Absolute-frequency measurements of the D_2 line and fine-structure interval in ^{39}K

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We report a value for the D_2-line frequency of ^{39}K with 0.28 ppb uncertainty. The frequency is measured using an evacuated ring-cavity resonator whose length is calibrated against a reference laser. The D_2 line presents a problem in identifying the line center because the closely spaced energy levels of the excited state are not resolved. We use computer modeling of the measured spectrum to extract the line center and obtain a value of 391 015 578.040(110) MHz. In conjunction with our previous measurement of the D_1 line, we determine the fine-structure interval in the $4P$ state to be 1 729 997.132(120) MHz. The results represent significant improvement over previous values.

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I. INTRODUCTION

Precise measurements of atomic energy levels continue to play an important role in the development of physics. The energy levels of alkali atoms are particularly important because these atoms can be laser-cooled to ultralow temperatures for subsequent use in precision spectroscopy experiments. For example, precise measurements of the D_1 line in Cs [1], Rb, or K [2], in conjunction with photon-recoil shift measurements in an atom interferometer [3], could yield an independent value of the fine-structure constant α. In addition, a precise value of the frequency of the D_2 line in Cs [4] is required for atom-interferometric measurements of the local gravitational acceleration [5].

We have recently developed a technique for measuring the absolute frequencies of optical transitions with sub-MHz precision [6,7]. The frequency is measured using a ring-cavity resonator whose length is calibrated against a reference laser locked to the D_2 line of ^{87}Rb. The frequency of the reference laser is known to an accuracy of 10 kHz [8]. The chief advantage of the technique is that we can use a (narrow) range of reference frequencies, which checks for certain classes of systematic errors in difference-frequency measurements. We have already used this technique to measure the D_1 lines in the alkali atoms ^{39}K, ^{85}Rb, and ^{87}Rb with 0.13 ppb uncertainty [2], to facilitate measurements of α.

In this paper, we apply this technique to measure the D_2 line of ^{39}K with an uncertainty of 0.28 ppb. This represents an improvement of more than two orders of magnitude over tabulated values [9]. Furthermore, in combination with our previous measurement of the D_1 line, we obtain the fine-structure interval in the $4P$ state of ^{39}K with very high precision. Knowledge of fine-structure intervals is useful in the study of atomic collisions and relativistic calculations of atomic energy levels. Indeed, a combination of improved methods of calculation and increasingly precise measurements of atomic fine and hyperfine structure (e.g., in Li [10]) can lead to a precise value of α [11].

The D_2 line in K presents a problem in determining the line center because transitions to individual hyperfine levels of the excited state are not resolved in conventional saturated-absorption spectroscopy. This is because the various hyperfine levels in the $4P_{3/2}$ state lie within 30 MHz of each other [12], while the natural linewidth is 6 MHz. We have recently demonstrated a technique to resolve such closely spaced transitions [13], however in this work we use computer simulation of the measured spectrum to extract the line center with an accuracy of $\sim$100 kHz.

II. EXPERIMENTAL DETAILS

The experimental schematic is shown in Fig. 1 and has been described extensively in a previous publication [2]. The four-mirror ring cavity is placed inside a vacuum chamber and evacuated to a pressure of $\sim 10^{-2}$ torr to eliminate frequency shifts due to dispersion of air. Lasers 1 and 2 are standard external-cavity diode lasers stabilized using optical feedback from a piezomounted grating [14]. The reference laser (Laser1) is locked to the D_2 line of ^{87}Rb using saturated-absorption spectroscopy in a vapor cell, and the cavity is locked to the reference laser. In general, the fre-

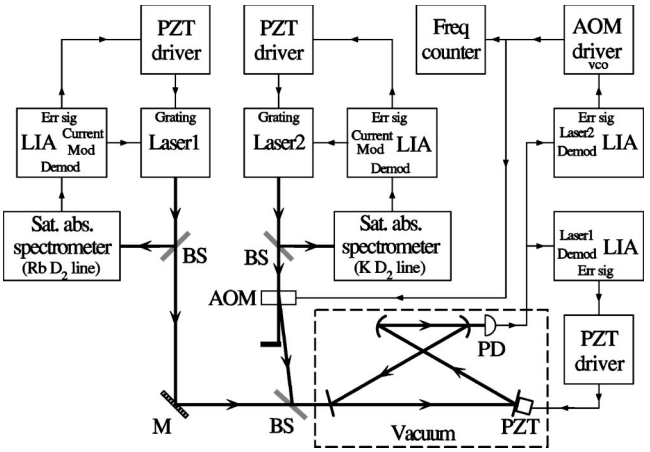

FIG. 1. Schematic of the experiment. PZT, piezoelectric transducer; AOM, acousto-optic modulator; vco, voltage-controlled oscillator; LIA, lock-in amplifier; Sat. abs., saturated absorption; BS, beam splitter; PD, photodiode; M, mirror.

