Measurement of natural linewidth of atomic transition using saturated absorption spectroscopy

Poonam Arora*, Pratyush Jha, Ashish Agarwal & Amitava Sen Gupta
Time & Frequency Division, National Physical Laboratory (CSIR), New Delhi 110 012, India
* E-mail: arorap@mail.nplindia.ernet.in
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Hyperfine structure of the 852 nm $6^2S_{1/2} \rightarrow 6^2P_{3/2}$ (D2 line) transition in $^{133}$Cs atoms has been investigated. Natural linewidth of the transition has been measured using saturated absorption spectroscopy. The measured value of linewidth is 5.09 MHz which is close to the literature value of 5.2 MHz. Such novel technique is easily realizable and useful for quick investigations of hyperfine structure of atomic samples in normal vapour cells.

Keywords: Linewidth, Laser cooling and trapping, Frequency control, Spectroscopy

1 Introduction

Since last few decades, several new techniques have been developed to precisely measure frequencies and linewidths of atomic transitions\(^1\). With the advent of laser cooling of atoms, detailed studies of atomic hyperfine structure have become imperative. Spontaneous transition rate between the excited and ground state of transition is an important key parameter which determines lot of laser cooling parameters. Different modified forms of optical spectroscopy have been used to investigate atomic spectra for various important parameters such as transition frequencies, transition rates, hyperfine splitting, isotope shifts, excited state lifetime, transition linewidths etc\(^2\)\(^-\)\(^9\). Doppler-free saturated absorption spectroscopy is one such technique which has been widely used to explore the hyperfine structure of atomic energy levels\(^10\)\(^-\)\(^12\).

Cesium, due to its attractive properties, is widely used in a variety of atomic physics experiments such as highly precise laser-cooled atomic standards of time and frequency. Fig. 1 shows the fine structure of $^{133}$Cs and hyperfine structure of D2 line which is the cooling transition.

In this paper, we have used saturated absorption technique to measure the natural linewidth of the 852 nm $6^2S_{1/2} \rightarrow 6^2P_{3/2}$ (D2 line) transition in $^{133}$Cs. In saturated absorption, two laser beams at the same frequency interact with the same group of atoms, those with no velocity component parallel to the beams. In these conditions, the stronger beam, the pump beam reduces the absorption experienced by the weaker overlap probe beam. Therefore, dips corresponding to hyperfine transitions appear in otherwise Doppler broadened absorption line. This happens only over a very narrow range of frequencies that under proper conditions can approach the natural linewidth determined by the lifetime of the excited state.

Apart from Doppler broadening, there are mechanisms like collisional broadening and power broadening which broaden the linewidth. Collisional broadening results from collisions between molecules in a gas which can be neglected in this case as vapour pressure of Cs is not very high at room temperature. In power broadening, at sufficiently large laser intensities, the optical pumping rate on an absorbing transition becomes larger than the relaxation rates. This results in a noticeable decrease in the population of the absorbing levels. This saturation of the population densities causes the additional line broadening. The dependence of linewidth at any given pump power ($\gamma_p$) on intensity is given by the formula:

$$\gamma_p = \gamma_0 \sqrt{1 + \frac{I}{I_s}} \quad \ldots (1)$$

where $\gamma_0$ is the natural linewidth, $I$ is the intensity of pump beam and $I_s$ is the saturation intensity. From Eq. (1), we see that in the limit when the laser power becomes very small, the spectral line width approaches the value of the natural line width $\gamma_0$. This fact has been used in our work for the determination of the natural line width of the $^{133}$Cs D2 line. Excited state lifetime and spontaneous transition rate are then...
calculated from the measured natural linewidth of the transition which are quite close to the theoretical value reported in literature. Such novel technique is affordable to use and is easy to realize. One can measure natural linewidths of atomic samples in normal vapour cell without cooling the atoms in ultra-high vacuum.

