Project A: Rydberg Atoms

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I. Investigation of the Reference Cavity

In the previous discussion, it was shown that the two lasers of 960 nm and 780 nm are locked in the same stable reference cavity to generate the two photon transition. The optical reference cavity consists of two curvature mirror as illustrated in Figure.1

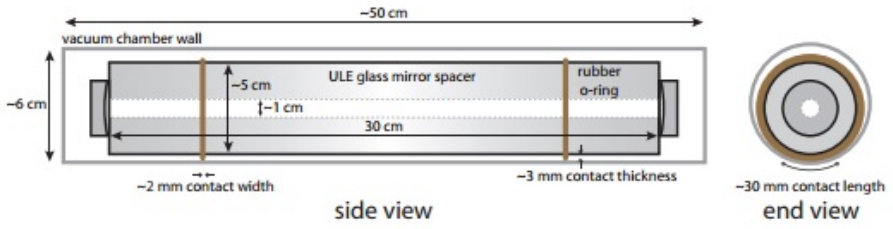


Figure 1: Side View of the Optical Cavity[1]

A little misalignment of the laser mirrors causes different path length for different rays inside the cavity. The fractional frequency change is proportional to the fractional length change of the cavity as described in Equation.1

$$\frac{\delta\nu}{\nu} = \frac{\Delta L}{L} \tag{1}$$

The laser frequency can be calculated by using Equation.2

$$\nu = \frac{c}{\lambda}. \tag{2}$$

As shown in the Figure.1, the distance between two mirrors in the cavity is L=30 cm. In addition, it is obtained from the experiment that line width measurement of the laser systems is 2 kHz. Applying to the equation 1, gives a changed in the cavity length allowed, which are 1.92 pm for 960 nm and 1.56 pm for 780 nm which can play an important factor when trying to have a coupling of two lasers in the same cavity.

Based on the manufacturer specification, the intensity reflectivity of the mirror is R = 0.99997 and the cavity finesse F $\approx$ 100, 000. Performing direct measurement of the reflectivity is quite difficult. Another approximation in the experiment to measure the reflectivity is done by scanning the laser frequency through a narrow line width cavity resonance. The cavity is not at full power before the laser get out from the resonance. A little frequency jump beyond the cavity line width and exhibit a damped ringing behavior that is consistent with slight power buildup. It is required

n bounces from mirrors of intensity reflectivity R to reduce the cavity power to 1/e as stated in the Equation.3

$$R^n = \frac{1}{e} \tag{3}$$

The relation between ring down and n bounce follow the Equation.4

$$\tau_{ring} = \frac{nL}{c} \tag{4}$$

The cavity length is known and the observed ringdown time $\tau_{ring} \approx 50 - 75\mu$s, The estimation of mirrors reflectivity is .99998 < R < .999987, thus giving an estimated finesse 157,000 < F < 235,000. CCompared to the manufacturer specification, the measured value is higher. Further analysis to get comprehensive estimation is needed since considering to get highly reflectivity coating is not easy.

As stated previously, the cavity is assumed to be stable. Cavity vibration and thermal drift might cause slight extension and change the center frequency of the locked lasers. In order to maintain the stability of the cavity from these factors, passive vibration isolation was applied to the table, and the cavity was put in a temperature stabilized vacuum chamber. However, based on the experiment, these factors are considered to be insignificant compared to the duration of the lasers have been locked to the cavity. From the observation, there is difference between the lasers being locked for a short time and reaching equilibrium after many hours of being locked. This require the lasers to be locked to the cavity most at all times.

It is possible that air could leak to the vacuum cavity and change the resonant frequency. The maximum air pressure leak to the cavity can be obtained by Equation.5 [3]

$$n = 1 + \frac{\lambda}{2L\Delta p} \tag{5}$$

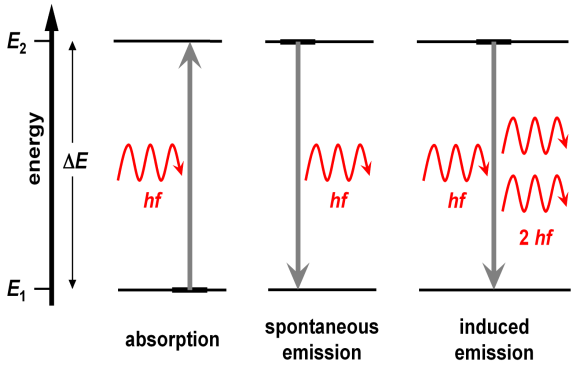
Assume the Edlen value is (n-1 = 0,000286) for given initial condition of $P_0 = 1.01 \cdot 10^5$ Pa and T_0 = 200C [4]. The temperature of the cavity are kept at 25^0C, and the length of the cavity has been known L=30 cm, thus give Δp of 960 nm wavelength is 575 Pa and 468 Pa for 780 nm wavelength.

