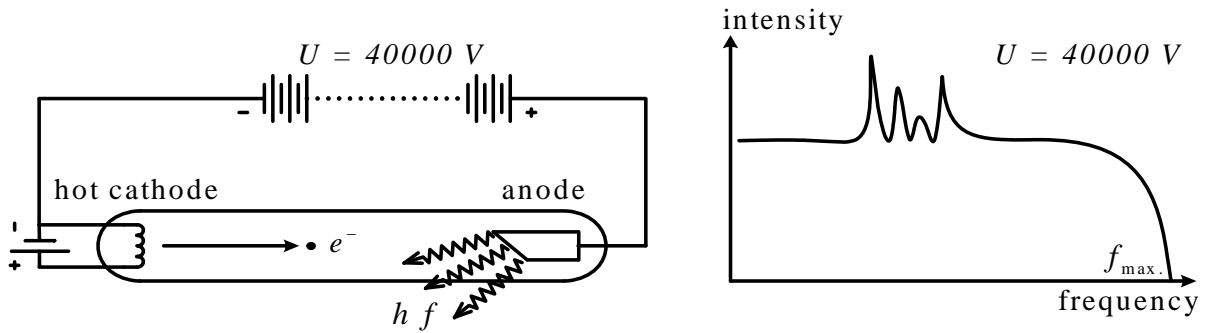# X-rays

The electromagnetic radiation of wavelength range from $10^{-8} m$ to $10^{-12} m$, is called x-rays. It was discovered by Röntgen in 1895. X-rays are produced when accelerated electrons strike a metal target. The hot cathode x-ray tube and the intensity distribution of the radiation are shown on the next figure.


The spectrum has a continuous part on which there are some peaks at defined frequencies. These peaks are at different frequencies for different elements. Important characteristic feature of the spectrum, that it has a cut off frequency f_{max}, above which the continuous spectrum does not exist. The continuous spectrum and the peaks arise in different ways, which we next discuss separately.

The continuous x-ray spectrum:
The anode produces x-rays by slowing the electrons. It is the result of the electrodynamics that accelerating charges emit electromagnetic waves. This process is called braking radiation. The electrons are decelerated by a series of collisions and interactions with anode atoms, so produces a continuous spectrum of electromagnetic radiation. The electron may lose an amount of energy ΔE_{kin}, which will appear as the energy of an x-ray photon that is radiated away. The frequency of the photon can be obtained from the energy equation $\Delta E_{kin} = hf$. If the incident electron loses all its initial kinetic energy $\Delta E_{kin,max} = hf_{max}$ we can obtain the maximal emitted frequency f_{max}.

The characteristic x-ray spectrum
The accelerated electron strikes an atom in the target metal and knocks out one of the atom's deep-lying (inner shell) electrons. Due to this, on this shell remains a vacancy, or hole. An electron in one of the upper shells with a higher energy jumps to the vacancy, filling the hole in this shell, but at the same time a new vacancy appears. This will be filled by an electron from still farther out in the atom.
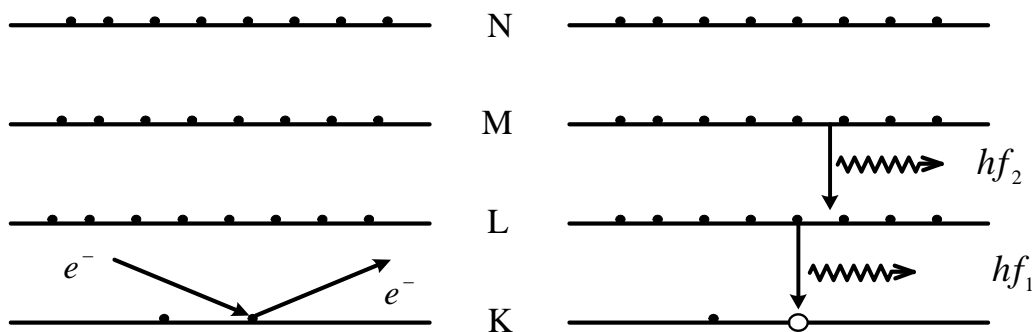
So the knock out of one electron from the inner shell causes several jump and several x-ray photon emission. As we have already seen the energy of the atom could be only discrete value, the emitted spectrum is line spectrum. The emitted frequencies can be ordered in series.
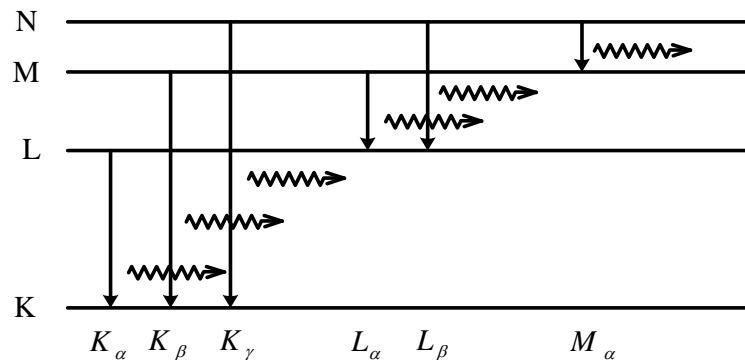
1913 Moseley studied the spectra of different metal targets in detail using x-ray diffraction techniques. He found that the most intense high frequency line in the characteristic x-ray spectrum is characteristic for the target element. He wrote the connection for the frequency of the so called K_α line in with the element's atomic number Z. Measuring the frequency the element can be specified.

