Fortgeschrittenen-Praktikum – Rayleigh-Scattering

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This experiment is done within the scope of the advanced lab course for Bachelor Students at Freie Universität Berlin. It should give an experimental introduction to Rayleigh scattering processes, the Scattering-Ring-Down Spectroscopy and should give a better understanding of Rayleigh scattering phenomenon in nature.

1 Theoretical Principles

Rayleigh Scattering is a type of elastic scattering of electromagnetic waves at particles, which are significantly smaller than the wavelength of the photon. Rayleigh-scattering can be explained by the Mie-theory, which explains the dependence of the scattering-process from the wavelength.

If there is a collision of an electromagnetic wave with an atom, the atom will be subject of a change of the electromagnetic field produced by the photon. This change will be sinusoidal and hence the atom will resonate. Therefore, the atom can be described as a dipole. The electric and magnetic dipole field can be described the following way[1]:

$$\vec{E}(\vec{r},t) = -\frac{\mu_0 p_0 \omega^2}{4\pi}\frac{\sin\theta}{r}\cos\left(\omega\left(t-\frac{r}{c}\right)\right)\hat{e}_\theta \tag{1}$$

$$\vec{B}(\vec{r},t) = -\frac{\mu_0 p_0 \omega^2}{4\pi}\frac{\sin\theta}{r}\cos\left(\omega\left(t-\frac{r}{c}\right)\right)\hat{e}_\phi, \tag{2}$$

where ω is the dipole-frequency and p_0 the dipole-moment. The probability that a scattering process will take can be described by the scattering cross-section σ:

$$\sigma(\nu) = \frac{8}{3}\pi\frac{e^2}{m_e c^2}\frac{\nu^4}{\omega^4}, \tag{3}$$

where ν is the frequency of the wave. Since (in our case) we have oscillating atoms, $\omega \ll \nu$, because $\lambda \gg$ size of the atom. We may replace $\nu = {}^{c}/_{\lambda}$ to get the dependence of the wavelength. In the case of several atoms N and the resulting refraction-index n we can rewrite σ as:

$$\sigma(\lambda) = \frac{8\pi(n^2-1)^2}{3N^2\lambda^4} \tag{4}$$

With this scattering-cross-section it is easy to get the scattering factor β:

$$\beta = N\sigma = \frac{8\pi(n^2-1)^2}{3N\lambda^4} \tag{5}$$

2 Set-Up

To measure the Rayleigh-scattering, in this experiment a cavity-ring-down-spectrometer ist used. The cavity-ring-down-spectrometer is made of two spherical mirrors and a tube, which can be evacuated. A laser-beam is introduced into the cavity and may be reflected several times, to maximize the length of interaction with the medium in the cavity. This way, scattering with a very small number of particles can be measured. The reflectance of the mirrors is at about $R = 99.98\%$, so each time the beam hits one of the mirrors about 0.02% of the light is transmitted. Behind one of the mirrors is a detector which measures the transmitted part of the beam. The signal intensity I which is recorded this way is decreasing exponentially with the time t. This is caused by two different mechanisms: Scattering and reflection:

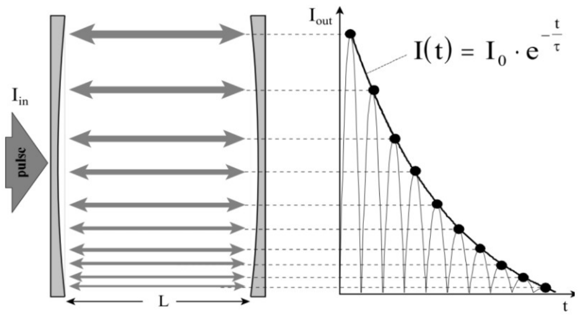

Figure 1: Schematic set-up of a cavity-ring-down-spectrometer [2]

$$I(t) = I_0 e^{-t\left(\beta c + \frac{1}{\tau_0}\right)}, \tag{6}$$

where I_0 is the starting intensity and τ_0 the damping by reflection. It can be expressed the following way:

$$\tau_0 = \frac{L}{c(1-R)}, \tag{7}$$

with L the length of the cavity. This is the damping, when the cavity is evacuated. If a gas is introduced, we get:

$$\tau(t) = \frac{L}{c(1-R(\lambda)+\beta(\lambda)L)} \tag{8}$$

By comparison of the damping constant in the evacuated and the non-evacuated case, the coefficient β can be calculated.

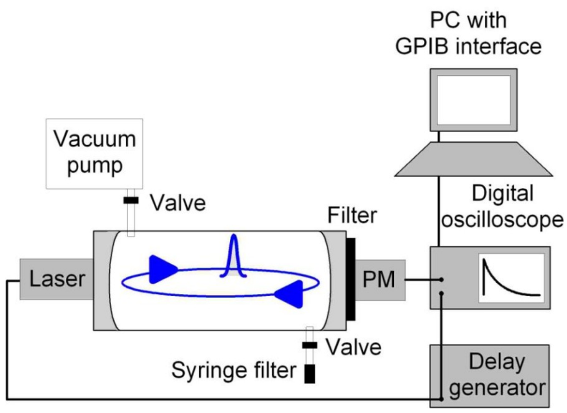

Figure 2: Set-up of the experiment [2]

References

[1] David J. Griffiths. *Introduction to Electrodynamics (3rd Edition)*. Addison Wesley, 1999. ISBN 013805326X.

[2] FU Berlin. Ba15 - rayleigh-streuung, 2011. URL `https://wiki.physik.fu-berlin.de/fp/`.