CAIE Physics A-level

Topic 22: Quantum Physics

Notes

22 - Quantum Physics

22.1 - Energy and Momentum of a Photon

So far, we have discussed light in terms of its wave-like behaviour, electromagnetic radiation can also be described as coming in **discrete packets** of energy known as **quanta**. Another term for a quantum of electromagnetic radiation is a **photon**.
The energy E carried by a single photon is proportional to its frequency f:

$$E = hf$$

The **Planck Constant** is defined as $h = 6.63 \times 10^{-34} Js$.
We will make use of the **electronvolt (eV)** which is equal to $1.6 \times 10^{-19} J$, and is defined as the **kinetic energy of one electron after it is accelerated from rest through a potential difference of one volt**. This quantity is used to establish the energies of quantum particles at a scale more suited to their energies than the measurement of a joule.

The **momentum,** p of a photon can be given by

$$p = \frac{E}{c}$$

22.2 - Photoelectric Effect

One of the key pieces of evidence for the quantum nature of light is the photoelectric effect, discovered by Albert Einstein in 1905. The effect describes the **stimulated emission** of a **photoelectron** due to an incident photon on a metal surface. The photon incident on a metal surface will interact with the electrons in the material, and if the photon's frequency/wavelength (therefore energy) exceeds a **threshold frequency/wavelength** then an electron will be emitted. The minimum photon energy required to cause an electron to be emitted is called the **work function** Φ. The emitted electron carries kinetic energy $\frac{1}{2}mv_{max}{}^2$ equivalent to difference between the photon energy hf and the work function:

$$hf = \Phi + \frac{1}{2}mv_{max}{}^2$$

The maximum kinetic energy of the photoelectron is **independent of the intensity of the incident radiation**. This is because intensity relates to the density of a group of photons, and so is not a property of an individual photon. Since only one photon interacts with one electron at a time, the only factors which influence the kinetic energy of the emitted electron are the photon energy and the work function of the material.

22.3 - Wave-Particle Duality

Observations of phenomena such as the photoelectric effect provide evidence for the particulate nature of electromagnetic radiation. On the other hand, we can clearly observe light exhibiting features such as diffraction and interference, which are the behaviours of waves. The fact that electromagnetic radiation behaves as both a wave and a particle is known as the **wave-particle duality**.

This duality extends to quantum particles such as electrons, which also exhibit some degree of wave-like behaviour. If a beam of electrons is passed through a graphite filter - a one atom thin sheet of carbon atoms in a hexagonal arrangement - the electrons will display the property of diffraction.

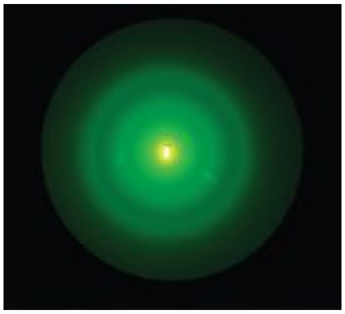

Figure 25.6 Electron diffraction pattern of graphite

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Remember that diffraction occurs most when the radiation wavelength is similar to the size of the gap through which it travels - in the case of graphite, this is about $10^{-10}m = 1$ Å . This suggests that electrons have a wavelength property of a similar size. This wavelength is known as the **de Broglie wavelength:**

$$\lambda = \frac{h}{p}$$

22.4 - Energy Levels in Atoms and Line Spectra

In an atom, the electrons orbiting the nucleus can only occupy specific discrete energy levels. This is another one of the ways in which atomic particles are ‘quantised’. These levels are analogous to storeys (floors) in a skyscraper: the electron can only be on particular floors, not between them. These can be represented in an **energy-level diagram.**

In normal circumstances the electrons will occupy the lowest available level called the **ground state**. If the energy of the electron changes due to say the absorption of a photon, the electron can jump into a higher energy level: an **excited state**. Once in an excited state, the electron is unstable and will emit a photon in order to decay back down to the more stable ground state.