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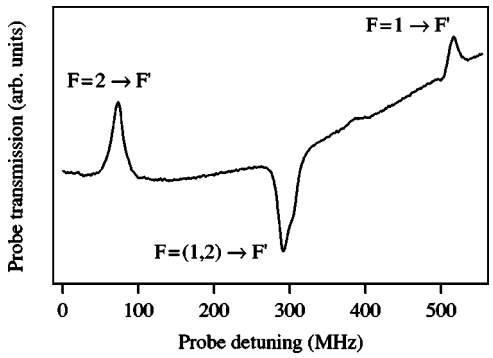

FIG. 2. Typical saturated-absorption spectrum of the D_2 line in ^{39}K showing all three sets of transitions. The inverted peak in the center is a ground crossover resonance.

quency of the laser to be measured (Laser2) will be offset from the nearest cavity resonance. This offset is compensated by using an acousto-optic modulator (AOM) between Laser2 and the cavity. The AOM is locked to this frequency difference and its frequency is read using a counter. The exact mode number of the cavity is determined by measuring the cavity's free-spectral range using different lock points of the reference laser, as described in Ref. [6]. The mode number and the AOM offset together yield the frequency of Laser2. A second AOM kept between the reference laser and its saturated-absorption spectrometer allows us to vary the reference frequency continuously so that the AOM offset measured for Laser2 is always close to a given value. This eliminates potential systematic errors due to changes in the direction of the beam entering the cavity.

The error signals needed for locking the diode lasers are produced by modulating the injection current at a frequency of 20–50 kHz. The error signal is obtained from the saturated-absorption signal by phase-sensitive detection at the third harmonic of the modulation frequency [15]. This produces narrow dispersive signals that are free from effects due to the underlying Doppler profile or intensity fluctuations. The error signal for locking the cavity is only a first-derivative signal since the cavity modes appear against a flat background.

The spectroscopy on ^{39}K is performed in an ultrahigh vacuum glass cell maintained at a pressure below 10^{-8} torr by an ion pump. K vapor is produced by heating a getter source [16] with a current of 2.6 A. The ultrahigh vacuum environment is necessary to minimize linewidth broadening arising as a result of background collisions. The getter source also gives us control over the amount of K vapor in the cell, which we optimized to obtain the narrowest linewidth.

Figure 2 shows a typical saturated-absorption spectrum of the D_2 line covering the two ground-hyperfine levels. Each peak is actually a convolution of six peaks. However, the individual hyperfine transitions are not resolved because the different hyperfine levels of the excited state lie within 30 MHz of each other. To determine the line center, we therefore performed computer simulations of the spectrum. We first fixed the locations of the six peaks (with respect to the line center) according to the known hyperfine shifts [12]. We then set the peak amplitudes to correspond to those obtained in saturated-absorption spectroscopy, under our experimental conditions. This was possible because the D_2 line in ^{39}K has a structure almost identical to the D_2 line in ^{87}Rb, in which the individual peaks are clearly resolved. In particular, the two lines have nearly the same natural linewidth ($\sim$6 MHz) and saturation intensity ($\sim$1.7 mW/cm^2), and identical values of total angular momentum F. Therefore, effects of intensity variation and optical pumping (that determine peak amplitudes) are the same in both atoms. For the simulation, we further assumed that the linewidth of all the transitions is the same. We calculated the spectrum for a given value of the line center and linewidth.

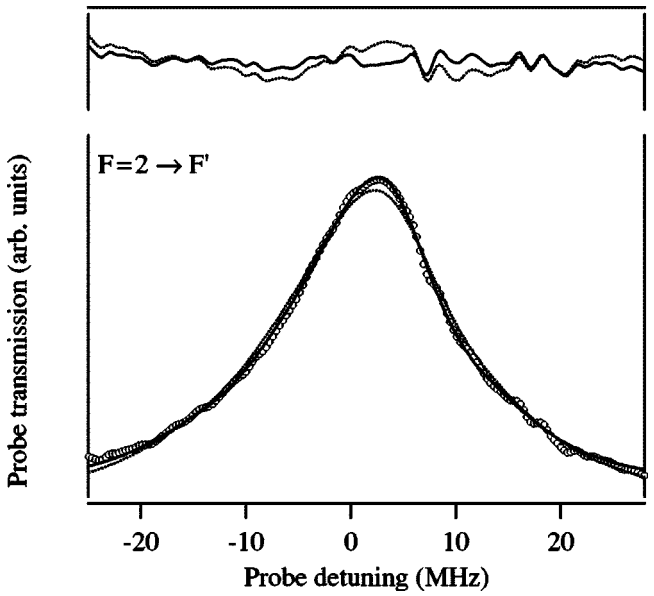

FIG. 3. Measured and calculated spectra for $F=2\rightarrow F'$ transitions. The measured spectrum, shown as open circles, is a convolution of six peaks. The solid curve is the best fit obtained with a linewidth of 12.3 MHz. The dotted curve is the calculated spectrum with a linewidth of 15 MHz. Even with such a small change in linewidth, the curve does not fit the measured spectrum very well, as seen from the residuals shown on top.

