9 Oscillation on other wavelengths

The red line at 632.8 nm is not the only possible line of a HeNe laser. The very first HeNe laser in fact oscillated at an infrared transition with wavelength 1.15 µm, and oscillation is possible on numerous other wavelengths both in the visible and the infrared. In this section we shall examine the energy levels of Ne and the conditions required for producing population inversion and hence laser action.

9.1 Electronic shell structure of Ne

Ne has atomic number 10, and in its ground state the neutral atom has 2 electrons in the filled n = 1 shell and 8 electrons in the filled n = 2 shell, n being the principal quantum number of a shell. The weakest bound electrons are the 2p electrons, and in the discharge one of these can be excited to one of the states ns, np, nd .., with n = 3, 4, 5,....

Fig.9.1 shows symbolically the electronic structure of Ne in the ground state and in one of its excited states, and a simplified level scheme is shown in Fig.9.2 together with the lowest excited levels of the He atom.

The Ne levels are shown as grey boxes labelled by the electronic configuration, where we have omitted the filled n = 1 shell and the 2s subshell. In the left column one of the 2p electrons is excited to an ns state where n = 3, 4 or 5. In the right column excitation

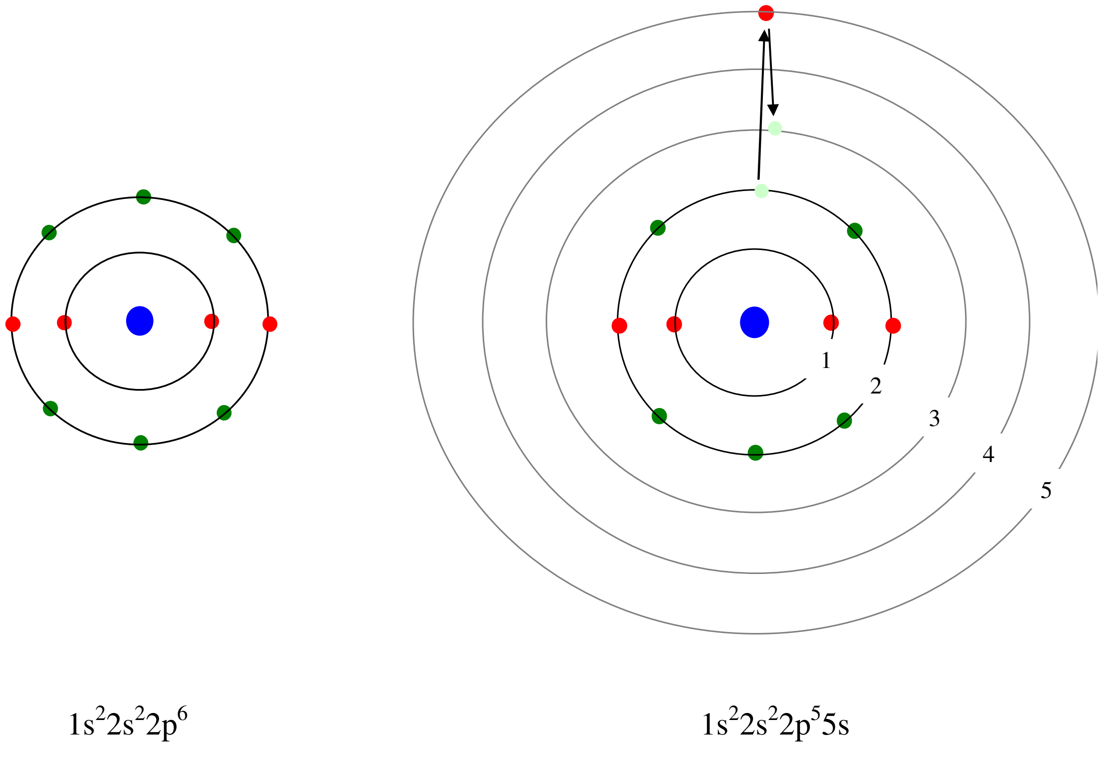

Fig.9.1 Ground state and excited state of Ne

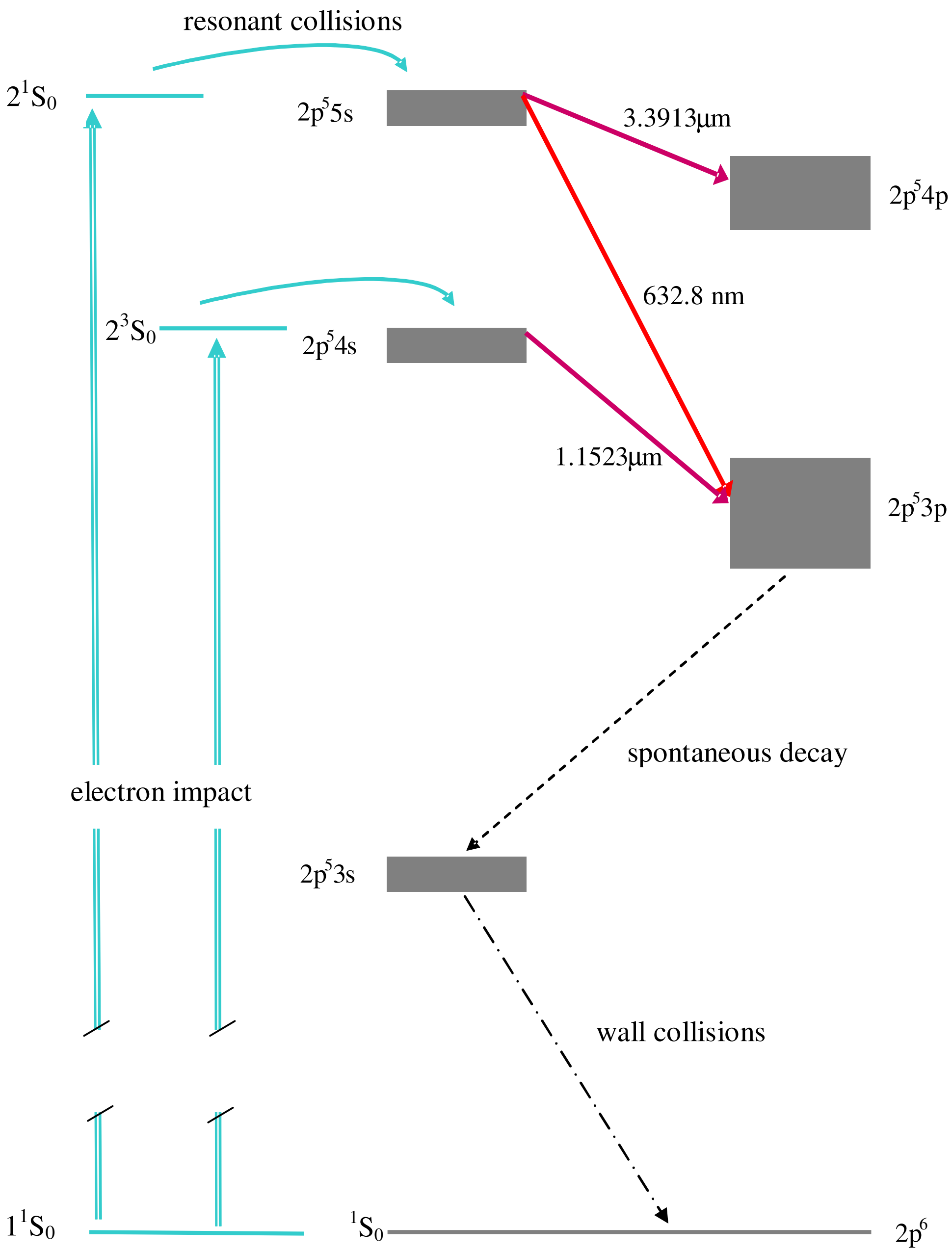

Fig.9.2 Simplified level scheme of He and Ne with laser transitions in red

is to 3p or 4p. Each box represents a multiplet composed of 4 levels if the excited electron is in an s state, and 10 levels if it is in a p state. Laser oscillation occurs on transitions between individual levels of the different multiplets. In the red HeNe laser the upper laser level is one where a 2p electron is excited to the 5s multiplet, and the laser transition takes it down to the 3p multiplet. However, the distinctive red color of the discharge is caused by spontaneous decay from the 3p to the 3s multiplet.

