Calcium Spectroscopy

by

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1 Introduction

This thesis describes the spectroscopy of calcium–40 that was performed during my four week long internship in July 2017 at the Institute of Quantum Optics and Quantum Information (IQOQI) in Innsbruck, Austria.

The long–term goal of the internship was to devise a simple experimental setup to simplify the calibration of a wavemeter. Laser wavemeters are an integral part of many quantum–optical experiments. They facilitate the exact tuning of a laser to a specific frequency. For example, in our experiment, we used a wavemeter to ensure that the laser was scanning across the correct range of frequencies.

Wavemeters tend to drift over time and require recalibration. Normally, recalibration requires an atomic clock that is time–consuming and expensive to procure. However, if the frequency of a single transition in an absorption spectrum is known, this frequency can be compared with a direct measurement of the frequency using the uncalibrated wavemeter. This simplifies the determination of the offset or net drift of the wavemeter. The goal of my internship was to devise a simple setup to measure the frequency of a specific calcium transition.

In this experiment, calcium was heated in a low–pressure environment to create calcium vapor. Then, a Doppler–free setup was used to find the so–called Lamb dip and measure the exact frequency of the absorption line at 422.673 nm. In addition, the optimal conditions for observing the absorption spectrum and Lamb dip were determined.

1.1 Doppler–free spectroscopy

Doppler–free spectroscopy allows the observation of the natural line width of a transition by eliminating Doppler broadening. In this method, two overlapping laser beams — one stronger than the other but at identical frequencies — are sent through a medium in opposite directions. To understand how Doppler broadening works, it helps to classify the speeds of the atoms in the medium. There are those atoms that move towards the pump beam and thus away from the probe beam, those atoms that move towards the probe beam and thus away from the pump beam, and finally those atoms that move laterally to both beams. Atoms moving laterally are virtually stationary in relation to either laser beam. Atoms that move towards one beam but away from the other can only be excited by one beam due to the Doppler shift. However, stationary or laterally moving atoms will be excited by both beams. In this case, the pump beam saturates the transition, which makes the medium transparent for the probe beam. This causes a small increase in

probe beam intensity commonly known as the Lamb dip. Ideally, this Lamb dip reflects the natural width of the transition, which is the inverse of the life time of the transition [1, p. 45 ff.].

2 Setup

Setting up and aligning the optical elements as well as installing the spectroscopy cell was a major part of the experiment, which was originally designed by Michael Bacher in 2005 [1]. The goal was to review parts of the experiment to verify existing data presented in the thesis and simplify the experiment for use as a calibration reference.

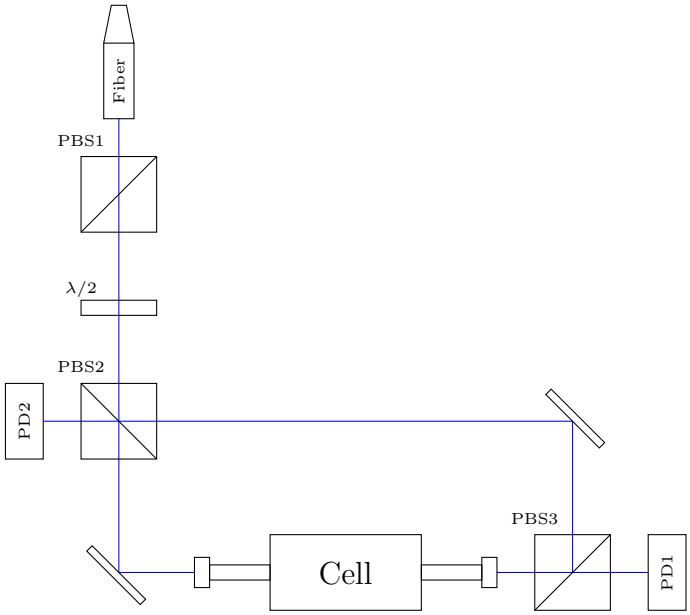

Fig. 1: Experimental setup. Laser beams travel through the spectroscopy cell which contains calcium vapor. The beams' varying intensities are measured using the two photodiodes.

2.1 Spectroscopy cell

The spectroscopy cell was not in use for several years and had been modified slightly after Bacher's thesis was published, so the cell had to be partially disassembled to understand how it works. Documentation available on the temperature sensor and the heating coil was insufficient. Therefore, we performed several experiments to verify that both components were still working.

These experiments also allowed us to gather some data on the thermocouple built into the cell. According to [1, p. 77], the device is a FeCuNi type L thermocouple. The experiment confirmed that the measurements acquired from this device match measurements obtained from type J thermocouples and their corresponding temperature tables (see Table [2, p. 2]).