Figure 3 shows a close-up of the measured spectrum (open circles) for $F=2\rightarrow F'$ transitions. The solid curve is a best fit to the spectrum, obtained with a linewidth (for each transition) of 12.3 MHz. In order to check that this linewidth is reasonable, we tuned the diode laser to the D_1 line of K (at 770 nm), where the individual hyperfine transitions are clearly resolved. The linewidth obtained for those transitions was 14 MHz, which is close to the fit value for the D_2 line [17]. To check the linewidth further, we changed the linewidth for the calculated spectrum and held it constant during the fitting. The best-fit calculated spectrum for a linewidth of 15 MHz is also shown in Fig. 3. Even with this small change, the line shape deviates from the measured data. Finally, the fitted linewidth is close to the value obtained for individual transitions in the D_2 line in ^{87}Rb, under similar conditions. As mentioned earlier, the D_2 lines in ^{39}K and ^{87}Rb have nearly identical properties, therefore this acts as a further check on our fit procedure.

The fit linewidth of 12.3 MHz, however, is larger than the natural linewidth of 6 MHz. The primary causes for this in-

crease are power broadening due to the pump beam and a small angle between the counterpropagating pump and probe beams. The effect of stray magnetic fields and background collisions is negligible. We have verified this by studying the variation of the linewidth as a function of pump power. With near-perfect alignment of the pump and probe beams (using polarizing beam-splitter cubes), we find that the extrapolated linewidth at zero power is close to the natural linewidth.

In order to account for the effect of optical pumping on the peak center, we studied the variation in the fit by changing the peak amplitudes. Again, we could get an idea about the changes in the relative amplitudes of the peaks by studying these effects in ^{87}Rb. With the best fit to the spectrum in Fig. 3, we found that its maximum lies 2.600(10) MHz above the line center, where the error is the statistical error in the fit. We then varied the relative peak amplitudes to account for optical pumping. The position of the peak relative to the line center changed by less than 110 kHz. We further varied the positions of the hyperfine levels to account for the uncertainty in the knowledge of the hyperfine constants [12]. The effect on the peak position was only about 100 kHz. Taking into account both of these effects, we expect a total systematic uncertainty of less than 150 kHz in determining the line center. Similar modeling for transitions starting from the $F=1$ ground level shows that the maximum in the spectrum lies 12.03(15) MHz below the line center.

III. ERROR ANALYSIS

The errors in our frequency measurement technique have been discussed extensively in earlier publications [2,6,7]. We present here a brief overview for the sake of completeness. There are two classes of potential systematic errors that we consider. The first class of errors comes from systematic shifts in the laser frequencies. For the *reference laser*, changes in the line shape of the peaks due to optical pumping effects are taken care of by carefully adjusting the pump and probe beam intensities in the saturated-absorption spectrometer (to a ratio of about 3). Shift in its lock point due to peak pulling from neighboring transitions, the underlying Doppler profile, or phase shifts in the feedback loop are minimized by third-harmonic detection for the error signal. Collisional shifts in the Rb vapor cell and the effect of stray magnetic fields are negligible. We have earlier shown that the frequency of the reference laser, after accounting for the above effects, is locked to the peak center with an uncertainty of less than 30 kHz [6]. For the laser on the K D_2 line, we expect that it is locked to the peak center with similar uncertainty. However, the larger source of error arises from uncertainty in using our fit to determine the line center. As discussed earlier, this error is about 150 kHz.

The second class of systematic errors is inherent to our technique because we are really comparing the wavelength (and not the frequency) of the two lasers. The most important source of error is dispersion inside the cavity, which is eliminated by using an evacuated cavity. However, there could be wavelength-dependent phase shifts at the dielectric coated mirrors used in the cavity. Such errors can be corrected by repeating the measurement at different cavity lengths. We have shown earlier [2] that this error is negligible when the unknown laser differs from the reference laser by up to 25 nm. In the current work, the wavelength difference was only 13 nm, therefore the measurements were done at a single cavity length of ~178 mm.

TABLE I. Error budget.

