

# Rayleigh Scattering

Laboratory Report by

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# 1 Introduction

Rayleigh scattering describes the process of light scattering at particles which are much smaller in size than the wavelength of the incoming light. The smaller the wavelength, the more light is scattered. The result of Rayleigh scattering can be observed everyday in the blue color of the sky, as the smaller, i.e. blue, wavelengths of the broad sunlight spectrum get scattered in all directions within the earths atmosphere, leading to the blue tint. It is also the cause for red skies at dusk or dawn and the blue tint of opal glass. [1]

Rayleigh scattering is a special case of Mie theory which describes a broader range of light scattering effects, such as the Tyndall effect. An example of the Tyndall effect is visible rays of sunlight through misty air. [1],[5]

Using cavity-ring down spectroscopy this experiment aims to explore the different features of Rayleigh scattering and determine the scattering coefficient of the air in the laboratory.

## 2 Theoretical overview

### 2.1 Cavity ring-down spectroscopy

With Cavity Ring-Down Spectroscopy (CRDS) the absorption spectra of a material can be measured. A typical CRDS set-up consists of a cavity with two concave highly reflective ( $R > 99.98\%$ ) mirrors, facing each other, thus creating an optical resonator, as shown in fig. 1. A laser pulse is introduced into the cavity and continuously reflected between the two mirrors, leading to path lengths of many thousands of kilometers.

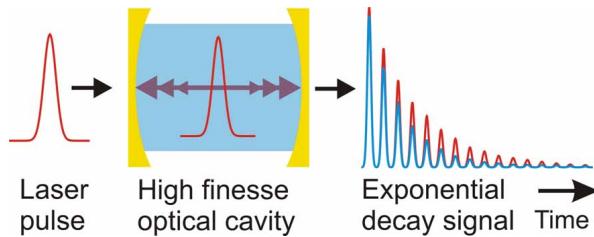


Figure 1: Schematic overview of cavity ring down spectroscopy, where the laser pulse arrives within the optical resonator and gets reflected multiple times. A small part of the light leaves the cavity at every reflection, with an intensity that decays exponentially over time. [3]

Whenever the laser pulse arrives at the mirrors the majority of it is reflected, however, a minuscule amount, dependent on the reflection coefficient  $R$ , leaves the cavity. Thus the intensity of the light pulse decreases over time. This light intensity leaving the cavity at the time  $t$  is recorded using a photodetector, and is described by equation 1.

$$I(t) = I_0 e^{-t/\tau} \quad (1)$$

Here  $I_0$  is the initial intensity of the laser pulse and  $\tau$  the ring-down time. The ring down time describes the time at which the intensity has fallen by  $\frac{1}{e}$  of the initial intensity. In an empty, vacuum-filled cavity, therefore assuming that molecular scattering is negligible,  $\tau$  is

only dependent on the distance between the mirrors  $d$  and the reflection coefficient  $R$ .

$$\tau_0(\lambda) = \frac{d}{c(1 - R(\lambda))} \quad (2)$$

The light speed is denoted with  $c$ .

If a medium is introduced into the cavity, the intensity now not only decreases at the mirrors but also through scattering or, depending on the medium, absorption, at the medium. The scattering of photons at the medium deviates them from their stable paths in such a way, that the photons do not reach the mirror at the end of the cavity. Thus, through scattering or absorption the light intensity decreases more rapidly. This is reflected in the ring down time which is now also dependent on the scattering coefficient  $\kappa(\lambda)$ .

$$\tau(\lambda) = \frac{d}{c[(1 - R(\lambda)) + \beta(\lambda)d]} \quad (3)$$

The amount of round trips  $N$  which the light takes in the time  $\tau$ , can be calculated with the reflection coefficient of the mirror:

$$R^{2N} = \frac{1}{e} \rightarrow N = -\frac{1}{2} \ln(R) \quad (4)$$

An equation for  $\beta$  can be found using equation 2 to substitute  $d$  in equation 3.

$$\beta(\lambda) = \frac{1}{c} \left( \frac{1}{\tau(\lambda)} - \frac{1}{\tau_0(\lambda)} \right) \quad (5)$$