Before performing these measurements, calcium powder residues from previous experiments had to be removed. Judging by the metallic color of the granules, the calcium was still largely unoxidized. The cell had not been reevacuated for some time, so apparently it had not been leaking significantly.

Potential short circuits between the heating coil and the metal enclosure were eliminated to ensure safe operation. In order to remove any gases that had accumulated over time (for example hydrogen), the cell was resealed in an empty state and evacuated. The empty cell allowed the testing of the heating coil across a wide range of temperatures while avoiding the unnecessary vaporization and therefore loss of calcium. Fig. 2 shows the thermocouple voltage against supplied heating coil current.

Next, the cell was reopened and 2.5 g of pure calcium–40 granules were deposited at the center of the tube. The chamber was then resealed and evacuated to a pressure of around 10^{-6} mbar. Note that in general, vacuum pressure does not influence gas pressure significantly. A pressure of 10^{-3} mbar was used by Bacher [1].

2.2 Experimental setup

After completion of the initial tests, the next step was to design a suitable optical setup. We significantly simplified Bacher's layout as follows (see Fig. 1): Light from a frequency–doubled laser passes through an optical fiber to the optical table. The light first travels through a polarizing beam splitter (PBS1) to stabilize the polarization state. The light then passes through a $\lambda/2$ plate and PBS2. The orientation of the $\lambda/2$ plate determines the intensities of the two beams leaving the PBS. These beams are used as *pump* and *probe* beams, the probe beam being the one that passes straight through the splitter. The probe beam is then reflected through the spectroscopy cell and through PBS3 onto a photodiode (PD1). PBS3 reflects the pump beam through the cell, opposite to the direction of the probe beam. After passing through the cell, the pump beam is reflected onto a second photodiode (PD2) by PBS2.

Care was taken that the pump and probe beams do not reflect off the sides of the cell but actually pass straight through. This was checked by adjusting the mirror in front of the cell and verifying that the exiting beam travels correctly and does not change shape.

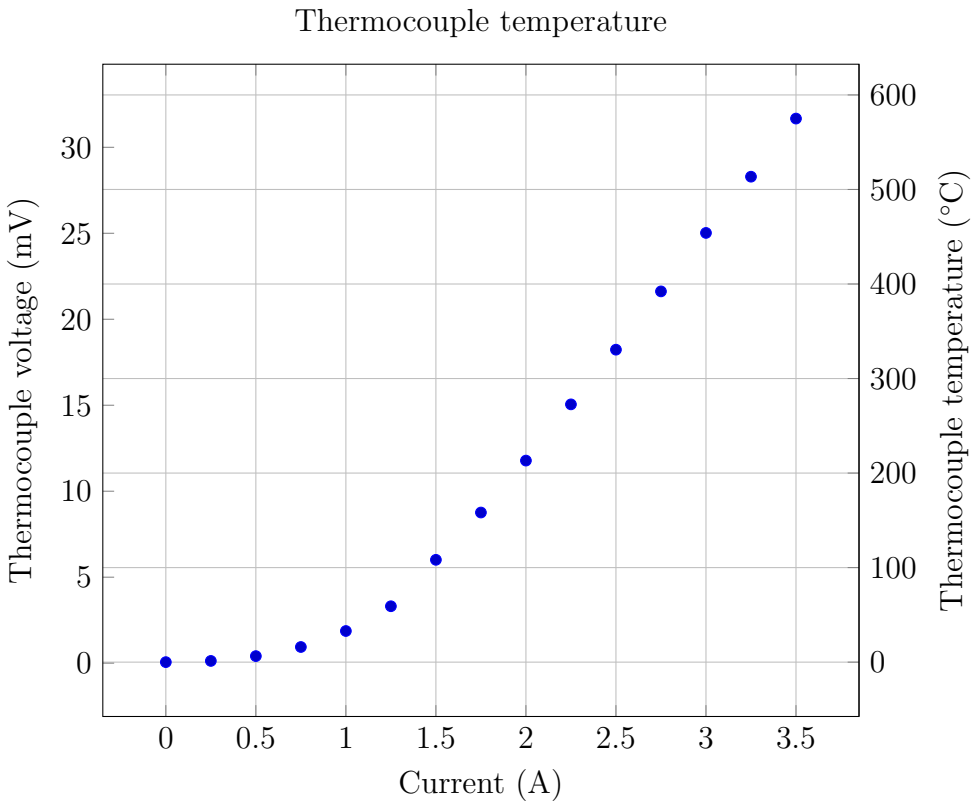

Fig. 2: This depicts the voltage of the thermocouple in relation to the supplied current. The voltage measured across the thermocouple leads is shown on the left axis, while the approximate temperature, taken from table [2], is shown on the right axis.

Our measuring equipment was set up in a way that allowed simultaneous monitoring of the two photodiodes while measuring the voltage from the thermocouple with a sensitive voltmeter. Furthermore, the current for the heating coil was regulated by a power supply.

