Precise measurement of hyperfine intervals using avoided crossing of dressed states

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Abstract. – We demonstrate a technique for precisely measuring hyperfine intervals in alkali atoms. The atoms form a three-level Λ system in the presence of a strong control laser and a weak probe laser. The dressed states created by the control laser show significant linewidth reduction. We have developed a technique for Doppler-free spectroscopy that enables the separation between the dressed states to be measured with high accuracy even in room temperature atoms. The states go through an avoided crossing as the detuning of the control laser is changed from positive to negative. By studying the separation as a function of detuning, the center of the level-crossing diagram is determined with high precision, which yields the hyperfine interval. Using room temperature Rb vapor, we obtain a precision of 44 kHz. This is a significant improvement over the current precision of ~1 MHz.

There has been much excitement in recent times in the use of atomic coherences to modify the properties of light beams passing through an atomic vapor. For example, atomic coherences have been used to slow light to low velocities and even to stop and “store” light [1]. In electromagnetically induced transparency (EIT) experiments, an initially absorbing medium becomes transparent to a probe beam when a control laser is applied to an auxiliary transition [2]. The control laser creates atomic coherences that shift the absorption away from the line center. EIT techniques have several practical applications in probe amplification [3], lasing without inversion [4] and suppression of spontaneous emission [5–7]. In many of these experiments, the atoms form a three-level system and the control laser strongly drives two of these levels. As is well known, the strong driving creates dressed states of the system [8]. It is the coherence between the dressed states that is the basis for the phenomena mentioned above. Experimental observations of these phenomena have been facilitated by the advent of low-cost tunable diode lasers which can be used to access transitions in alkali atoms such as Rb and Cs. Alkali atoms have convenient energy levels with strong oscillator strengths which form almost ideal three-level systems.

In this paper, we show that such “coherent control” techniques can be adapted to make precise measurements of hyperfine intervals in alkali atoms. There are two properties of the
dressed states that are important for this measurement. First, the coherence between the dressed states results in linewidth narrowing well below the natural linewidth [9]. Hence it is possible to measure small shifts in the location of the dressed state. Second, the dressed states have opposite symmetry. Therefore, as the detuning of the control laser is changed from positive to negative, the dressed states go through a characteristic avoided crossing. These two features can be combined to determine the exact center of the level-crossing diagram, which yields the hyperfine interval. In our case, we work with room temperature Rb vapor. The linewidth of the hyperfine peaks is about 27 MHz, but the technique allows us to extract the hyperfine interval with a precision of 44 kHz.

To understand our technique, let us first consider the three-level Λ-type system in Rb in some detail. The measurements are done on the $D_2$ line in $^{87}$Rb ($5S_{1/2} \leftrightarrow 5P_{3/2}$ transition). As shown in fig. 1, $^{87}$Rb has two hyperfine levels in the ground state with $F = 1$ and 2. The excited state splits into four hyperfine levels; of these, the $F' = 2$ level couples to both ground levels and can be used to form the Λ system. The control laser drives the $F = 1 \leftrightarrow F' = 2$ transition with Rabi frequency of $\Omega_R$ and detuning from resonance of $\Delta_c$. The weak probe laser measures absorption on the $F = 2 \leftrightarrow F' = 2$ transition at a detuning $\Delta$. The spontaneous decay rate from the excited level is $\Gamma$.

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The absorption of the weak probe in the presence of the control laser has been derived previously [7,10]. As is well known, the strong control laser creates two dressed states due to the ac Stark shift [8]. The probe absorption gets modified due to this and shows peaks at the
location of the two dressed states (Autler-Townes doublet), given by

$$\Delta_\pm = \frac{\Delta_c}{2} \pm \frac{1}{2} \sqrt{\Delta_c^2 + \Omega_R^2}. \tag{1}$$

Here $\Delta_+$ and $\Delta_-$ are the values of the probe detuning where the peaks occur. The corresponding linewidths ($\Gamma_\pm$) of these peaks are different because of the coherence between the two dressed states, and are given by

$$\Gamma_\pm = \frac{\Gamma}{2} \left( 1 \mp \frac{\Delta_c}{\sqrt{\Delta_c^2 + \Omega_R^2}} \right). \tag{2}$$

It is clear from the above expression that, if $\Delta_c = 0$, the two peaks are symmetric and have identical linewidths of $\Gamma/2$. However, for any non-zero detuning, the peaks have asymmetric linewidths. The first peak has larger linewidth while the second peak has smaller linewidth by precisely the same factor, in such a way that the sum of the two linewidths is equal to the unperturbed linewidth, $\Gamma$.