9.2 Term values for Ne

In the notation of Fig.9.2 the electrons are thought of as independent, but this is a simplification. The orbital motions of different electrons are coupled by electrostatic interactions, and the magnetic moment associated with the spin of an electron interacts with the magnetic moment associated with its orbital motion. Since all of these interactions are internal to the atom, the total angular momentum is a constant of the motion, and therefore any state of the atom as a whole can be labelled in terms of a quantum number J representing the total angular momentum.

The coupling of individual angular momenta is determined by the relative magnitude of the electrostatic interaction and the magnetic interaction. If electrostatic interaction dominates, the orbital angular momenta $\bar{l}_i$ of different electrons are coupled to produce a total orbital angluar momentum $\bar{L}$. Likewise the individual spins are combined to produce a total spin $\bar{S}$, and eventually, the magnetic interaction couples $\bar{L}$ and $\bar{S}$ to produce the total angular momentum $\bar{J}$. This type of coupling is called L-S coupling, and can be symbolically represented as

$$\left\{(\bar{l}_1\bar{l}_2)(\bar{s}_1\bar{s}_2)\right\} \Rightarrow \left\{\bar{L}\bar{S}\right\} \Rightarrow \bar{J}$$

On the other hand, if magnetic interaction dominates, the orbital angular momentum $\bar{l}_i$ and the spin $\bar{s}_i$ of individual electrons are coupled to produce a total angular momentum for each electron, and the electrostatic interaction subsequently couple these to the total angular momentum $\bar{J}$. This type of coupling is called j-j coupling, and can be represented as

$$\left\{(\bar{l}_1\bar{s}_1)(\bar{l}_2\bar{s}_2)\right\} \Rightarrow \left\{\bar{j}_1\bar{j}_2\right\} \Rightarrow \bar{J}$$

Neon turns out to be an intermediate case which can be adequately described neither by L-S, nor by j-j coupling [6]. We first note that any filled shell will have total orbital angular momentum L = 0 and total spin S = 0. This implies that J = 0, so that the term symbol for the ground state will be $^1S_0$.

If we remove one 2p electron from the filled n=2 shell, we are left with nine electrons in the configuration $1s^2 2s^2 2p^5$, and this electron configuration together with the nucleus constitutes what is called the parent ion. Removing one electron from a filled shell leaves us with a total orbital angular momentum and total spin corresponding to a single electron. The magnetic interaction within the parent ion is larger than the electrostatic interaction with the excited electron, and therefore L-S coupling will apply for the parent ion, where we have $l = 1$ and $s = 1/2$, which can couple to produce $j = l - s = 1/2$ and $j = l + s = 3/2$. Thus, for the parent ion we have the two possible term values $^2P_{1/2}$ and $^2P_{3/2}$, and by Hund's third rule the latter is lowest in energy.

For the interaction between the parent ion and the excited electron, however, the electrostatic interaction is stronger than the magnetic interaction, and therefore the orbital angular momentum $\bar{l}$ of the excited electron couples to the total angular momentum $\bar{j}$ of the parent ion to produce an intermediate angular momentum $\bar{K}$. Finally, $\bar{K}$ couples to the spin $\bar{s}$ of the excited electron to produce the total angular momentum $\bar{J}$. This intermediate case is called l-j coupling, and symbolically it can be represented as

$$\{[(\bar{l}_1\bar{s}_1)\bar{l}_2]\bar{s}_2\} \Rightarrow \{[\bar{j}_1\bar{l}_2]\bar{s}_2\} \Rightarrow \{\bar{K}\bar{s}_2\} \Rightarrow \bar{J}$$

A term produced by l-j coupling is usually specified in the Racah notation as

$$({}^{2S+1}L_j)\,nl\,[K]_J$$

where the first brackets enclosing the term symbol for the parent ion is followed by *n* and *l* for the excited electron. If the excited electron is an ns electron, we get four terms, while an np electron leads to a total of 10 terms as listed in Table 9.1 for 5s and 3p.