2 Experimental Details

The schematic of saturated absorption spectroscopy using cesium vapour cell is shown in Fig. 2. The laser light source from the external cavity diode laser (ECDL) is directed into the optical isolator with the help of mirrors. The optical isolator prevents light from re-entering the laser and damaging it. The light then passes through the half wave plate where its plane of polarization is rotated. It then passes through the anamorphic prism pair where the elliptical shape of the beam is changed to circular. It again passes through a half wave plate and then enters a polarizing beam splitter. The combination of the wave plate and the PBS allows us to change the intensity of the laser beam. A part of the laser beam after getting reflected from the PBS enters the Cs cell. This beam is known as the pump beam. After passing through the Cs cell, it goes through a neutral density filter where its intensity is reduced. It then gets reflected by a mirror and retraces its path into the cesium cell. This is the probe beam which is much weaker than the pump beam. This probe beam after travelling through the cell enters the photodiode (PD). The photodiode is connected to an oscilloscope to obtain the absorption spectrum of cesium as shown in Fig. 3. In order to find the absorption spectrum, the laser frequency is tuned by changing the laser current and piezo voltage. The piezo voltage is a ramp function in time. For the first half of the ramp, frequency increases linearly and decreases linearly in the second half and one obtains the spectrum as a function of time as shown in Fig. 3.

3 Results

Figure 3 shows the $F = 4 \rightarrow F'$ transition profile. Peaks corresponding to the hyperfine levels along with cross-over peaks are identified within the big Doppler envelope. In order to measure the linewidth, the Doppler envelope has to be subtracted from the transition profile. The base profile function is calculated and fitted to the original profile as shown in Fig. 4(a). This base function is subtracted from the
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profile data set in order to get hyperfine peaks on a flat base as shown in Fig. 4(b). For fitting a function to the base profile, few points from the base except those on the hyperfine peaks are taken and a function is fitted to this new base profile using least square fit method. This fitted function was then subtracted from the base profile. For the best fit, a horizontal line was obtained after subtraction of the fitted profile. After subtracting the same fit function from the experimentally obtained spectrum, we got all the peaks on a flat base as shown in Fig. 4(b).

After getting all the peaks on a flat base, we need to calibrate the x-axis. Actually, the x-axis in the profile taken from the oscilloscope is time (s). We know the theoretical value of the energy difference (in frequency) between any two peaks. If we find the distance between two peaks on time axis, we can calculate the calibration and with this we change the time axis into the frequency axis. From Fig. 3, we know the frequency separation between 4-5' peak and 4-4' & 4-5 cross-over peak to be 125.5 MHz (i.e. half of the 251 MHz frequency separation between 4-5' and 4-4' peaks). Now, on the time axis, these two peaks correspond to 0.0055 s. So, the calibration is 22818.18 MHz/s.

After having the hyperfine peaks on a flat base, the cross-over peak 4-4',5' is selected and a Lorentzian line-shape function is fitted to the data as shown in Fig. 5. The full width at half maximum of this fitted profile is then the linewidth of the transition. In order to find the natural linewidth, the same experiment was done for different pump powers. Due to power broadening mechanism, the linewidth increases with increasing pump power. Fig. 6 shows the linewidth as a function of $\sqrt{1+\frac{I}{I_c}}$ and a straight line is fitted to the data points. As mentioned in Eq. (1), this straight line is extrapolated to get the natural linewidth which is the value of linewidth at zero power. The natural linewidth comes out to be 5.09 MHz. These measurements have been repeated several times and gave similar value of the linewidth every time. The error bars show the maximum variation of linewidths.

Fig. 4 — Transition profile with a fitted base function (a) and after subtracting the base function (b).

Fig. 5 — Lorentzian line-shape fitted to one of the hyperfine peaks.

Fig. 3 — Experimentally observed transition profile $F = 4 \rightarrow F'$.
in several repeated measurements. The lifetime of $^6\text{P}_{3/2}$ state is then 31.28 ns and the spontaneous decay rate is $31.97 \times 10^6 \text{ s}^{-1}$. These values are quite close to the theoretical values of 30.47 ns and $32.42 \times 10^6 \text{ s}^{-1}$, respectively, as reported in literature$^{13}$.

4 Conclusions

The natural linewidth of the 852 nm $^6\text{S}_{1/2} \rightarrow ^6\text{P}_{3/2}$ (D2 line) transition in $^{133}\text{Cs}$ has been measured using saturated absorption spectroscopy technique. The measured linewidth is 5.09 MHz and is quite close to the literature value of 5.2 MHz. Once the natural linewidth is measured, excited state lifetime and spontaneous transition rate is calculated. This technique gives a quick estimate of the linewidth and requires a small and easily realizable set-up and atomic samples in normal vapour cells rather than cold atoms in a MOT (magneto-optical trap).

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References