Source of error	Reference (kHz)	^{39}K line (kHz)
1. Determination of line center due to optical pumping and light shifts	30	110
2. Knowledge of hyperfine constants	10	100
3. Laser lock to peak center	7	7
4. Differential phase shift at mirrors		35
5. Stray magnetic fields	20	20
6. Collisional shifts	10	10
7. Misalignment into cavity	5	5

An important source of error in wavemeters based on a scanning Michelson interferometer, as described in our earlier work [14], is the geometric alignment of the reference and unknown beams into the interferometer. Any misalignment angle between the beams would change the measured wavelength. By contrast, the cavity technique used in the current work is completely insensitive to geometric factors. The geometric alignment of the beam determines (very sensitively) the degree of mode matching into the cavity, but the cavity resonance condition depends only on the wavelength. Furthermore, we check the mode structure to verify that no higher-order cavity modes are excited [18], which could cause peak pulling of the fundamental mode.

The different sources of error and their sizes are summarized in Table I.

IV. RESULTS

The results of our measurements are listed in Table II. Each value is an average of 50–100 individual measurements. The statistical error in each set is only ~7 kHz. The quoted error includes the total systematic error from Table I, and is clearly dominated by the error due to uncertainty in the fit. The statistical error and the error due to the 10-kHz uncertainty of the reference frequency do not contribute to the total error. To check for long-term variations, we repeated

TABLE II. Measured frequencies for the center of different transitions in the D_2 line of ^{39}K. The frequencies were measured with two lock points of the reference laser: Ref. f_1 denotes the $F=2 \rightarrow F'=(2,3)$ transition and Ref. f_2 denotes the $F=1 \rightarrow F'=(1,2)$ transition.

Measured transition	Frequency (MHz)	
	Ref. f_1	Ref. f_2
$F=2 \rightarrow F'$	391 015 404.938(160)	391 015 404.994(160)
$F=1 \rightarrow F'$	391 015 866.574(160)	391 015 866.495(160)

these measurements over a period of several weeks. In addition, we used two different lock points of the reference laser, namely the $F=2\rightarrow F'=(2,3)$ transition and the $F=1\rightarrow F'=(1,2)$ transition. The frequencies for these transitions differ by 6622.886 MHz. The consistency of our values for the two cases acts as a check on our ability to determine the correct cavity mode number since the cavity free-spectral range is only about 1.7 GHz. This also checks for possible errors due to geometric alignment into the cavity because the direction of the diode-laser beam changes when the reference transition is changed, and this requires realignment of the beam to get good mode matching. Another check on our results is that the measured frequencies for the two transitions should differ by the ground hyperfine splitting in ^{39}K. Our value of 461.569(210) MHz overlaps very well with the accepted value of 461.720 MHz [12].

The values in Table II can be combined to yield the hyperfine-free frequency of the D_2 line in K,

$$4P_{3/2}-4S_{1/2}: \quad 391\,015\,578.040(110)\ \text{MHz}.$$

The slightly smaller error comes from averaging over the $F=1\rightarrow F'$ and $F=2\rightarrow F'$ measurements, which have independent systematic errors. For example, the effect of asymmetric optical pumping into Zeeman sublevels is of opposite sign for the two transitions. The above value is consistent with the value of 391 015 585(30) MHz from the National Institute of Standards and Technology energy-level tables [9], but the accuracy is improved by more than two orders of magnitude. The result can be combined with our earlier measurement of the D_1 line [2] to yield the fine-structure interval in the D line in K,

$$4P_{3/2}-4P_{1/2}: \quad 1\,729\,997.132(120)\ \text{MHz}.$$

This value overlaps at the 1σ level with our earlier measurement of the fine-structure interval using a home-built wavemeter [19], 1 729 993(5) MHz, but again the accuracy is improved considerably.

V. CONCLUSION

In conclusion, we have measured the D_2-line frequency and fine-structure interval in ^{39}K with an uncertainty of about 110 kHz. The measurement is complicated by the fact that the closely spaced hyperfine transitions in the line are not resolved in conventional saturated-absorption spectroscopy. We use computer simulation of the measured spectrum to extract the line center. The frequency is measured using a Rb-stabilized ring-cavity resonator that has general applicability to precise frequency measurement of optical transitions [6]. The technique has already been used to measure the D_1 lines of K and Rb with 0.13 ppb precision [2], which, in combination with atom-interferometric measurement of the photon-recoil shift, will facilitate QED-independent measurements of the fine-structure constant α. Similar precision has been achieved with the frequency-comb technique to measure the D lines of Cs: 0.12 ppb for the D_1 line [1] and 0.31 ppb for the D_2 line [4]. In the future, we plan to apply our technique to measure the D lines and fine-structure interval of other alkali atoms such as Li and Na.

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