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

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Abstract

We report a value for the $D_2$-line frequency of $^{39}\text{K}$ with 0.25 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 modelling of the measured spectrum to extract the line center and obtain a value of 391 015 578.040(75) 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(90) MHz. The results represent significant improvement over previous values.

PACS numbers: 06.30.Ft, 42.62.Eh, 32.10.Fn

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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 ultra-low temperatures for subsequent use in precision spectroscopy experiments. For example, precise measurements of the $D_1$ line in Cs, Rb, or K, in conjunction with photon-recoil shift measurements in an atom interferometer, could yield an independent value of the fine-structure constant $\alpha$. In addition, a precise value of the frequency of the $D_2$ line in Cs is required for atom-interferometric measurements of the local gravitational acceleration.

We have recently developed a technique for measuring the absolute frequencies of optical transitions with sub-MHz precision. 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. 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, to facilitate measurements of $\alpha$. In this paper, we apply this technique to measure the $D_2$ line of $^{39}$K with an uncertainty of 0.25 ppb. This represents an improvement of more than two orders of magnitude over tabulated values. 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) can lead to a precise value of $\alpha$.

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, while the natural linewidth is 6 MHz. We have recently demonstrated a technique to resolve such closely-spaced transitions, 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 piezo-mounted 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 frequency 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.

Fig. 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 6 peaks (with respect to the line center) according to the known hyperfine shifts. We then set the peak amplitudes to correspond to those obtained in saturated-absorption spectroscopy. 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 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 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, close to the fit value for the $D_2$ line. To check the linewidth further, we changed the linewidth for the calculated spectrum and held it constant during the fitting. The best-fit calculated spectra for a linewidth of 15 MHz is also shown in Fig. 3. Even with this small change, the lineshape deviates from the measured data. The fit linewidth of 12.3 MHz, however, is larger than the natural linewidth of 6 MHz. The primary causes for this increase 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.

With the best fit to the spectrum in Fig. 3, we found that its maximum lies 2.60(10) MHz above the line center. Similar modelling for transitions starting from the $F = 1$ ground level shows that the maximum in the spectrum lies 12.03(10) MHz below the line center.

III. ERROR ANALYSIS

The errors in our frequency measurement technique have been discussed extensively in earlier publications. 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 lineshape 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.

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 \( \sim 178 \) mm.

IV. RESULTS

The results of our measurements are listed in Table I. Each value is an average of 50–
100 individual measurements, and the quoted error includes our estimate of the systematic
error. To check for long-term variations, we repeated 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. Another check on our results is that the measured
frequencies for the two transitions should differ by the ground hyperfine splitting in \(^{39}\text{K}\).
Our value of 461.569(210) MHz overlaps very well with the accepted value of 461.720 MHz
[12].

The values in Table I can be combined to yield the hyperfine-free frequency of the \( D_2 \)
line in \(^{39}\text{K}\):

\[
4P_{3/2} - 4S_{1/2} : \quad 391\,015\,578.040(75) \text{ MHz}
\]

This 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 above result can be combined with our earlier measurement of the $D_1$ line \cite{2} to yield the fine-structure interval in the $D$ line in K

$$4P_{3/2} - 4P_{1/2} : 1\,729\,997.132(90)\,\text{MHz}$$

This value overlaps at the $1\sigma$ level with our earlier measurement of the fine-structure interval using a home-built wavemeter \cite{17}: $1\,729\,993\,(5)\,\text{MHz}$, but again the accuracy is improved considerably.

V. CONCLUSION

In conclusion, we have measured the $D_2$-line frequency and fine-structure interval in $^{39}\text{K}$ with uncertainty less than 100 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 \cite{6}. The only other technique of measuring optical frequencies with comparable precision is the frequency-comb method \cite{1}. By comparison, our technique is low-cost and easier to implement. In the future, we plan to measure the $D$ lines and fine-structure interval of other alkali atoms such as Li, Na, and Cs. These measurements could play an important role in QED-independent determinations of the fine-structure constant $\alpha$.

This work was supported by the Board of Research in Nuclear Sciences (DAE), and the Department of Science and Technology, Government of India.

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TABLE I: 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. $f_1$ | Frequency (MHz) Ref. $f_2$ |
|---------------------|-----------------------------|-----------------------------|
| $F = 2 \rightarrow F'$ | 391 015 404.938(150)       | 391 015 404.994(150)       |
| $F = 1 \rightarrow F'$ | 391 015 866.574(150)       | 391 015 866.495(150)       |
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.
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.
FIG. 3: Measured and calculated spectra for $F = 2 \rightarrow F'$ transitions. The measured spectrum, shown as open circles, is a convolution of 6 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.