2.3 Laser use

The laser used for the experiment was a 422 nm frequency–doubled tunable laser. The tuning range of around 3 to 5 GHz was affected by various environmental factors such as humidity and temperature, which most likely interfered with the internal alignment and electronics. About 80 to 100 μW of laser power were available for the experiment.

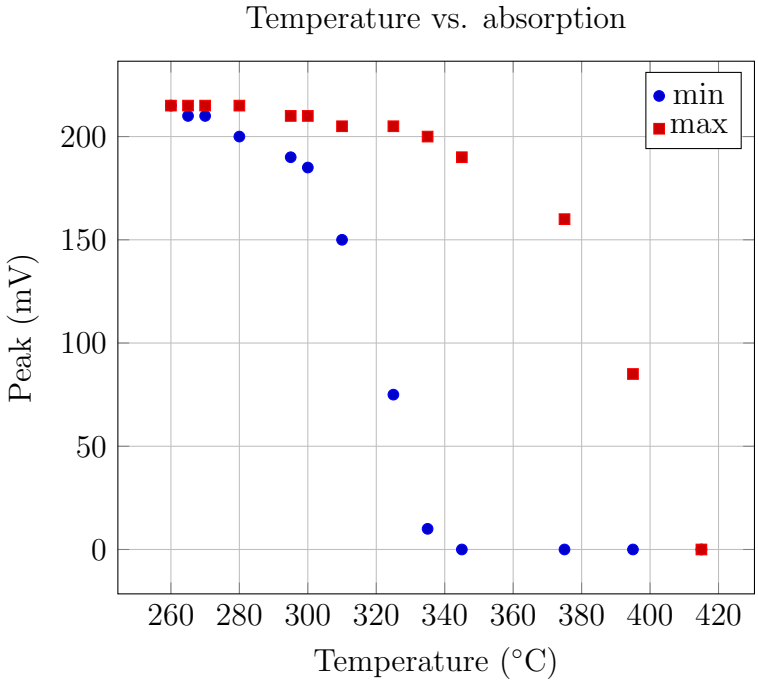

Fig. 3: Size of the absorption dip based on measured temperature. Measurements were taken off the probe beam. "Min" and "max" show the minimum and maximum values of the peak. Note that beyond 340°C, the laser beam is completely absorbed at the right frequency, hence the value is 0 mV for "min" beyond this temperature.

3 Spectroscopy

3.1 Temperature and peak intensity measurements

The size of the absorption dip depends mainly on the temperature inside the cell. Therefore, the minimum and maximum intensity of the probe beam was measured and plotted against the temperature. Due to insufficient laser power, increasing the temperature further would have caused the density of the calcium vapor to increase, which in turn would have completely absorbed our already weak beam (see Fig. 3).

3.2 Simple spectroscopy

By heating the cell to an appropriate temperature and scanning the laser light across the absorption frequency, it is possible to acquire an absorption spectrum: near the absorption frequency, the laser intensity decreases after passing through the cell because it is absorbed by the calcium vapor. However, the intensity dip is several times wider than the natural line width due

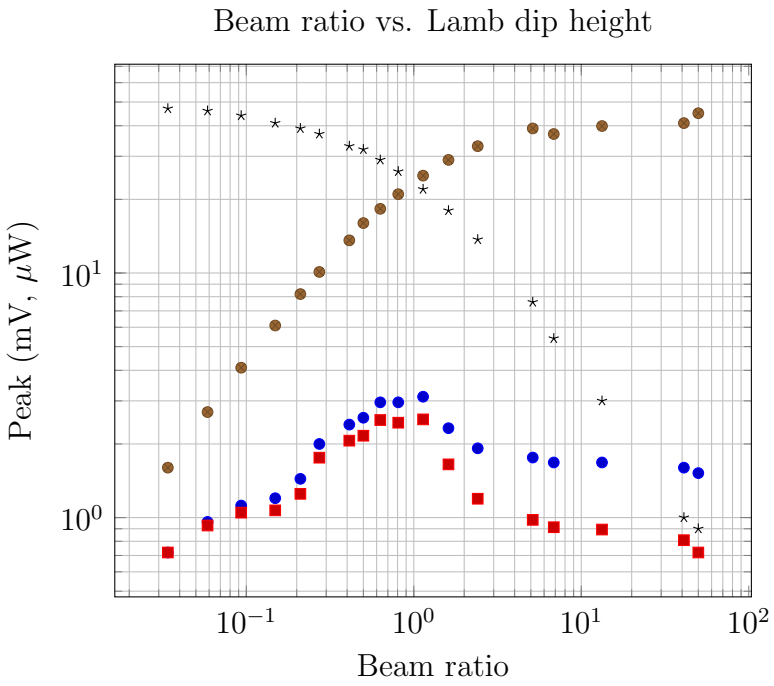

Fig. 4: This graph shows the height of the Lamb dip for varying intensities of probe beam and pump beam. Beam ratio is probe power (brown) divided by pump power (black). Peak–to–peak (blue) was measured for the probe beam. The corrected graph (red) compensates for the increase in noise caused by increased beam intensity.

to Doppler broadening caused by the movement of atoms inside the vapor. As a result, the vapor atoms will be excited across a range of frequencies because different frequencies affect atoms with different velocities due to the Doppler effect. This broadening is described by the Gaussian–shaped Maxwell–Boltzmann distribution.