CRDS allows for highly sensitive measurements using a relatively simple set-up. Since the rate of intensity decay is measured, laser fluctuations have little effect on the result and the absorption can be measured on an absolute scale. Additionally only a small sample of material is necessary to achieve proper results due to the long absorption paths accomplished by the continuous reflections. However compared to other highly sensitive spectroscopy methods such as laser-induced fluorescence (LIF) and resonance enhanced multi-photon ionization (REMPI), it is not as sensitive as these methods also remove background radiation. Nevertheless, CRDS can be applied when fluorescence or ionization of the material, and therefore also LIF or REMPI analysis, is not possible or in high pressure samples such as flames and plasmas. [1][2]

### 2.1.1 Optical resonators

The cavity with mirrors on either side is the central part of the CRDS set-up and creates an optical resonator. The light between the two mirrors interferes with itself and creates different interference patterns within the cavity. Those patterns which occur with every round trip reflection are called stable modes. For CRDS the desired stable modes of the resonator are optically stable and non-confocal and therefore must fulfill,

$$0 < d < 2r \quad (6)$$

or,

$$r < d < 2r. \quad (7)$$

With  $r$  being the radius of the mirrors and  $d$  the distance between them. [2] [4]

## 2.2 Rayleigh scattering

According to the linear scattering theory the power scattered by a single scatterer like a molecule or an atom in a full  $4\pi$  angle is proportional to the incident intensity. This proportionality constant is called a scattering cross section, which is typically denoted with a  $\sigma$  and its unit is that of the surface area. Since we are not scattering on a single molecule we need to regard a volume filled with scatterers. In this case the total scattering power is actually a superposition of the single scattering power of each molecule/atom. This is integrated into the formula by multiplying the proportionality factor by  $N$ , the number of concentration. The resulting proportionality is the defined scattering coefficient  $\beta$  in Formula 5. We write:

$$\beta(\lambda) = N\sigma(\lambda) \quad (8)$$

In the Rayleigh theory the scattering molecules are approximated by oscillating hertzian dipoles, which reemit incident electromagnetic waves. This leads to the scattering coefficient depending on the fourth power of the wavelength as follows:

$$\beta(\lambda) = \frac{8\pi^3(n^2 - 1)^2}{3N\lambda^4} \quad (9)$$

Due to this dependency a Photon with a smaller wavelength, which appears blue, is scattered more efficiently than a photon with a bigger wavelength, which appears red. With this formula one can determine the magnitude of the Rayleigh scattering coefficient if one knows the exact wavelength. This value can then be compared with the one obtained in the CRDS measurement as given in formula 5 [1].

## 3 Experimental setup

The experimental set up mainly consists of a laser, an optical cavity, a vacuum pump and a photomultiplier. All of these components are schematically shown in figure 2.

The laser pulses a repetition rate of about 100 Hz a power of 100 mW, which is controlled by a delay generator. To make sure the measured radiation losses correspond to Rayleigh scattering, the laser has to be in a wavelength range relatively far from absorption resonances of most abundant air constituents. The wavelength used to ensure this is approximately 405 nm.

Two highly reflective spherical mirrors form the optical cavity. The mirrors are arranged with a distance of 50 cm in between and have a radius of curvature of 100 cm. Both have highly reflective dielectric coatings where the reflectivity  $R$  is  $R > 99.98\%$ .

To remove the air from the cavity, a vacuum pump is used. When air is pumped back in as part of the experiment, a syringe filter removes bigger aerosol particles.

The measurement itself happens through a photomultiplier and a digital oscilloscope, where the emerging light is captured. A band pass filter improves the measurement. The results then are evaluated with the GPIB interface on a PC. [1]

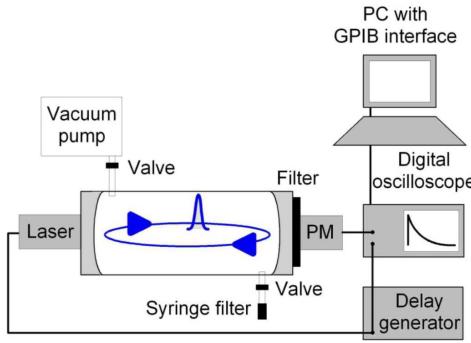


Figure 2: Experimental set up.[ 1]

## 4 Experimental technique

The aim is to determine the Rayleigh scattering coefficient  $\beta$ . To obtain  $\beta$ , two ring-down times of the optical cavity are measured, where in one measurement the cavity is evacuated and in the second it is filled with filtered air at atmospheric pressure.

