A2 Level Physics

Chapter 12 – Space

12.2.1 Electromagnetic Radiation from Stars

Notes

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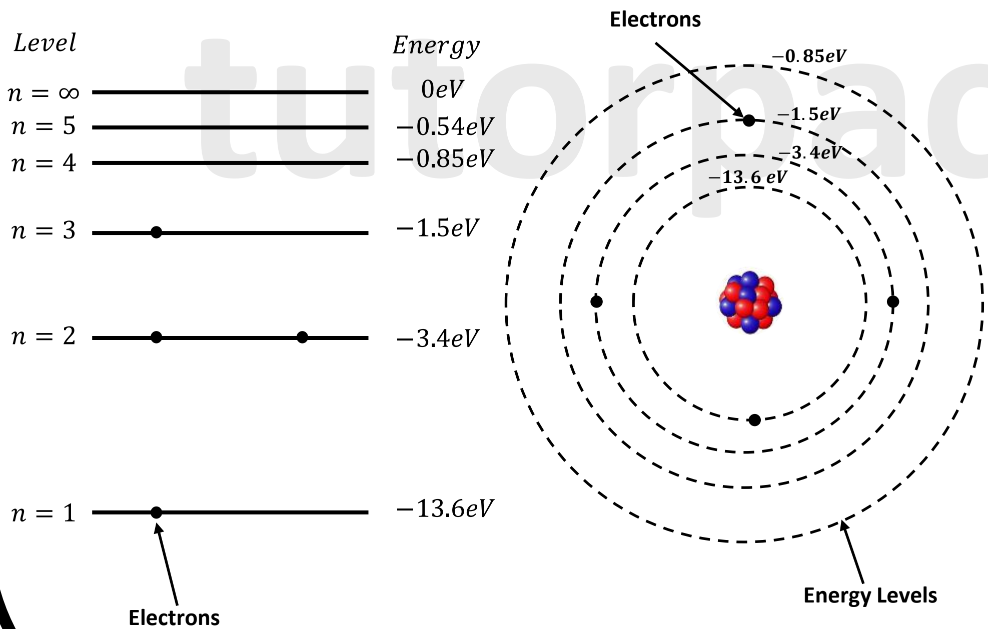
Energy Levels of Electrons

In an atom, electrons can only occupy a number of discrete energy levels. The word discrete refers to separate or distinct.

The diagram below shows a typical arrangement of energy levels and comparing it to a typical atom with energy levels. The vertical axis of the diagram on the left is a scale of electron energy, E. The horizontal lines indicate the different permitted energy levels. Each level is assigned a number, with $n = 1$ representing the ground state. The dots represent electrons occupying the different levels.

It's worth noting that the energy scale normally starts at the top with $E = 0$.

Energy can be expressed in J or eV.



Energy Levels of Electrons

When an electron gains energy or is excited, it goes from one level to another. It can only do so by absorbing a photon with an energy equal to the difference between the two levels; for example, to raise an electron from $n = 1$ to $n = 2$, you'd require $10.2\ eV$ ($13.6\ eV - 3.4\ eV$); there cannot be any energy left over.

However when the electron is excited or gains energy it doesn't like being in an energy level above where its supposed to be usually. As a result, once it has absorbed the energy it will want to immediately return to its original energy level. When an electron loses energy or is de-excited, it falls, from one level to another. It does so by emitting a single photon whose energy corresponds exactly to the difference between the two levels and has a specific wavelength. For example, an electron excited to $n = 2$ will de-excite and return to $n = 1$, releasing a $10.2\ eV$ photon. The equation below can be used to show a transition between the two energy levels:

$$\Delta E = E_1 - E_2 = hf = \frac{hc}{\lambda}$$

Where:

E = change in energy in J

E_1 = energy of initial energy level in J

E_2 = energy of final energy level in J

hf = photon energy

h = the Planck constant ($6.63 \times 10^{-34}\ Js$)

f = frequency in Hz

c = speed of light in a vacuum ($3 \times 10^8\ ms^{-1}$)

λ = wavelength in m

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Energy Levels of Electrons

It's important to remember that electrons can't have an energy value that's halfway between two levels. The electron will be pulled back to its original level if it does not have enough energy to go to the next level.

The values of all energy levels are negative, with the ground state having the largest negative value. The energy of an electron that is completely free from an atom is 0. This negative sign is used to represent the amount of energy necessary to remove an electron from an atom.

