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Lecture 3 He-Ne Laser

3.1. He-Ne laser

Helium Neon laser is the first laser operating at cw and the first gas laser demonstrated. Its most popular emission wavelength is 632.8 nm, which involves a transition from $^3S_2$ to $^2P_4$ level of Ne. The helium gas (like the nitrogen molecules in the CO_2 laser) serves as the metastable species for transferring energy from the hot electrons to the appropriate levels in Ne. In a typical He-Ne laser tube, the partial pressure ratio of He to Ne is typically 5 to 1 (or 20 to 1). It uses Brewster windows for polarization control (TM will be selected as there is no reflected beam, while TE will have reflected beam), similar to that in CO_2 laser. The following table summarizes typical parameters:

Emission wavelengths	632.8, 543.5, 594, 612, 1152.3 nm
Spontaneous linewidth/gain bandwidth	1.5 GHz, Doppler Broadened
Typical cavity length (L)	0.3 m (several longitudinal modes possible)
Typical laser diameter	2 – 8 mm (p d ~ 0.36 torr-cm, p = part. pres.)
Absorption cross section σ_{ul}	3×10^{-17} m^2 at 632.8 nm
Single pass gain (exp (σ_{ul} $\Delta N_{ul} L$))	0.03
Output power	0.5 – 100 mW, TEM dominated

The spectroscopic notation for Ne is rather confusing, but it has been widely used. The numbers and letters are just names of the states. For instance, the transition from $^3S_2$ to $^2P_4$ gives the 632.8 nm emission, the $^2P_4$ to $^1S_3$ transition, which is one of the spontaneous decay routes for the $^2P_4$ state down to the ^1S states, gives the 594.4 nm emission. It is noted that the $^2P_4$ to ^1S_x transitions (x = 2 –5) all have large A coefficient (see below) and they are relatively difficult to lase. (Ne: ^1S, ^2S and ^3S have 4 states, ^2P and ^3P have 10).

3.1.1. Pumping sequence

(a) Electric power is transferred to electrons via electric discharge, with a typical current in the 5 to 100 mA range.

(b) Helium is the majority gas present inside the medium, it is excited by hot electrons (at the high energy tail of the Maxwellian distribution of electrons):

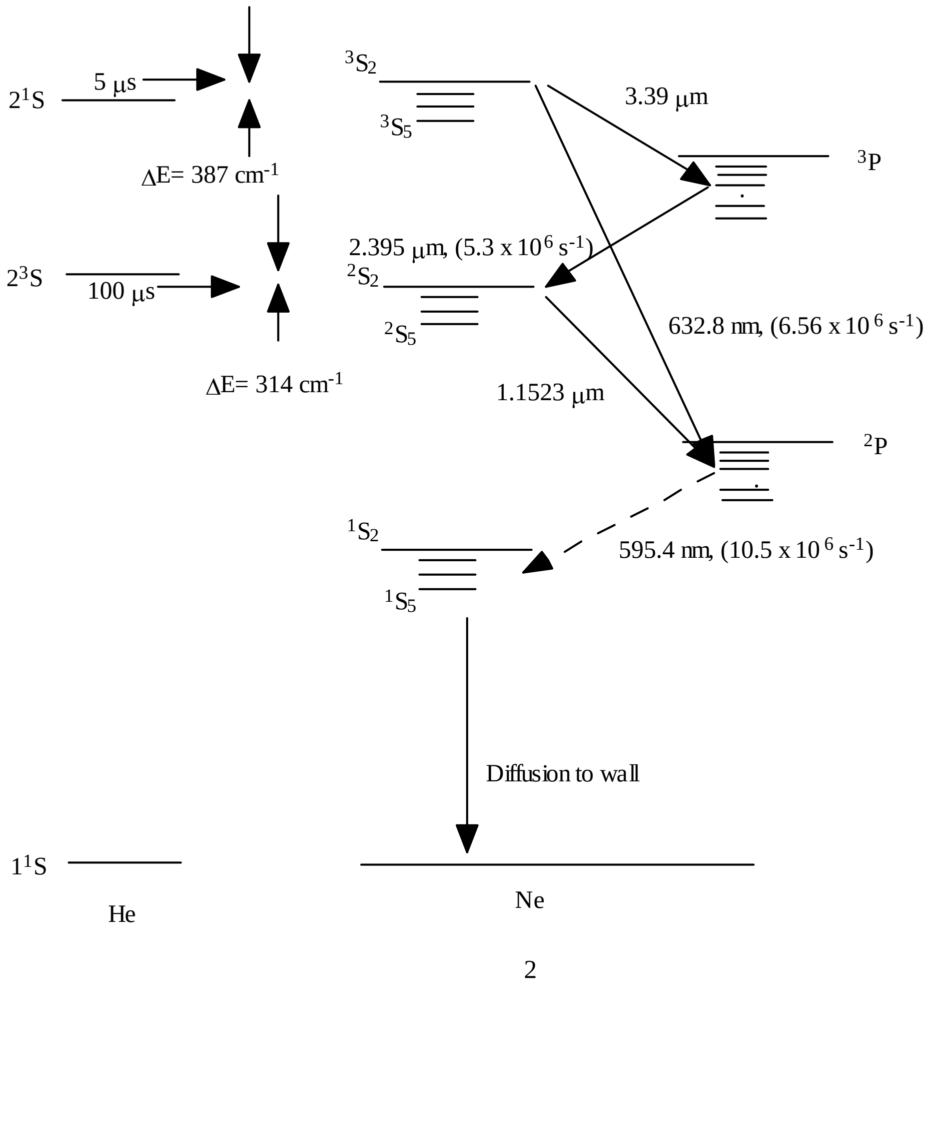
e(k.e.) + He (1^1S) ➔ He (2^1S) + e(k.e. – 20.6 eV)