$$f_{K_\alpha} = 2.48 \cdot 10^{15} \cdot (Z-1)^2 \, Hz$$

X-ray fluorescence (XRF) is a widely used non-destructive method for elemental analysis and chemical analysis. In this method the investigated material has been excited by bombarding with high-energy x-rays or gamma rays. After the excitation the emission of characteristic "secondary" (or fluorescent) x-rays are measured and the elements can be specified. We can say that the x-ray fluorescence is a powerful quantitative and qualitative analytical tool for elemental analysis of materials.

Applications of x-rays
X-rays have many practical applications in medicine and industry. The energy of the x-ray photons are high, so they can penetrate into solid objects. They can be used to visualize the interiors of materials that are opaque to ordinary light, such as broken bones or defects in structural steel. If the accelerated voltage is about 100 000 V, the x-ray is called hard and it has industrial applications. If the accelerated voltage is around 30 000 V, the x-ray is called soft and it has medical applications.

The investigated object is placed between the x-ray source and the detector for example a photographic film. The greater the radiation exposure result the darker area on the image. Bones are much more effective x-ray absorbers than soft tissue, so bones appear as light areas. A crack or air bubble allows greater transmission and shows as a dark area.

A widely used x-ray technique is computed tomography; the instrument is the CT scanner. In this case images are detected from several directions, and the computer reconstructs the picture. Tumours and other anomalies can be seen by the CT.

Laser

We have already seen that the energy of the electron in an atom is quantized: It means that it has discrete values. At the line spectra we discussed two processes in which light interact with atoms.

The first interaction is called absorption. If we denote the two different energy levels in the atom by E_1, and E_2, the atom can absorb a photon whose frequency is f, and fulfil the Bohr-frequency condition. $hf = E_2 - E_1$.

E_2 ——————————————

hf

⟿

E_1 ——————————————

absorption
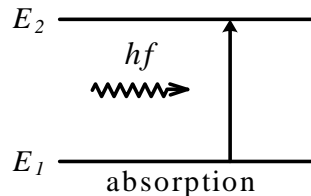
Some time later, generally it is $\approx 10^{-8} s$ the excited atom returns to the lower level by emitting a photon with the same frequency as the one originally absorbed. For some excited states, this mean life time is $\approx 10^{-3} s$ as much as $\approx 10^5$ times longer than, the normal mean life time of the excited atom. Such long-lived states are called metastable states, and they play an important role in laser operation. The process is called spontaneous emission (until this chapter we used only emission, but now we completed by the word spontaneous.

E_2 ——————————————

hf

⟿

E_1 ——————————————
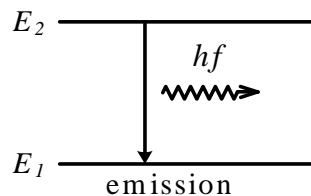
emission

The direction and phase of the spontaneously emitted photons are random.

There is a third process was proposed by Einstein in 1916 called stimulated emission. In case of stimulated emission, the atom is again in excited state, and a photon passes by the atom. This photon of energy hf can stimulate the atom to return to the lower energy level; during this the atom emits an additional photon, whose energy is also hf.

E_2 ——————————————

hf hf

⟿   ⟿

⟿

hf

E_1 ——————————————

induced emission
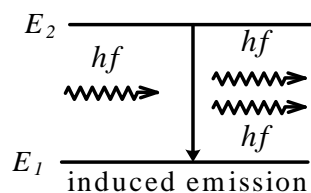
The emitted photon has the same frequency, and it is emitted in the same direction, its phase and polarization as the incident photon, which is not changed by the process. For each atom there is one photon before a stimulated emission and two photons after, so we call it light amplification. The name "laser" is an acronym for "**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation."

To produce laser light, we must have more photons emitted than absorbed; that is, we must have a situation in which the probability of stimulated emission is greater. Thus, we need more atoms in the excited state than in the lower energy or for example in ground state. This situation is called population inversion. Such a population is a nonequilibrium distribution, and not consistent with thermal equilibrium. The question is how can we produce this nonequilibrium distribution?

The necessary population inversion can be achieved in a variety of ways.

