F = 1/2$) to be 6 739 701.287(80) kHz (uncertainty from counting statistics only). The 110 Hz difference is 1.3 standard deviations and well within the 300 Hz systematic uncertainties used for the J02 interval.

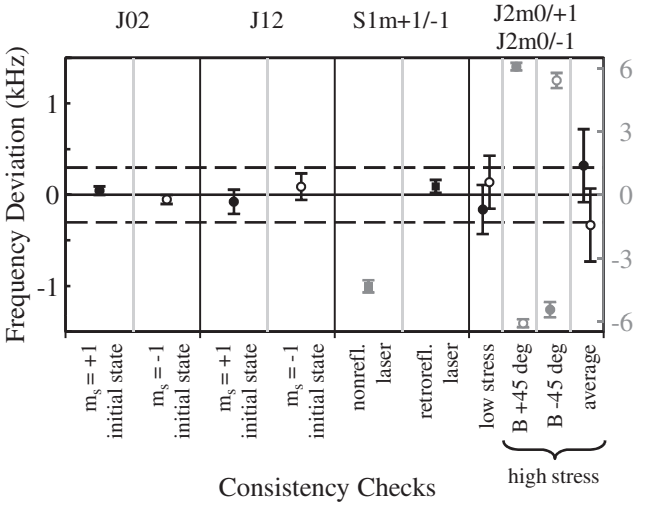

FIG. 6. Consistency checks (right-hand scale for shaded data points).

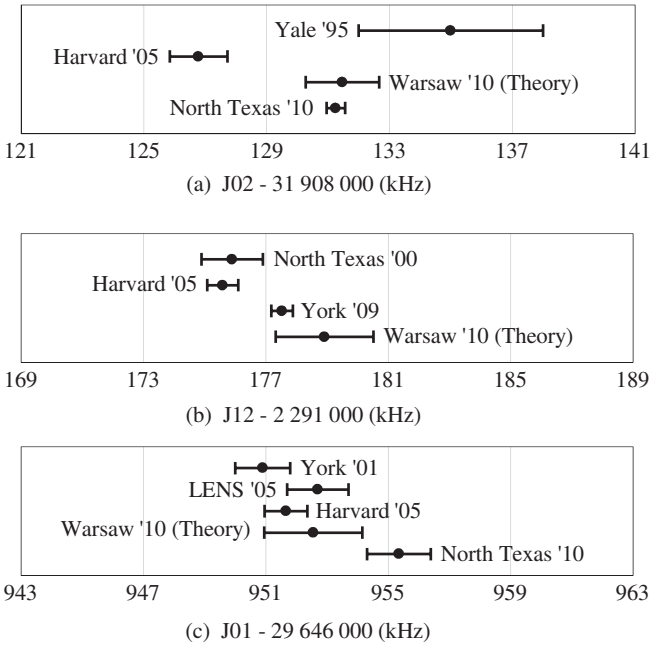

FIG. 7. Comparison of precision results for the three fine structure intervals in the 2^3P state of helium.

Our new value for the J02 fine structure interval in the 2^3P state of helium is 31 908 131.25(30) kHz. A comparison to other results is given in Fig. 7(a). The Yale value of Shiner and Dixson [15] differs from this value by $+3.75$ kHz (1.2σ), while the Harvard result [7] differs by -4.5 kHz (4.5σ). The recently reported theoretical result by Pachucki and Yerokhin [1] (adjusted to incorporate the new more accurate value of α from the electron g factor [16]) differs by $+0.22$ kHz (0.2σ). With respect to the other intervals, our previously reported value [9] for the J12 interval [Fig. 7(b)] is subtracted from our new value for the J02 interval to yield an updated value for the J01 interval. This is shown in Fig. 7(c) for comparison to the York [17] and LENS [8] groups, among others.

Given our result, and the negligible 20 Hz numerical uncertainty in the calculated terms [1], we can conclude that the size of uncalculated terms of order $m\alpha^8$ and beyond for J02 is $-0.22(30)$ kHz. This is smaller than the rough estimate of 1.2 kHz [18] for the dominant $m\alpha^8$ term but close to the estimate of the leading $m\alpha^8 \ln\alpha$ terms [5]. Also, due to singlet-triplet mixing terms in the $J = 1$ level, the size of uncalculated terms for the other intervals may not be as small [1]. To determine an independent value for the fine structure constant, we use the potential 1.2 kHz contribution for an estimate of the size of uncalculated terms. With this, $\alpha^{-1} = 137.035\,999\,55(64)(4)(260)$ is obtained, with the experimental uncertainty and the uncertainties due to calculated and uncalculated terms given. This yields a combined uncertainty of 20 ppb. In Fig. 8, we compare this value with other determinations. The better than 5 ppb experimental precision is similar to that obtained from recoil measurements in Cs [19] and Rb [20], which provide for the best alternative values of α outside

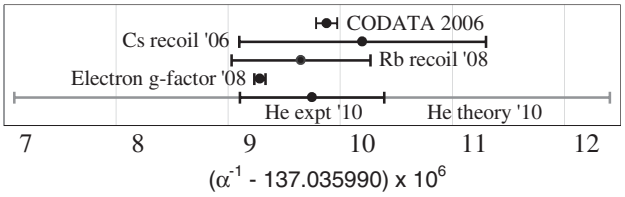

FIG. 8. Comparison of precision determinations of α. Error bars for both experiment and theory are shown for He.

the electron g factor [16]. Further improvements to helium theory are thus desirable to not only provide more stringent tests on this fundamental system, but also to provide a more competitive alternative determination of α. Other measurements in He and He-like ions could provide independent tests of this theory.

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