II. Two level Systems

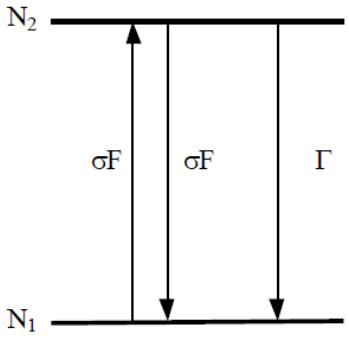
A two level system is the most general way of describing matter, if we are interested in a natural change of the system we have to take into account its interaction with an incoming electromagnetic field or the change produced by an outgoing field. As discussed in the first part of this project Einstein was able to model probability rate of absorption or emission of light by an atom or molecule by taking into account three principle components, light absorption, stimulated emission and spontaneous emission as shown in Figure.2a. In the case of a closed system as shown in Figure.2b we can assume that the number of electrons N_k in the hole system is constant $N_1 + N_2 = N$, for this two level system, σ is the absorption cross section for transition $1 \leftrightarrow 2$, F is the amount of photons per area and second and Γ is the inverse of the upper state life time $\Gamma = 1/T$. There exists a relation between the amount of photons per area and the upper state life time given by

$$F = \frac{\Gamma}{2\sigma} \tag{6}$$

. One of the most interesting parts of these systems is the population in each level, in general we can find the population by using Einsteins coefficients as was shown and thoroughly discussed by D. Steck in Reference [2].



(a) General description of the allowed transition in two level system or analogs to this.



(b) Specific example of a two level system where the rates of absorption and induced emission are the same.

Figure 2: Two level systems showing the different fundamental components, where a. discussed general transitions for two level systems and b. is a specific example used where the rates of absorption and induced emission are the same.

One of the most important traits of a two level system population is the fraction of excited electrons for a given input intensity, which given by Equation.7 where Δ is the detuning and I_s is the saturation intensity. The relation given for the fraction of excited electrons holds for all intensity's so if we consider the case where the intensity tends to infinity we can see that the fraction of excited electron becomes half of the total population.

$$f_{exc} = \frac{\frac{I}{2I_S}}{1 + \frac{I}{I_S} + \left(\frac{2\Delta}{\Gamma}\right)^2}, \quad \lim_{I\to\infty} f_{exc} = \frac{1}{2} \tag{7}$$

We can understand this phenomena by keeping in mind that the average life time in a rubidium atom of a spontaneous decay is $T \approx 0.17\mu s$ and a spontaneous emission rate goes up with the intensity of the filed. Now if we have an infinitely strong light source we would be constantly exciting electrons to the upper state, but at the same time there would be enough intense light to drive a spontaneous emission and bring the electron to the lower state, the balance in this system would become evident since we would make the rate of absorption and emission equal. Since the stimulated emission is dependent of the incoming light and not a life time if we have a very intense source the factor of spontaneous emission becomes less relevant.

Lets consider a more realistic case of intensity for the system shown in Figure.2b, driven by an intensity equal to the saturation intensity $I = I_s$. Now we are interested in how many photons per transition cross section are and life time would correspond to the saturation intensity, or in other words what would σ be for this system at the given intensity. Steck's also covers a general way to

find the cross section for these types of transition, which can be written as [2]:

$$\sigma = \frac{\sigma_0}{1 + 4(\Delta/\Gamma) + (I/I_s)},\ \sigma_0 = \frac{\hbar w \Gamma}{2I_s} \tag{8}$$

In the cases of saturation we get that the scattering cross section σ drops to half of the weakly pumped value σ_0. Now to put some values in we have the specific case of rubidium, where $I_s \approx 35.8 W/m^2$, $\Gamma = 35.8$ MHz, $w \approx 384.2$ THz for a $\lambda \approx 780$ nm giving a cross section of $\sigma \approx 10.2$ fm^2. The relation that the absorption cross section σ has with the absorption coefficient α is directly proportional attenuated by the atomic number density N_0 as $\sigma = \alpha / N_0$. An other interesting parameter for are case of saturated intensity would be what is the population difference if the upper-lower state difference is N at zero intensity. Using the rate equations for the system in Figure.2b we can do the following calculation:

$$\frac{dN_1}{dt} = -\sigma F N_1 + \sigma F N_2 + \Gamma N_2\ ,\ \ \frac{dN_2}{dt} = \sigma F N_1 - \sigma F N_2 - \Gamma N_2 \tag{9}$$

$$N = N_2 + N_1 \rightarrow \frac{dN_1}{dt} = -\frac{dN_2}{dt} \tag{10}$$

if we calculate the fraction of exited atoms for $I = I_s$ we get that $N_2 = N/4$

$$\sigma F N_1 = \sigma F N_2 + \Gamma N_2\ \rightarrow N_1 = \left(1 + \frac{\Gamma}{\sigma F}\right) N_2 \rightarrow N_1 = 3N_2 \tag{11}$$

thus, giving that the population difference is $\Delta N = 1/2$. If we consider the specific transition $5s\ ^2S_{1/2}(F = 2) \rightarrow 5p\ ^2P_{3/2}(F = 3)$ for ^{87}Rb what power would we need to saturate this transition. From Reference [2] we get that the saturation intensity for this transition is $I_s = 3.58$ mW/cm^2 and assuming that we have beam with a 100 μm radius, one can find that the power is $P = I_s A = 1.125 \mu$W which is a relative low power but its need to be very prices to saturate a single transition in rubidium.

References

[1] "Rabi oscillations and excitation blockade between ground and Rydberg states of single optically trapped Rubidium atoms", Todd Johnsson, Phd Thesis.

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