APPENDIX D LASERS

The wavelength $\lambda$ of light is related to the frequency $\nu$ of a light wave through

$$\lambda = \frac{c}{\nu},$$

where $c$ is the velocity of light. You may recall that, according to quantum mechanics, light consists of individual particles, photons, whose energy $E$ is connected with the frequency $\nu$ of the light wave through:

$$E = h\nu, \quad \text{hence} \quad E = \frac{hc}{\lambda},$$

where $h = 6.63 \times 10^{-34}$ Js is a fundamental constant of nature, Planck’s constant.

You may also recall that atoms can exist only in states with certain, well defined, energies. If an atom is in its state of lowest energy, the ground state, one can lift it into one of the states of higher energy, an excited state, by bombarding it with photons whose energy $E = h\nu$ is exactly equal to the energy difference $\Delta E$ between the ground state and the excited state.

Once in an excited state, an atom will usually decay rapidly to the ground state by emitting another photon of the same energy $E = \Delta E$. It was Albert Einstein who realized that an atom that is already in an excited state can be de-excited by a photon of the proper energy $E = \Delta E$. In going back down to the ground state it will, of course, emit another photon of that same energy.

Is it, perhaps, possible to design an amplifier for light based on this process? You see how it might work: take a large number of atoms in an excited state and shoot in a photon of just the right energy. This photon will de-excite one of the atoms creating another photon. Now we have two photons of the same energy which can hit two atoms and de-excite them creating two more photons which in turn, etc. etc. This should work all the better since the secondary photons share with the original ones not only the energy, they also have the same phase and travel in the same direction.

Normally atoms are in their ground state while the excited states are unoccupied. To make this scheme work one needs to create a population inversion: lots of atoms in the upper and few in the lower state.

For decades after Einstein’s discovery physicists believed that ‘one could show’ that such an inversion could not be accomplished. According to Einstein, those atoms that can be easily excited will easily decay to the ground state by spontaneous emission. Those that do tend to linger in the excited state are those that are difficult to excite in the first place.

If something is really forbidden by a law of nature it just cannot happen. However, it is often the case that it is not really forbidden, just that people have just not been clever enough. Such is the case here. Several ways are now known to put atoms into an excited state and keep them there until they can be de-excited by incident photons. The good example is the well-known helium-neon gas laser and we shall discuss it briefly.

The helium atom has an excited state that is metastable: it lives about thousand times longer than excited atomic states normally do. According to Einstein, it should be a thousand, or so, times harder to excite than other states, and it is harder to do so ... by photons. However, it can quite readily be excited by bombarding the He atom with electrons, as in a gas discharge. It is thus possible to produce large numbers of metastable He atoms in the so-called $2S$ state (see Figure 1).

\[^1\text{The labels } 2S, 3S_2, \text{ etc. give the experts detailed information about the quantum state.}\]
By the luckiest of coincidences, the neon atom has a long-lived excited state, the $3S_2$ state, that has almost exactly the same energy as the metastable He state. When an excited He atom collides with a Ne atom in its ground state, it quite often transfers its energy to the Ne atom, returning itself to the ground state while leaving the latter in the excited $3S_2$ state, as shown in Figure 1. When hit by a photon with a wavelength of 632.8 nm the Ne atom will be de-excited to the lower, but still excited $2P_4$ state. It is between the $3S_2$ and the $2P_4$ states of neon that the laser action takes place.

Figure 1: How a HeNe laser works

Why between these two states? There are many atoms in the Ne ground state so that it will be quite impossible to pump enough Ne atoms into the $3S_2$ state to achieve a population inversion. The $2P_4$ state of neon, being an excited state itself, is empty.

To make a laser really work one needs a good bit of amplification, i.e. the photons must encounter a large number of atoms in the upper state. This can be accomplished by either making the laser tube very long or, more practically, by putting a mirror at either end, making the photons bounce back and forth many times. This requires a great deal of precision: the secondary photons are in phase with the primary ones, and must remain so upon reflection by the mirrors. This requires that the latter are an integer number of wavelengths apart. In other words, a laser tube is a highly precise interferometer.