(c) The He (2^1S) state is metastable, like the excited states in N_2, it cannot decay back to the ground state by emitting a photon (because ΔJ would then be zero). Thus the 2^1S is long-lived (lifetime ~ seconds) and it is more likely to transfer its energy via collision with Ne:

$$He(2^1S) + Ne(ground) + 387\ cm^{-1} \rightarrow He(1^1S) + Ne(^3S_2)$$

The 387 cm^{-1} is from the kinetic energy of the colliding atoms. This transfer process is therefore quite selective! The $^3S_2$ state forms the upper state of the 632.8 nm laser transition, while the ^2P state forms the lower state. In order to be an effective transition, the ^2P states must have a short radiative lifetime.

The following figure shows the pertinent transitions in He-Ne lasers, the values in parenthesis are A's in unit of s^{-1}.



(d) Competing processes:

(i) Helium can be excited to another metastable state, 2^3S, which can subsequently transfer its energy via collision to Ne ^2S_x (x= 2 to 5) and form another possible upper state for the laser transition to $^2P_4$ state. A particular transition among them, $^2S_2$ – $^2P_4$ lases at 1152.3 nm which competes for the same lower state of the $^3S_2$ – $^2P_4$ transition. This results in low efficiency for both!

(ii) Another competing transition which compete for the upper state of the $^3S_2$ – $^2P_4$ transition is the $^3S_2$ – $^3P_4$ transition which emits at the 3.39 μm wavelength. This has a large stimulated emission cross-section as well.

(iii) Ne can also be excited in the electron transfer process. In this process, the ^1S_y states can be excited to ^2P_x, so the lower state can become populated, severely limiting the emission power of the laser (see below).

So the design of the laser cavity is very important for the operation of 632.8 nm laser. Let's examine the 632.8 nm transition using a simple model. Ignore first the rate equations for the electrons and the ions and assume the electron density is directly proportional to the current. Second, focus on the He 1^1S to 2^1S transition and denote M as the metastable 2^1S state that transfers its energy to the Ne $^3S_2$ state (denoted as the upper state 2) at a rate r_t. M can also diffuse to the wall and de-activate, or it can be ionized by a second collision with another electron,

$$\frac{d[M]}{dt} = n_e < \sigma_m v_e > [He] - \frac{[M]}{\tau_m} - r_t[M][Ne] - n_e < \sigma_i v_e > [M] \qquad (1)$$

In equation 1, n_e is the electron density, v_e is the electron velocity, [Ne] is the neon molecule density, σ_m is the collision cross section between the electrons and M, σ_i is the cross-section for collision with another electron for ionization, τ_m is the diffusion rate of M to the wall. < > denotes averaging over an assemble. The first term in (1) represents the 1^1S -- 2^1S transition process, the second represents the diffusion to the wall, the third represents the transfer to neon, the fourth denotes the ionization.