For simplicity, the notation is often contracted by omitting the reference to the parent ion, and instead providing the symbol for the excited electron with a prime if the parent ion has j = 1/2. This is used in Fig.9.3, where the levels are shown with correct order and spacing, using data given in [7] and reproduced in section 4.1 of part C.

excited electron	parent ion	K	J	Racah notation
5s	$^2P_{1/2}$	1/2	0	$(^2P_{1/2})5s\,[1/2]_0$
			1	$(^2P_{1/2})5s\,[1/2]_1$
	$^2P_{3/2}$	3/2	1	$(^2P_{3/2})5s\,[3/2]_1$
			2	$(^2P_{3/2})5s\,[3/2]_2$
3p	$^2P_{1/2}$	1/2	0	$(^2P_{1/2})3p[1/2]_0$
			1	$(^2P_{1/2})3p[1/2]_1$
		3/2	1	$(^2P_{1/2})3p[3/2]_1$
			2	$(^2P_{1/2})3p[3/2]_2$
	$^2P_{3/2}$	1/2	0	$(^2P_{3/2})3p[1/2]_0$
			1	$(^2P_{3/2})3p[1/2]_1$
		3/2	1	$(^2P_{3/2})3p[3/2]_1$
			2	$(^2P_{3/2})3p[3/2]_2$
		5/2	2	$(^2P_{3/2})3p[5/2]_2$
			3	$(^2P_{3/2})3p[5/2]_3$