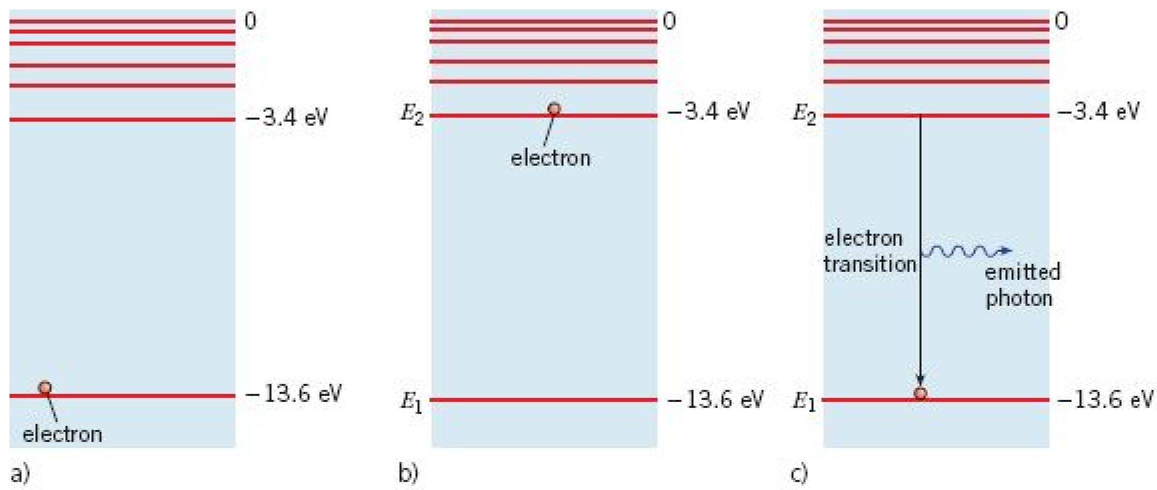

Figure 25.10 Electron in a hydrogen atom a) in its ground state, b) in an excited state, c) returning to its ground state with photon emission

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The energy of the emitted photon depends on the difference between the energy levels E_1 and E_2 of the transition which produced it:

$$hf = E_1 - E_2$$

As the emitted photon has a discrete energy and frequency, it is situated at a particular wavelength along the electromagnetic spectrum. Monochromatic lasers, which emit light of one wavelength only, operate on this basis. This gives rise to an **emission spectrum**, which is the range of discrete photon wavelengths emitted by the electron transitions (deexcitation) in an atom.

An emission spectrum has the appearance of a few monochromatic lines, representing transitions, on a black background.

As well as an emission spectrum, we could also obtain an **absorption spectrum**, which can be observed when white light is passed through a gas because the specific wavelengths of photons absorbed by the atoms (through excitation) do not appear in the spectrum.

These spectra can be used to determine the chemical composition of unknown substances, because the emission/absorption lines act like parts of a fingerprint. If you were to 'add together' the emission and absorption spectra for the same element you would obtain a complete EM spectrum.

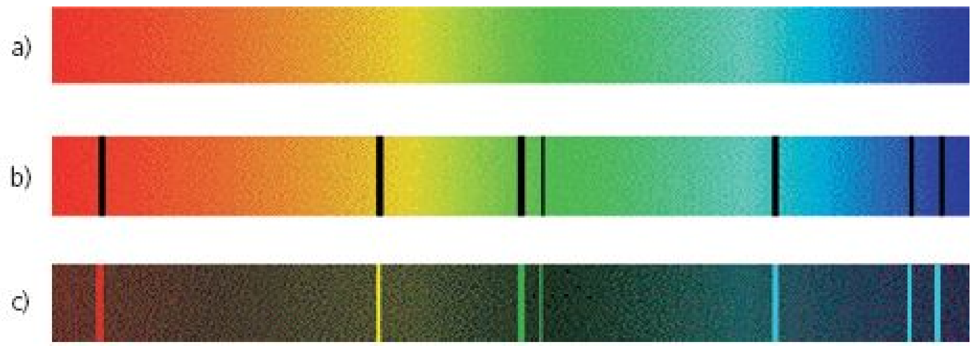

Figure 25.14 Relation between an absorption spectrum and the emission spectrum of the same element: a) spectrum of white light, b) absorption spectrum of element, c) emission spectrum of the same element

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