The ruby laser
The ruby laser is a solid-state laser that uses artificially growth ruby single crystal (synthetic) as its laser medium. A ruby laser most often consists of a ruby rod that must be pumped with very high energy, usually from a flashtube, to achieve a population inversion. The rod is often placed between two mirrors, forming an optical cavity, which oscillate the light. The ruby laser produce light in the visible range of the spectrum, at 694.3 nm, in a deep red colour, with a very narrow linewidth of 0.53 nm. The ruby laser is a three level solid state laser.
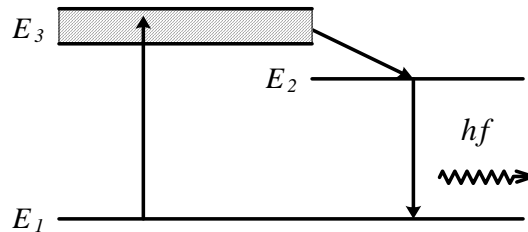
The laser medium is a ruby single crystal Al_2O_3 +0.05% Cr_2O_3, and 8-10 cm long and 1 cm diameter rod. The ruby has very broad absorption band in the visual spectrum, at 400 and 550 nm. The E_3 level is excited by optical pumping, typically by a xenon flashtube. After that from E_3 level, to E_2 level there is a non radiative transition. The E_2 level is a metastable state its life time is about 10^{-3}s so population inversion occurs. The laser transition is between E_2, and E_1 level. The duration of the laser impulse is a bit shorter than the pump impulse of the flash lamp, this is a so called pulsed laser.

The Helium–Neon Gas Laser

The common type of laser is the He-Ne gas laser. A glass discharge tube is filled with a 9:1 mixture of helium and neon gases, as laser medium. Pumping can be done by inserting two electrodes into the gas container. About 3000V sufficiently high voltage is applied to the electrodes and electric discharge occurs. In the discharge current the accelerated electrons about 3000eV energy excite the helium atoms by collisions (but not the more massive neon atoms). Then the helium atoms excite the neon atoms to level E_2 by energy exchange collisions.
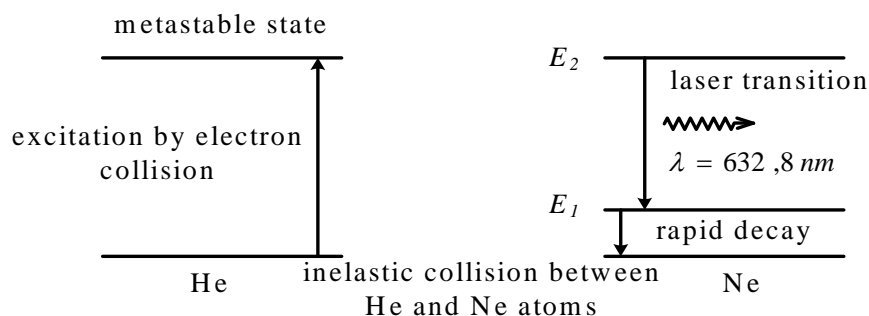
The population inversion is continuous between E_2, and E_1 levels.

Semiconductor laser

An electrically pumped semiconductor laser is in which the active medium is formed by a p-n junction of a semiconductor diode. The light-emitting diode (LED) is a p-n junction diode that emits light.

To increase the intensity of the laser beam, and to improve the light beam quality a so called mirror resonator is applied. The laser material is between two mirrors, one is totally reflecting the other mirror is partially transparent, so a portion of the beam emerges. The distance between the mirrors is: $L = n\dfrac{\lambda}{2}$. The process starts with a spontaneous photon emission. Such a photon can trigger the stimulated emission event, which can trigger other stimulated emission events as a chain reaction. The coherent beam of laser light, moving parallel to the laser material axis, can build up rapidly. This light moves through the laser material many times by successive reflections from mirrors T_1, and T_2. A small fraction of the laser light escapes to form the external beam.
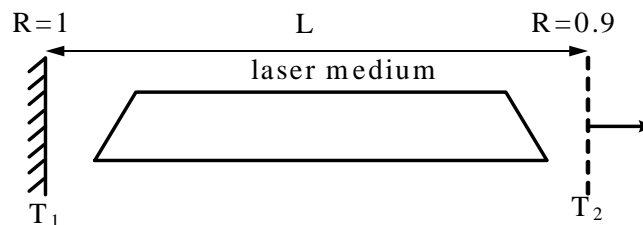
The laser light has the following characteristics:

Laser light is highly monochromatic. At $f \approx 10^{15}\,Hz$, $\Delta f \approx 10^{3}\,Hz$. It means that it is very sharp.
A laser beam spreads very little, other words the divergence is small.
Laser light is highly time and spatially coherent wave.
Laser light can be sharply focused, and the power density is very high 10^{17} W/cm^2.

The application of laser

reading bar codes
reading compact discs and DVDs
manufacturing, drilling
performing surgery
welding auto bodies
laser printers,……