In the same manner, we can describe, in the absence of stimulated emission, the N2, which is the upper state $^3S_2$ (Do not confuse N_2 with the nitrogen molecule!),

$$\frac{d[N_2]}{dt} = r_t[M][Ne] - A_2[N_2] \quad (2)$$

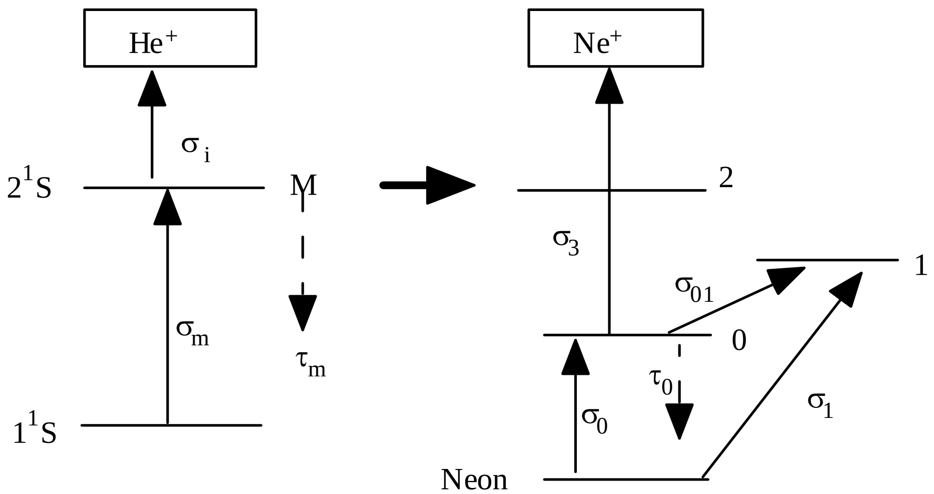
In equation 2, A_2 is the spontaneous emission rate of N2 states. For simplicity, let's assume that the spontaneous decay of N2 states end up in state 0 (i.e. ^1S Ne state) and not to N1 states (i.e. $^2P_4$ Ne). We have two processes to populate N1, the lower state. One is via direct electronic excitation of the ground state of neon (with cross-section σ_1), the other is via electronic excitation from state 0 (with cross section σ_{01}),

$$\frac{d[N_1]}{dt} = n_e \left\{ < \sigma_1 v_e > [Ne] + < \sigma_{01} v_e > [N_0] \right\} - A_1[N_1] \quad (3)$$

In equation 3, N_0 is the density of the state 0, and A_1 is the spontaneous decay rate for N1. In the same manner, we can describe N_0 with,

$$\frac{d[N_0]}{dt} = n_e < \sigma_0 v_e > [Ne] + A_1[N_1] + A_2[N_2] - n_e < \sigma_{01} v_e > [N_0] - \frac{[N_0]}{\tau_0} - n_e < \sigma_3 v_e > [N_0] \quad (4)$$

where σ_0 is the cross-section of the electronic excitation from the neon ground state to state 0, τ_0 is the diffusion rate to the wall, σ_3 is the collision rate with a second electron. Try to interpret each term of equation 4 by yourself. These equations can be summarized by the following figure:



At steady state, all the time derivatives are equal to zero, from Eq. 1, we get,

$$[M] = \frac{n_e < \sigma_m v_e > [He]}{\frac{1}{\tau_m} + r_t[Ne] + n_e < \sigma_i v_e >} \tag{5}$$

From Eq. 2,

$$[N_2] = \frac{r_t[M][Ne]}{A_2} \tag{6}$$

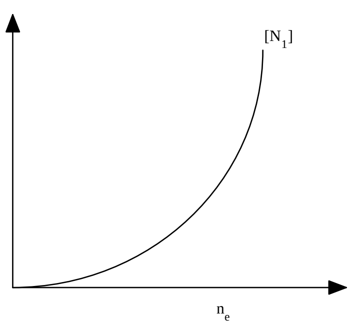
From equations 3, 4, we have

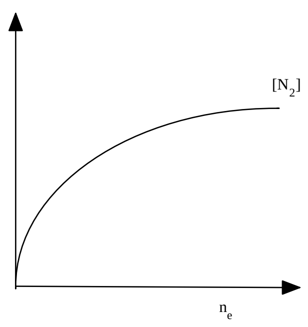
$$[N_0] = \frac{n_e < \sigma_0 v_e > + < \sigma_1 v_e > [Ne] + A_2[N_2]}{\frac{1}{\tau_0} + n_e < \sigma_3 v_e >} \tag{7}$$

