High-resolution laser spectroscopy of hot Cs and Rb vapor confined in a thin optical cell

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Abstract. We propose a novel use of an optical cell of micrometer thickness filled with Cs vapor in view of studying the collisions between two different alkali atoms of strongly different densities. We demonstrate narrow and good-contrast sub-Doppler resonances at the Rb D2 line for a mean-free-path of the Cs atoms comparable to the optical cell longitudinal dimension; the resonances are completely destroyed when the mean-free-path of the Cs atoms is more than two orders of magnitude shorter than the longitudinal dimension of the thin cell.

1. Introduction
The field of photonics has undergone immense technological and scientific advancement in the past decade related to the miniaturization of various optical sensors. An important task in this respect is to induce atom-photon interactions in hot and dense atomic vapor confined in optical cells of sub-millimeter thickness. Such confinement makes it possible to build a high-density but optically thin atomic vapor layer that will be capable of producing diatomic Cs molecules alongside the atoms, while allowing one to perform linear transmission spectroscopy studies of the molecular ensemble.

In our experimental study, we used two cells of micrometer thickness, similar to the one described in [1] but with nearly parallel internal sides of the cell windows. Both cells were filled with Cs vapor, which naturally contains Rb atoms in an extremely small concentration. If heated to temperatures above 200 °C, such a cell will contain a mixture of alkali atoms: predominantly Cs atoms, a more than an order of magnitude lower concentration of Cs dimers and single Rb atoms. Under such conditions, the Cs atoms and dimers can be considered as a kind of buffer gas for the Rb atoms. Thus, such a mixture will make it possible to measure precisely the pressure effects on the Rb spectral profiles as the Cs density is raised.

2. Energy level diagram and experimental setup
The natural isotopic abundance of Rb is about 72.2% 85Rb and about 27.8% 87Rb [2]. Figure 1 presents their energy level diagrams, which should be involved in the analysis of the experimental results.

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In our experiment, we explored the D$_2$ line of Rb in a 700-micrometer-thick cell and the D$_1$ line of Rb in a 60-micrometer-thick cell. The Rb D$_1$ line of consists of two ground state levels and two excited state levels [3]. The corresponding atomic numbers for the ground state levels of $^{87}$Rb are Fg=1 and Fg=2; for excited state levels these are Fe=1 and Fe=2 (see figure 1). The D$_2$ line of Rb is slightly more complicated and consists of the same ground state levels as for D$_1$ line and four excited state levels. The corresponding atomic numbers for $^{87}$Rb are Fg=1 and Fg=2 and for the excited state levels Fe=0, Fe=1, Fe=2 and Fe=3.

The experimental setup is shown in figure 2. The light source was a distributed-feedback diode laser (DFBDL) emitting linearly polarized light with a short-term linewidth of 3 MHz and a maximal power of 150 mW. The laser frequency was scanned by varying the laser current. The laser beam was split in two by a beam splitter, its main part directed to the micrometric cell, and the second part used for reference. In the reference part of the setup we employed saturated absorption spectroscopy to observe the Rb resonances in a 5-cm-thick optical cell.

![Figure 1. Rubidium isotopes energy levels diagram. The frequency separation between hyperfine levels is indicated in MHz.](image1.png)

![Figure 2. Experimental set up: DFBDL – distributed feedback diode laser; NDF – neutral density filter; MTS – micrometric thick cell; BS – beam splitter; M – mirror; PD Ref. – photodiode reflection signal; PD Tr. – photodiode transmission signal; PD Fl. – photodiode fluorescence.](image2.png)

Before entering the micrometric cell, the main part of the laser beam passes through a variable neutral density filter controlling the laser beam power. It is then directed by a mirror nearly perpendicularly to the cell internal window surface. The laser light interaction with the cell and the vapor gives rise to the three signals collected, namely, transmission, reflection and fluorescence. The reflection signal consists of three components – the back-surface reflection of the first window, the...
signal from the Rb atoms and the reflection from the front surface of the second window. The reflections from the external surfaces of the cell windows propagate in directions different from that of the reflection signal because the windows are formed as wedges. The signal reflected from the cell propagates close to the incident beam and is directed to the receiving photodiode by a small mirror. The fluorescence signal is collected perpendicularly to the laser beam. The transmission, reflection and fluorescence, as well as the saturated absorption signal from the 5-cm-thick cell, are registered by photodiodes and stored by a digital oscilloscope.

The micrometric cell is placed in an oven where it is heated to the temperature required of the atomic source. This temperature, which is indicative of the Cs atoms density, is measured by a thermocouple attached to the atomic source reservoir.