Table 9.1

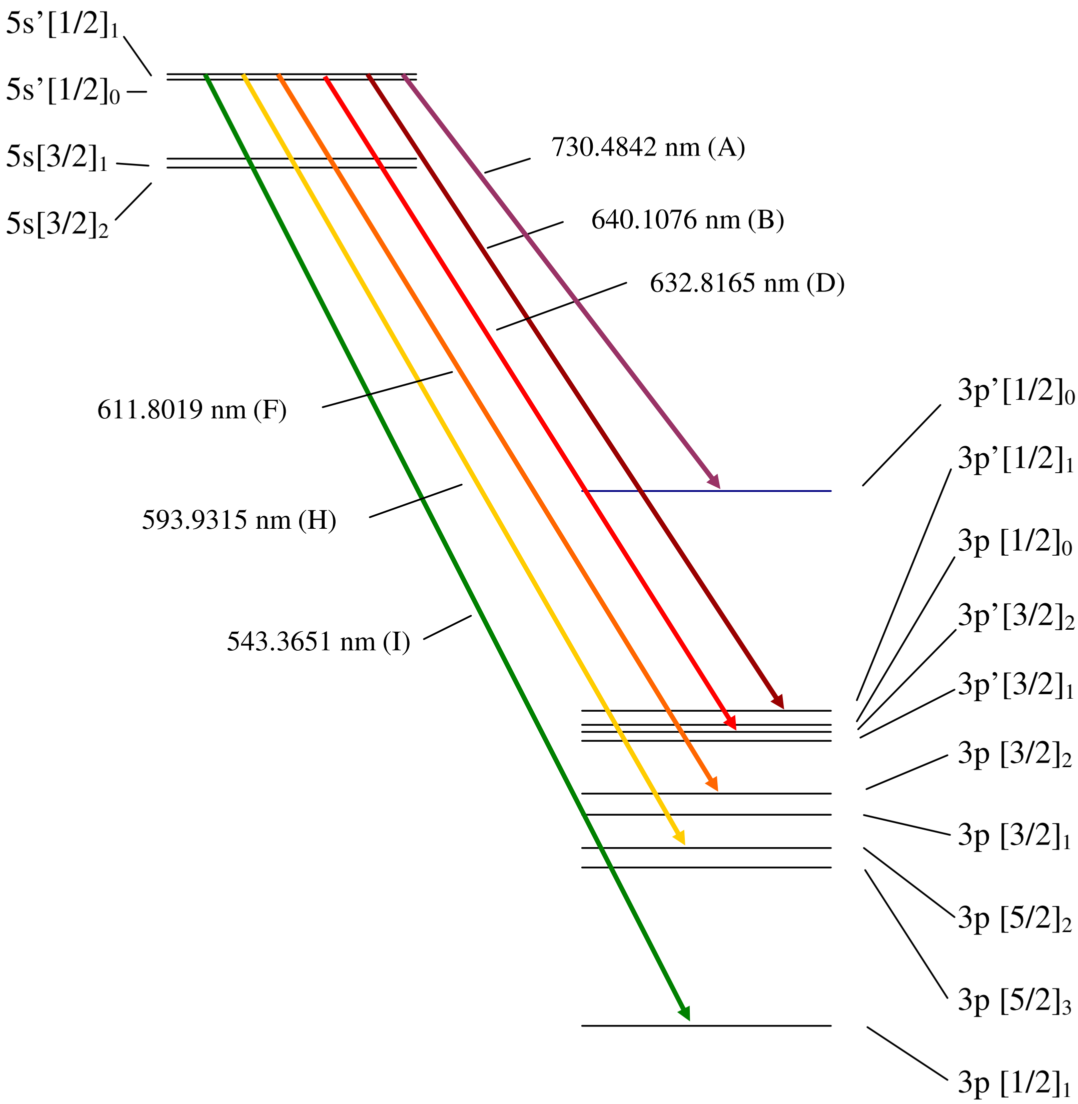

Fig.9.3 Laser transitions from the 5s to the 3p levels. Labels given as capital letters refer to Sec.4.1 of part C.

Allowed transitions are determined by selection rules. One rigorous selection rule for electric dipole transitions is that transitions are only allowed between states of different parity. Since no internal interaction can mix states of different parity, the parity of a state in the l-j scheme is the same as that of the independent particle configuration from which it originates. Consequently, in Fig.9.2 the ns states have odd parity (due to the parent ion) and n’p states have even parity, so that only transitions ns ↔ n’p are allowed.

J represents the total angular momentum of the atom, and since this cannot be changed by internal interactions, J is a strictly good quantum number for any type of coupling. This leads to the selection rule

$$\Delta J = 0, \pm 1 \qquad \text{(except} \quad 0 \Leftrightarrow 0)$$

9.3 Conditions for inversion

A condition for laser action is that population inversion can be created between the upper and lower laser level, cf. Fig.9.2. This requires that atoms can be transferred into the upper level and remain there long enough for population to build up. In addition, once they have decayed to the lower level by stimulated emission, this level must be emptied sufficiently fast to avoid population build-up.

Excitation of atoms to the upper laser level occurs directly from the ground state by electron impact. However, a more important mechanism is energy exchange between Ne atoms in the ground state and He atoms excited to the lowest lying metastable singlet and triplet states, which are nearly resonant with the 2p5s and 2p4s manifolds of Ne.

From the upper laser level the atoms can decay very fast to the ground state by emitting VUV radiation. However, this radiation is reabsorbed, and due to this radiation trapping, the effective radiative lifetime of the upper level becomes that for transitions to the $2p^5 3p$ manifold, which is on the order of 10^{-6} s. From the lower laser level atoms can decay to the $2p^5 3s$ manifold, and the radiative lifetime for this is about 10^{-7} s, i.e. an order of magnitude shorter.

The levels of the $2p^5 3s$ manifold are similar to those of $2p^5 5s$ given in Table 9.1, with J = 0, 1, 1 and 2. Thus two of these are metastable, since the ground state has J = 0, and $0 \leftrightarrow 0$ as well as $2 \leftrightarrow 0$ are forbidden. The remaining two levels have J = 1, and can decay radiatively to the ground state. However, as discussed above, this radiation is reabsorbed, so that the states become long lived. This is bad because a build-up of population in $2p^5 3s$ would lead to reabsorption of radiation from the lower laser level, and hence be detrimental to population inversion. For this reason the diameter of the discharge tube is kept small, so that by diffusion and subsequent collisions with the wall $2p^5 3s$ can be depopulated.