To acquire a spectrum, we heated the chamber to a temperature of 340°C (equivalent to a current of 2.2 A) and scanned the laser in a range of 3 to 4 GHz. These settings resulted in a well defined absorption spectrum. For simple spectroscopy, both beams may be used for measurements. If the Lamb dip (see Section 1.1) is not desired, the pump beam should be blocked after PBS2 and measurements be taken off the probe beam.

3.3 Doppler-free spectroscopy and Lamb dip

Resolving the Lamb dip with a reasonable resolution was quite difficult to accomplish, as the laser we used was rather weak. Therefore, we had to use a temperature below 340°C, which meant that the amplitude of the Lamb

dip barely exceeded that of the laser noise. For our setup, a temperature of about 330°C worked best. This corresponds to a current of 2.22 A, and due to the resistance of the heating coil of roughly 6.9 Ω, the voltage was about 15.3 V. Measurements revealed that the pump beam should only be slightly stronger than the probe beam in our setup. Fig. 4 shows the size of the Lamb dip in relation to the pump and probe beam strength.

3.4 Importance of regular evacuation

At the level of laser power used in our experiments, reevacuating the spectroscopy cell regularly increased the height of the Lamb dip. However, when using a more powerful laser, the increase in amplitude may become negligible in proportion to the overall height of the dip.

3.5 Signal enhancement with a lock–in amplifier

To enhance the Lamb dip signal, it is possible to use a lock–in amplifier in conjunction with a chopper wheel placed in the pump beam path between PBS2 and PBS3. We used a chop frequency of 320 Hz, which gave us a reasonably clean signal from the lock–in amplifier. The reason we only chop the pump beam is that this setup selectively chops the Lamb dip. Chopping the probe beam does not filter out laser intensity fluctuations like chopping the pump beam does. These fluctuations render the signal useless.

The lock–in amplifier is useful when set correctly. However, we found that showing the raw data from the photodiode in addition to the data processed by the lock–in amplifier is very helpful, especially for setting the right scan range and amplitude for the laser. Changing the chopper frequency has a significant effect on the signal quality. Some chopper settings led to fluctuations in the lock–in signal that we did not further investigate.

After finding the optimal settings for the lock–in amplifier, we turned off the laser frequency scan and attempted to maximize the Lamb dip signal by carefully changing the laser frequency. According to the National Institute of Standards and Technology (NIST) [3], the transition should have a wavelength of 422.673 nm in air. By using this information in conjunction with our setup, we can precisely calibrate equipment such as wavemeters.

4 Conclusion

In this experiment, we used an existing spectroscopy cell to find the calcium–40 transition at 422.673 nm. Several measurements were used to determine

the optimal conditions for observing a Lamb dip. The results show the optimal temperature of the cell as well as the best relationship between pump and probe beam intensities. Furthermore, we used a lock–in amplifier to improve our observations. The experiment was all in all successful and is expected to be useful in the future as a highly stable frequency reference.

5 Thanks and acknowledgements

I would like to thank Peter Jurcevic for helping me in conducting these experiments and sharing his knowledge. I would also like to thank everyone at the lab, especially Tiffany Brydges and Christine Maier for their frequent support and advice. Of course I would also like to extend my thanks to Dr. Christian Roos for making this internship possible and also Prof. Dr. Harald Giessen for introducing me to Mr. Roos.

References

[1] Michael Bacher, *Sättigungsspektroskopie an Kalziumdampf und Laserstabilisierung für Photoionisationsexperimente*, Innsbruck, May 2005. `http://www.quantumoptics.at/images/publications/diploma/diplom_bacher.pdf` (retrieved: 21.07.17)

[2] Fuehlersysteme type J thermocouple datasheet `http://www.fuehlersysteme.de/downloads/dl/file/id/231/manual.pdf` (retrieved: 19.07.17)

[3] Kramida, A., Ralchenko, Yu. Reader, J., and NIST ASD Team (2015). *NIST Atomic Spectra Database* (ver. 5.3), [Online]. Available: `http://physics.nist.gov/asd` [2017, July 26]. National Institute of Standards and Technology, Gaithersburg, MD.