and,

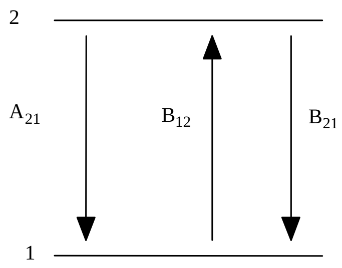
$$[N_1] = n_e < \sigma_1 v_e > [Ne] + n_e < \sigma_{01} v_e > [N_0] \tag{8}$$

From Eq. 5, we see that [M] increases with the electron density n_e until the ionization of He becomes dominant (i.e. the third term in the denominator of (5) becomes dominant), then [M] saturates. Since $[N_2]$ and $[N_o]$ follow [M], they have the same trend and saturate as well. However, $[N_1]$ goes like n_e for both terms, there is no saturation! Therefore, as n_e increases, $[N_2\text{-}N_1]$ goes to a maximum, then decreases to zero and finally becomes negative! This explains why the emission power saturates for He-Ne lasers.





3.2. Laser Basics: Einstein's relationships



Rates for upward and downward transitions:

$$W_{21} = (W_{21})_{induced} + (W_{21})_{spont} = B_{21}\,\rho(\nu) + A_{21} \tag{9}$$

$$W_{12} = (W_{12})_{induced} = B_{12}\,\rho(\nu) \tag{10}$$

At equilibrium:

$$N_2 W_{21}^{\,o} = N_1 W_{12}^{\,o} \tag{11}$$

Therefore,

$$N_2\,[B_{21}\,\rho(\nu) + A_{21}] = N_1\, B_{12}\,\rho(\nu) \tag{12}$$

However, at thermal equilibrium, the Planck's distribution of photons at temperature T (in degree Kelvin) is given by,

$$\rho(\nu) = \frac{8\pi n^3 h\nu^3}{c^3}\,\frac{1}{e^{\frac{h\nu}{kT}} - 1} \tag{13}$$

and the ratio of N's follows,

$$\frac{N_2}{N_1} = e^{-\frac{h\nu}{kT}} = \frac{B_{21}\,\rho(\nu)}{[B_{21}\,\rho(\nu) + A_{21}]} \tag{14}$$

Inserting Eq. 13 into ρ's in Eq. 14 and simplifying the expression, we get,

$$\frac{8\pi n^3 h\nu^3}{c^3\left(e^{\frac{h\nu}{kT}} - 1\right)} = \frac{A_{21}}{B_{12}e^{\frac{h\nu}{kT}} - B_{21}} \tag{15}$$

Thereby we obtain the famous Einstein relationships:

$$B_{12} = B_{21}$$

$$\frac{A_{21}}{B_{21}} = \frac{8\pi n^3 h\nu^3}{c^3} \tag{16}$$

Now, the next one is a major assumption! We take the same A and B's for the lasing process (note that they are obtained from the thermal equilibrium situation), based upon the argument that the lasing process involves a small departure from the thermal equilibrium situation!

$$W_{21} = W_i = \frac{A_{21}c^3}{8\pi n^3 h\nu^3}\,\rho(\nu) = \frac{c^3}{8\pi n^3 h\nu^3 t_{spont}}\,\rho(\nu) \tag{17}$$

where t_{spont} is the reciprocal of A_{21}. The net induced transition is then given by,

$$\begin{aligned}&(N_2W_{21})_i - (N_1W_{12})_i \\ &\quad = (N_2 - N_1)\, B_{21}\, \rho(\nu) \\ &\quad = (N_2 - N_1)\, \frac{c^3}{8\pi n^3 h\nu^3 t_{spont}}\, \rho(\nu)\end{aligned} \tag{18}$$

From Eq. 18, we can see that coherent amplification occurs only when $N_2 > N_1$. Otherwise we have attenuation (or absorption).