9.4 Paschen notation

For completeness it should be mentioned that a vast majority of literature on the HeNe laser uses the Paschen notation rather than the Racah notation for the energy levels. In the Paschen notation, the manifolds $2p^5 3s$, $2p^5 4s$, $2p^5 5s$, $2p^5 3p$ and $2p^5 4p$ are labeled 1s, 2s, 3s, 2p and 3p respectively. Within the s manifolds the levels are labeled in order of decreasing energy with a subscript 2 ...5, and within the p manifolds with subscripts 1...10. In this notation, the red 632.8 nm line is the transition $3s_2 \rightarrow 2p_4$ etc. The Paschen notation should be considered as merely a way of labelling the levels, and apart from the letters s and p it contains no information about the states or the interactions. Occasionally we shall use the Paschen notation since the trailing subscript provides a convenient sequential labeling of the levels in a multiplet. However, we shall omit the leading integer since its disagreement with the principal quantum number of the electron shell is strongly misleading.

9.5 Oscillation on transitions other than 632.8 nm

A list of the small signal gain coefficients for a number of laser transitions can be found in [8], and is given as Table 9.2, where the Paschen notation is used. A first condition for obtaining laser oscillation is that the small signal gain per double pass exceeds the losses. However, a further consideration is that all lines of the table originate from the same level, and hence the transitions would engage in what is called gain competition.

The line with the strongest gain would oscillate first, and this would drain population from the upper level and hence make oscillation on the other transitions less likely. Thus, simultaneous oscillation on strong and weak lines is generally not to be expected.

One way of obtaining oscillation on one of the weaker transitions is to build into the resonator a dispersive element such as a prism or a grating, which will enable the resonator to be aligned only for a certain wavelength. Alternatively, the mirrors can be narrow-band multilayer dielectric mirrors with reflectivity curves tailored to the desired wavelength.

output wavelength [nm]	color	lasing transition (Paschen notation)	label	gain %/m [various]	gain %/m [8]
543.3651	green	s2 → p10	I	0.52	0.59
593.9315	yellow	s2 → p8	H	0.5	0.67
604.6135	orange	s2 → p7	G	0.6	1
611.8019	red/orange	s2 → p6	F	1.7	2
629.3745	red	s2 → p5	E	1.9	2
632.8165	red	s2 → p4	D	10	10
635.1853	red	s2 → p3	C	1	1.25
640.1076	red	s2 → p2	B	4.3	2
730.4842	deep red	s2 → p1	A	1.2	1.25

Table 9.2 Gain on different laser lines, adapted from [8]

Lab 16: Oscillation on 640.1 nm

According to Table 9.2 the second highest gain is obtained on 640.1 nm, so it might be possible to obtain simultaneous oscillation on this line and on the normal 632.8 nm line. From Lab11, the total loss per double pass from sources other than the 1.4% transmission of the output coupler, amounts to 1.6%. Thus, the total loss per double pass is 3.0%, and with a gain length of 0.31 m the minimum small signal gain required for oscillation is 4.8%/m. This is more than is available on 640.1 nm, so transmission of the output coupler has to be reduced below the nominal 1.4%. One possibility is to change the output coupler to a totally reflecting flat mirror as was done in Lab12. However, a more flexible approach is to retain the 1.4% output coupler, and use the total reflector for retro-reflecting the laser output back towards the laser resonator. Viewed from the resonator, this combination of two mirrors constitutes a resonator with transmission characteristics similar to that discussed for the laser resonator in (8.5) and Fig.8.1. If losses other than those arising from transmission can be neglected, the reflectivity will vary between zero on resonance and a maximum value off resonance.

Monitor the laser output on the reflection from the Brewster window, and use an available grating or spectrometer for deciding whether or not 640.1 nm is lasing.

9.6 Line selection with prism

A prism incorporated in the resonator can provide line selection. However, to avoid detrimental Fresnel losses it is important that the refractive index and the apex angle are matched to the desired wavelength range. Fig.9.4 shows the minimum loss per double pass of a prism as a function of the refractive index for three different apex angles. It is seen that the losses for the 69.1° prism are very small around 1.457, which happens to be the refractive index of fused silica at a wavelength of 632.8 nm, and such a prism is commercially available.