3. Experimental results and discussion

We first present the main experimental results obtained for the 700-µm-long cell filled with Cs. As seen in figure 3, the transmission spectrum is of lower amplitude and does not show narrow, sub-Doppler features in the Doppler profiles. It consists of four Doppler profiles that are due to the absorption at the four sets of hyperfine transitions starting from the following ground state levels: \( F_g=2 \) hyperfine level of the \( ^{87}\text{Rb} \) isotope, \( F_g=3 \) hyperfine level of the \( ^{85}\text{Rb} \) isotope, \( F_g=2 \) hyperfine level of the \( ^{85}\text{Rb} \) isotope and \( F_g=1 \) hyperfine level of the \( ^{87}\text{Rb} \) isotope (figure 1). Unlike the transmission profiles, in the fluorescence (not shown in figure 3) and reflection spectra, well-expressed narrow dips in the Doppler profiles are observed. The formation of the sub-Doppler structures is attributed to the beam reflected from the second window of the 700-µm cell, contributing to the formation of saturated absorption resonances centered at the hyperfine transitions.

We further studied the fluorescence spectrum dependence on the atomic source temperature (figure 4). In the figure, only two sets of hyperfine transitions are shown in order to present the fluorescence profiles with a better spectral resolution. Due to the formation of narrow sub-Doppler reduced-absorption resonances, all three hyperfine transitions, starting from the \( F_g=2 \) level of the \( ^{87}\text{Rb} \) isotope

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\begin{align*}
\text{Cs cell } L &= 700 \text{µm}, \\
T_{\text{cell}} &= 320 ^\circ \text{C}, \\
T_{\text{sa}} &= 300 ^\circ \text{C}, \\
\text{Fluorescence} \quad &\text{Transmission} \\
\end{align*}
\]

![Figure 3](image3.png)

**Figure 3.** Transmission and reflection spectra of Rb measured in a 700-µm thick cell filled with Cs vapor.

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\begin{align*}
\text{Cs cell } L &= 700 \text{µm}, \\
T_{\text{sa}} &= 128 ^\circ \text{C}, \\
T_{\text{cell}} &= 200 ^\circ \text{C}, \\
\text{Fluorescence} \quad &\text{Transmission} \\
\end{align*}
\]

![Figure 4](image4.png)

**Figure 4.** Well resolved sub-Doppler structure observation, for the \( F_g=2 \) set of transition of \( ^{87}\text{Rb} \) isotope, at low atomic source temperature \( T_{\text{sa}} = 128 ^\circ \text{C} \).
are very well resolved. The optimal spectral resolution is observed for relatively low cell side arm temperature $T_{sa} = 128$ °C, i.e. a low Cs atoms density ($7.31 \times 10^{13}$ atoms/cm$^3$). For this atomic density, the Cs atoms mean-free-path (mfp) is estimated at 474 µm, which is close to the optical cell thickness of 700 µm. We studied in detail the sub-Doppler resonance behavior as a function of the atomic source temperature and found that the rise in the atomic density results in broadening the resonance and reducing its contrast, especially for $T_{sa}=235$ °C. The sub-Doppler structure disappears for $T_{sa}=(276-280)$ °C (figure 5). This is attributed to the collisions of the high-density Cs atoms with the Rb atoms of much lower density. Indeed, at $T = 276$ °C, the Cs atoms density ($2.01 \times 10^{16}$ atoms/cm$^3$) is higher by more than two orders of magnitude than that for $T_{sa}=128$ °C. The higher density determines a Cs atoms’ mfp of 1.91 µm for $T_{sa} = 276$ °C. Hence, the sub-Doppler resonances at the $^{87}$Rb $F_g=2$ set of transitions are destroyed at Cs atoms’ mfp that is lower by more than two orders of magnitude than the longitudinal dimension of the thin cell. Under such conditions, the collisions of Rb atoms with the thin cell walls are strongly suppressed due to collisions with Cs atoms. Hence, our result supports the theoretical model in [4], where it was shown that a large number of atomic collisions with the optical cell surfaces result in amplifying the sub-Doppler features.

Further on, we measured the fluorescence spectra of Rb vapor confined in a thin cell with $L = 60$ µm filled with Cs to explore the D$_1$ line of Rb (figure 6). Comparing the thin cell fluorescence spectra with the D$_1$ line spectrum in a conventional cell (i.e., one with a large longitudinal dimension), showed that even the 60-µm cell produces a Rb spectrum with a good signal/noise ratio. This result is promising for the development of a precise frequency reference to be further applied to Cs dimer study in thin optical cells.

4. Conclusions

In conclusion, we demonstrated a novel use of a micrometric thin cell filled with Cs vapor, which naturally contains Rb atoms in an extremely small concentration. The experimental results showed that it is possible to measure precisely the pressure broadening and destruction of sub-Doppler features in Rb spectral profiles as the Cs density is raised, in view of analyzing the processes involved in the

Figure 5. After spectral broadening and amplitude reduction, the sub-Doppler resonances disappear.

Figure 6. Fluorescence spectrum on the D$_1$ line observed for the significantly thinner optical cell.
formation of sub-Doppler resonances and studying the collisions between two different alkali atoms in thin optical cells.

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