Section 6: EMISSION/ABSORPTION OF EM RADIATION

In this section, we describe ways atoms respond to being excited and how they then undergo de-excitation. They link directly to how we detect radiation, modify and analyse materials using radiation and how radiation interacts with matter.

Emission/absorption of EM radiation

THE PHOTOELECTRIC EFFECT:

Emission of electrons from a material bombarded with em radiation. The classical and quantum mechanical views of this phenomenon are very different.

Classical electromagnetic-wave picture:

- Electron gains energy continuously from the radiation at a rate proportional to the radiation intensity and the electron is liberated when it has acquired sufficient energy to escape.
- When this occurs depends on the electron binding energy and the radiation intensity.
- The greater the binding energy the longer will be the time taken to liberate the electron.
- Conversely, the greater the intensity, the shorter will be the time required to liberate the electron.
- The time should be independent of the radiation frequency.

Experimental observation:

- There is a threshold frequency $\nu_0$ that depends on the material, below which no electrons are liberated at all, regardless of the intensity.
- If $\nu \geq \nu_0$, electrons are liberated immediately with a maximum kinetic energy given by

$$E_{\text{max}} \propto (\nu - \nu_0). \quad (4.2)$$

The constant of proportionality is Planck’s constant $h$.

- As the electromagnetic intensity is increased, there is no change in the emitted energies, but the rate of electron emission increases.
Quantum-mechanical picture

Energy is absorbed by the electrons in quantized amounts $h\nu$ equal to the energy of a photon.

- There is a threshold photon energy $(h\nu_0)$, which is the binding energy (BE) of the most weakly-bound electron.

- It is the minimum energy needed to remove an electron.

- If $h\nu < h\nu_0$, the electron cannot be liberated from the atom.

- The electron can be excited only if $h\nu$ corresponds exactly to an allowed electron transition in the atom.

- If $h\nu > h\nu_0$, the electron can be liberated with maximum kinetic energy (KE) given by

$$E_{\text{max}} = h\nu - \text{BE} = h\nu - h\nu_0.$$  \hfill (4.3)

- This is the observed KE of the most weakly-bound electron. The more strongly-bound electrons appear with lower kinetic energies.

- The intensity of the radiation is proportional to the number of incident photons per m$^2$ per second. Therefore, the electron flux (per m$^2$ per second) $\propto$ intensity.

The quantum-mechanical picture completely explains the experimental results and was one of the crucial pieces of evidence supporting the new quantum theory.

EMISSION SPECTRA

Suppose one of the two K-shell electrons is removed from an atom leaving a vacancy in the K-shell.

- This is rapidly filled by an electron from a higher shell (energy $E_n$) `dropping down' into the K-shell (energy $E_K$).

- At the same time a photon is emitted with energy

$$E_{\text{ph}} = h\nu = E_n - E_K$$  \hfill (4.4)

Since shell energies are characteristic of a particular element, the frequencies (or wavelengths) of the emitted photons are also characteristic of the element involved.

- Transitions from higher shells to the K-shell are called K transitions.

- A subscript is added to the transition name to identify the upper level from which the transition originated:

Transitions with final states in the K-shell are denoted $K_{\alpha}$, $K_{\beta}$, $K_{\gamma}$ etc.
If an L-shell electron has de-excited to fill a K-shell vacancy (emitting a $K_\alpha$ photon), a vacancy will exist in the L-shell.

- This vacancy will be rapidly filled by an electron from a still higher shell.
- Such transitions are called L transitions.
- Again, a subscript is added, which identifies the higher shell.

Energy level diagram showing several K and L transitions.

Emitted radiation is a series of sharp lines, corresponding to the frequencies of the characteristic radiation of that element.

It is called an **emission spectrum** and the emitted frequencies are called **spectral lines**.

- They occur only at certain discrete values.
- In general, the intensities of the lines vary from element to element.
Spectrum of intensity versus frequency for several K and L transitions.

- For hydrogen, the K series is just the **Lyman Series** (ultra violet).
- The L series is the **Balmer series** (visible).
- For other light elements, the characteristic spectral lines also lie in the visible or ultra-violet regions.
- For heavier elements (large $Z$) the lines are in the X-ray region, with energies $E_X$ up to many keV. $E_X$ is approximately proportional to $Z^2$.

**ABSORPTION SPECTRA**

Consider a beam of **monoenergetic** (or monochromatic) X-rays incident upon a slab of a heavy element (e.g. lead).

Some photons are absorbed by the material - mainly by the photo-electric effect. Therefore, the transmitted intensity, $I$, is less than the incident intensity $I_0$.

\[
\text{% absorption} = \left( \frac{I_0 - I}{I_0} \right) \times 100. \quad (4.5)
\]
Each additional slab will reduce the intensity by the same factor as the first, leading to an exponential decrease of intensity with absorber thickness.

Absorption decreases with beam energy - i.e. it becomes more penetrating.

Low-energy photons can only eject electrons from the outer shell but eventually, photons have sufficient energy to ionize electrons from the next more tightly-bound shell and so on, to the L- and finally, the K-shells.

As the photon energy successively exceeds the different shell energies, the percentage absorption increases sharply in what are known as absorption edges.

- The L-edge consists of several closely-spaced edges corresponding to the the L subshells, which have slightly different energies.
- Energies of the emission lines lie just below the energy of the corresponding edge.
- The edge energy is the energy required to ionize electrons and is equal to the binding energy of that shell.
- The emission-line energy is less than the binding energy of the lower shell.

**X-RAYS**

X-rays are produced by bombarding a heavy element target with a beam of high-energy (few keV to few MeV) electrons.

There are two main processes:
1) Photon emission, following the excitation and ionization of bound electrons.
   - Electrons in the beam collide with target electrons causing excitation or ionization and creating vacancies in the inner shells.
   - Characteristic X-rays are emitted as the vacancies are filled.
2) Inelastic electron scattering by target nuclei.

EM radiation (photon) can be emitted when a charge, such as an electron is accelerated (i.e. goes off in a different direction) when it is scattered by passing close to a nucleus.

The emitted radiation is called **bremsstrahlung** radiation (‘braking’ radiation). It has a continuous range of energies from approximately zero to a maximum value (= beam energy). Most electrons are scattered through small angles and lose little energy (emitting low-energy bremsstrahlung photons).

- Most of these low-energy (or ‘soft’) photons are absorbed.
- Electrons scattered through larger angles lose more energy and emit higher-energy photons up to the maximum energy.
- This part of the X-ray spectrum is independent of the target material.

The observed X-ray spectrum is the sum of the two contributions:
- The sharp emission lines **characteristic** of the target material.
- A continuous spectrum **independent** of the target material.

Note that K (and L) lines are seen only if the beam energy is sufficiently high to excite or ionize electrons from the K- (and L) shell.