For evacuation the vacuum pump is used and the pressure is monitored by a manometer until the lowest pressure possible is reached. For the measurement, a proper alignment of the optical system is required. For that, a second laser with a wavelength of 532 nm is used since it is well transmitted through the optical cavity and the green color is easily detectable for the human eye. If properly aligned, the characteristic signal will appear on the oscilloscope.

The cavity is then filled with air and the previous pumping requires a proper alignment once again. For both scenarios several measurements are taken.

In the measurement with an air-filled cavity the ring-down time will be shorter due to Rayleigh scattering.

## 5 Determining the scattering coefficients

The following measurements of the ring-down times were determined with the experimental set-up.

Table 1: Measured ring-down times for an empty  $\tau_0$  and an air-filled  $\tau$  cavity

Measurement	Ring-down time $\tau_0$ in $\mu\text{s}$	Ring-down time $\tau$ in $\mu\text{s}$
1	$10,19 \pm 0,09$	$8,89 \pm 0,18$
2	$10,14 \pm 0,09$	$8,73 \pm 0,18$
3	$10,09 \pm 0,09$	$9,20 \pm 0,18$
4	$10,35 \pm 0,09$	$8,99 \pm 0,18$
5	$10,11 \pm 0,09$	$8,73 \pm 0,18$

The noted errors in table 1 are the standard error of the arithmetic value. The arithmetic value and the standard error of the mean were calculated from the values listed in table 1. This resulted in the following ring-down times for an empty cavity  $\tau_0$  and an air filled one  $\tau$ :

$$\tau_0 = (10,18 \pm 0,06)\mu\text{s} \quad (10)$$

$$\tau = (8,91 \pm 0,09) \mu s \quad (11)$$

The mean values for the ring down times were used to determine the following scattering coefficient using equation 5:

$$\beta = (4,670 \pm 0,425) * 10^{-5} m^{-1} \quad (12)$$

The error was determined using gaussian error propagation.

Table 2: Conditions during the experiment

atmospheric pressure p	1012,6±0,2 hPa
temperature T	301,0±0,1 K

To calculate the theoretical value of  $\beta$  as in equation 9 we need the number of concentration N for which we used the ideal gas law:

$$N = \frac{p}{k_B T} \quad (13)$$

With the atmospheric pressure p and temperature T recorded in table 2, the literary value for the refraction index of air  $n=1,000292$  [6] and the wavelenght of the used laser  $\lambda = 405\text{nm}$  the following theoretical value for the scattering coefficient was determined.

$$\beta_{theo} = (4,303 \pm 0,001) * 10^{-5} m^{-1} \quad (14)$$

The error was calculated using gaussian error propagation. If we compare  $\beta$  and  $\beta_{theo}$  we conclude that the experimentally determined scattering coefficient is compatible with the theoretical value.

## 6 Summary

The experiment introduced the theory of Rayleight-scattering and how to measure the scattering coefficient of air using optical ring-down spectroscopy.

Comparing our measurements to the given values ( $\tau_0=10,2\mu s$  and  $\tau=8,98\mu s$  [1]) we can conclude that our experimental values are identical with them. It's notable that the measurements for the empty cavity are more consistent with each other than the ones for an air filled cavity, which is also why the latter has a bigger error.

As for the scattering coefficients, the experimentally determined one is identical to the one given  $\beta = 4,44 * 10^{-5} m^{-1}$  [1], while the theoretical value is not compatible with the given value  $\beta_{theo} = 4,19 * 10^{-5} m^{-1}$  [1]. This is probably due to the weather on the day of the experiment. Since it was very hot and stormy we had an elevated temperature and a lower atmospheric pressure than in the FP instructions [1].

In conclusion, we were able to get satisfactory results for the ring-down times and the scattering coefficient.

## References

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