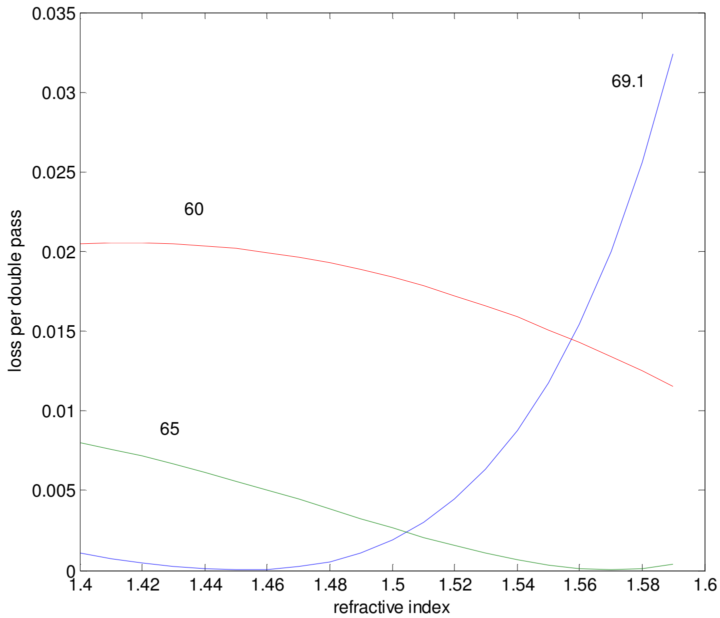

Fig.9.4 Minimum loss per double pass of Brewster prism as a function of refractive index for different apex angles

Lab 17: Wavelength selection with Brewster prism

For an angle of incidence corresponding to the Brewster angle, calculate the deflection of a 632.8 nm beam after transmission through a fused silica prism with 69.1° apex angle. Mount a short rail at this angle and position the flat, nominally totally reflecting mirror such that it retro-reflects the beam. Due to the small area of the mirror, the positioning is quite critical, and you might find it convenient to position and align the mirror by means of the beam of a green laser pointer sent backwards through the discharge tube. Note that it has to be green in order to ensure a decent transmission through the back end mirror, which is essentially totally reflecting at 632.8 nm. While this allows you to centre the mirror and to align it vertically, the horizontal alignment will be slightly off due to the difference in deflection angle for green and red light.

If the optics is clean this should allow you to achieve laser action on 611.8 nm in addition to 640.1 nm and 632.8 nm. If you achieve oscillation, try do devise a way of measuring the small signal gain and the saturation intensity for the two weak lines.

10 Spontaneous emission from the discharge

The characteristic orange-red color of the discharge is caused by numerous transitions between the $2p^53p$ and the $2p^53s$ manifolds, cf. Fig 9.2. These transitions can be observed with a suitable spectrometer looking at radiation emitted to the side. The allowed transitions are listed in [7], and are given in section 4.2 of part C.

If a laser transition gets above threshold and starts lasing, an immediate consequence is a massive transfer of atoms from the upper to the lower laser level. This in turn affects the population of all those levels that are coupled to these two levels either by radiative transitions, or by collisional transfer. These population changes can subsequently be detected as changes in the spontaneous emission from transitions involving these levels.

Lab 18: Population dynamics in the HeNe laser

Observe the radiation emitted to the side with a suitable spectrometer, and identify as many of the observed lines as possible using the NIST tables [7].

Record the spontaneous spectrum with lasing on both 632.8 nm and 640.1 nm (cf. Lab 16). Then kill 640.1 nm by blocking the beam path between the two mirrors constituting the output coupler, and record the spectrum again. Finally, kill oscillation in 632.8 nm by blocking the beam path in the main resonator, and record the spectrum a third time. Evaluating the difference between the spectra provides a clear indication of the effect of laser action on the different transitions.

Discuss the results in terms of population changes induced by the lasing transitions.