The above analysis shows how the three-level system is useful in many applications. For example, probe absorption at line center ($\Delta = 0$) is strongly suppressed in the presence of a resonant control laser because the dressed states created by the control laser are shifted by the Rabi frequency. This is the basis for EIT experiments. Similarly, it is clear from eq. (2) that the linewidth $\Gamma_+$ of the second dressed state can be much below the natural linewidth when the control laser detuning is large. The basic idea for our experiment is also contained in the above analysis. From eq. (1), the separation between the dressed states is $\sqrt{\Delta_c^2 + \Omega_R^2}$. As the detuning of the control laser is varied from negative to positive, the states exhibit an avoided crossing, so that the separation at zero detuning is not zero but equal to the Rabi frequency. Thus, by studying the variation of the separation with detuning, it is possible to determine the location of the level crossing precisely.

However, observing the Autler-Townes doublet in room temperature vapor is complicated by effects due to Doppler broadening. The above expressions are valid for a stationary atom; in room temperature vapor they have to be corrected for the thermal velocity distribution of the atoms. One consequence of this is that the linewidth appearing in eq. (2) is not the natural linewidth but the Doppler width, which is 560 MHz for room temperature Rb atoms. We have solved the problem of Doppler broadening in the following manner. A part of the probe laser is split off as a “pump” beam and sent through the vapor cell so that it is counter-propagating with respect to the probe and control beams. The intensity of the pump beam is chosen to be about 4 times higher than the probe. In this configuration, the zero-velocity group of atoms preferentially absorbs from the pump and the probe gets transmitted. This is a standard technique used in Doppler-free saturated-absorption spectroscopy [11] which we have adapted to the three-level case.

The experimental schematic for the hyperfine measurements in Rb is shown in fig. 2. The probe and control beams are obtained from two frequency-stabilized diode laser systems operating near the $D_2$ line in $^{87}$Rb. The linewidth of the lasers after stabilization has been measured to be below 1 MHz. The two beams co-propagate through a room temperature vapor cell containing Rb. The absorption through the cell is about 25%. The counter-propagating pump beam discussed above is generated from the probe laser using a beamsplitter. To set the frequency of the control laser, a part of the control beam is tapped off for saturated-absorption spectroscopy in a vapor cell. It can be potentially locked to any of the hyperfine peaks or crossover resonances in the spectrum. We lock it to the $F = 1 \leftrightarrow F' = (1, 2)$ crossover resonance. The remaining frequency offset (of about 78 MHz) to bring it close to the
Fig. 3 – Autler-Townes doublet. The figure shows probe transmission spectra as a function of probe detuning. The top trace is with the control laser off and shows a standard saturated-absorption spectrum of the $F' = 2$ peak. The linewidth of the peak is 27 MHz. In the middle trace, the control laser is turned on at a detuning of $+13.5$ MHz. The peak splits into an Autler-Townes doublet, with linewidths of 18 MHz and 9 MHz, respectively. The bottom trace is for a control laser detuning of $-13.5$ MHz. The symmetry of the peaks has changed, and the linewidths are now 9 MHz and 17 MHz, respectively. Slowly varying Doppler profiles have been removed from all traces.

Fig. 4 – Separation vs. AOM frequency. The figure shows the variation in the separation of the Autler-Townes doublet peaks as a function of AOM frequency. The minimum separation occurs when the control laser detuning is zero. The solid line is a fit to the expected variation from eq. (1) in the text, which yields a value of $78.433(44)$ MHz for the interval between the $F' = 2$ level and the $F = (1, 2)$ crossover resonance.

$F = 1 \leftrightarrow F' = 2$ is obtained using an acousto-optic modulator (AOM). The frequency shift in the AOM is varied to get different detunings and the value of the AOM frequency at which the level-crossing occurs gives the hyperfine interval between the $F = (1, 2)$ crossover resonance and the $F' = 2$ level. Note that the only absolute frequency entering the measurement is the frequency of the AOM; all other frequencies such as the separation of the dressed states or the Rabi frequency of the control laser are only important in their relative values.

The transmission of the probe laser as it is scanned across the $F = 2 \leftrightarrow F' = 2$ transition is shown in fig. 3. In the first trace, the control laser is turned off. The pump-probe configuration results in the appearance of a Doppler-free peak as for standard saturated-absorption spectroscopy. Ideally, the linewidth of the peak should be the natural linewidth of 6.1 MHz. The linewidth obtained in our case is about 27 MHz. There are many reasons for this broadening, the main two being misalignment between the counter-propagating beams, and power broadening due to the pump beam. However, as we will see below, the large linewidth does not seriously affect the measurement.

In the presence of the control laser, the $F' = 2$ peak splits into two peaks exactly as predicted by the above analysis. This is shown in the middle trace of fig. 3. The two peaks have asymmetric linewidths because of the non-zero detuning of the control laser, with the peak on the right having smaller linewidth. The detuning for this spectrum is $+13.5$ MHz. In the lowest trace of fig. 3, we show the same spectrum when the detuning has been changed to
−13.5 MHz. Notice that now it is the peak on the left that has the smaller linewidth, showing that the symmetry of the dressed states changes as the detuning changes from positive to negative. Furthermore, the sum of the linewidths of the two peaks in both cases is equal to the unperturbed linewidth, as predicted by eq. (2). However, as mentioned before, the unperturbed linewidth is 27 MHz and not the natural linewidth of 6.1 MHz.

The variation of the separation of the Autler-Townes doublet as a function of AOM frequency is shown in fig. 4. Since the frequency of the control laser is first shifted using the AOM, and then locked to the $F = 1 \leftrightarrow F' = (1, 2)$ crossover resonance, the AOM frequency at which the separation reaches a minimum yields the hyperfine interval to the $F' = 2$ level. The solid line in fig. 4 is the expected variation in separation as a function of control laser detuning from eq. (1). The best fit yields a value of 78.433(44) MHz for this hyperfine interval. Note that the absolute values of the control laser Rabi frequency and the separation of the peaks are not important. Any scaling error in obtaining these numbers from the measured experimental parameters will not affect the determination of the minimum. The only absolute number of consequence is the AOM frequency and this is measured very precisely using a frequency counter.

The accuracy of 44 kHz we obtain is significantly better than the accuracy with which hyperfine intervals in alkali atoms are currently known [12]. The values in ref. [12] are obtained by fitting to all the available data on alkali atoms with measurements from a range of techniques such as optical double resonance, cascade radiofrequency and level crossing. The typical error in ref. [12] for hyperfine intervals in the $5P_{3/2}$ state of Rb is about 1 MHz. There is a more recent measurement in Rb [13] using stabilized diode lasers similar to the lasers we have used in this work. Absolute frequencies of the different hyperfine levels are obtained using a Fabry-Perot interferometer and a stabilized HeNe laser as the frequency reference. The accuracy quoted in ref. [13] is 0.4 MHz. The frequency stability of the diode lasers is a limitation in obtaining higher accuracy with such an interferometric technique.

The most precise measurements in $^{87}$Rb to date have been reported in ref. [14] with a quoted error of only 4–9 kHz. The extremely small error in this work has been achieved using optical heterodyning of two ultra-stable tunable Ti-sapphire lasers locked to different hyperfine transitions. Several experimental advancements were used to bring down errors to this level. The linewidth of the hyperfine transitions was reduced to 7 MHz in the vapor cell using magnetic shielding and careful control of pump and probe intensities. The cells themselves were specially constructed to ensure ultra-high purity. The lasers were locked with 3 kHz precision to the line center using third-harmonic lock-in detection at the modulation frequency. Ultra-stable frequency standards were used to achieve stability of AOMs. By contrast, we have used standard locking of a low-cost diode laser to the hyperfine transition. The transition is broadened to a linewidth of 27 MHz in the vapor cell. We have therefore not really pushed the limits of precision for our technique. It is conceivable that, by using some of the advanced techniques mentioned in ref. [14], we can reduce our errors by a factor of 5 to 10. However, even at the level of 44 kHz, the technique is useful since hyperfine intervals in the other isotope of Rb, $^{85}$Rb, or in other alkali atoms are known only with $\sim$ MHz precision.

In conclusion, we have demonstrated a new technique for measuring hyperfine intervals in alkali atoms. The atoms form a three-level $\Lambda$ system with an excited level coupled to a ground level by a strong control laser, and the same excited level coupled to a different ground level by a weak probe laser. The control laser creates dressed states that show significant linewidth reduction when the control laser is detuned from resonance. In addition, the states go through an avoided crossing as the sign of the detuning is changed from positive to negative. Even though we work with room temperature vapor, we have adopted a technique of using a counter-propagating pump beam that allows us to overcome the Doppler effect and measure the separation of the dressed states very accurately. By studying the separation as a function
of detuning, we determine the line center of the level-crossing diagram with high precision. We work with room temperature Rb atoms, where we obtain a precision of 44 kHz. This is already a useful level of precision since typical accuracy for hyperfine intervals in alkali atoms is of order 1 MHz. However, we think that with foreseeable improvements, the error can be brought down to the few kHz level. The technique is easily extended to other alkali atoms such as Li, K, and Cs, where the transitions are accessible with low-cost tunable diode lasers.

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