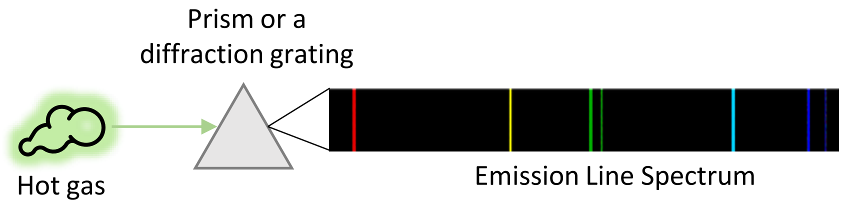
The ground state represents the most stable configuration. When the electrons in an atom occupy the lowest possible energy level, the atom is in the most stable state.

Energy Levels of Electrons

Continue to the next page.

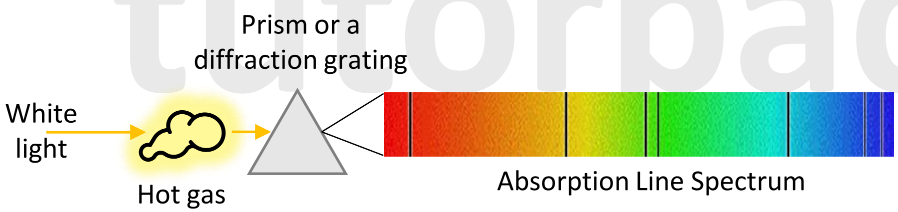
Spectra

When a gas is heated, it begins to glow. The gas produces light as it glows. If you take this light and pass it through a diffraction grating or prism, a spectrum is formed. The spectrum is made up of several discrete lines, indicating the presence of only certain wavelengths.

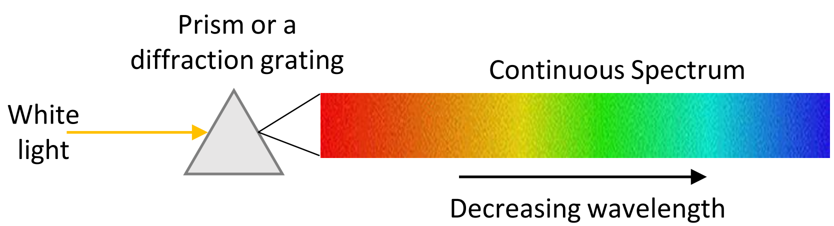


This is an emission line spectrum, rightfully called because it arises from the light emitted by a material.

When white light passes through a heated gas, it produces black lines in its spectrum. This absorption line spectrum shows that certain wavelengths have been absorbed.



If you split white light up with a prism, the colours all blend together, leaving no gaps in the spectrum. This simply demonstrates that white light has a continuous spectrum.



Spectra

Explaining Spectra

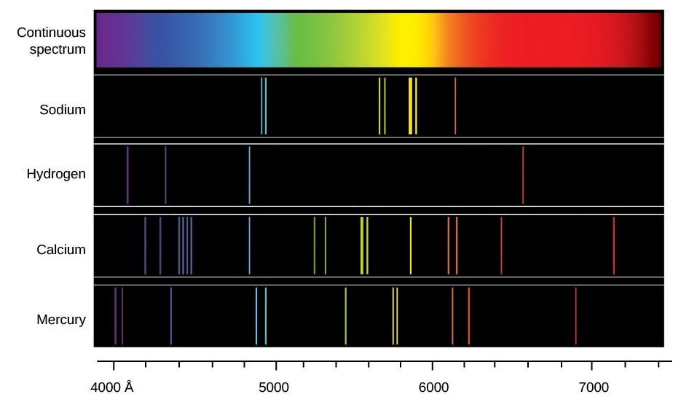
When an electron is de-excited, energy is released in the form of a photon of a specified wavelength. The photon's energy is calculated using $E = hc/\lambda$, where h is the Planck constant, c is the speed of light, and λ is the wavelength of the photon. The energy released is the difference between the initial energy level of the electron, and the final energy level of the photon. The transitions between the different energy levels emit photons of different wavelengths.

The wavelengths of light produced by the de-exciting of electrons varies for each element since each has its own set of discrete energy levels. When atoms in a gas are excited, spectroscopy is used to identify elements based on the wavelength of light emitted.

In an absorption spectrum, electrons jump up from lower levels to higher levels, absorbing photons in the process.

After measuring the wavelengths in a line spectrum, it is possible to work out the energy level diagram of the atoms producing the spectrum.

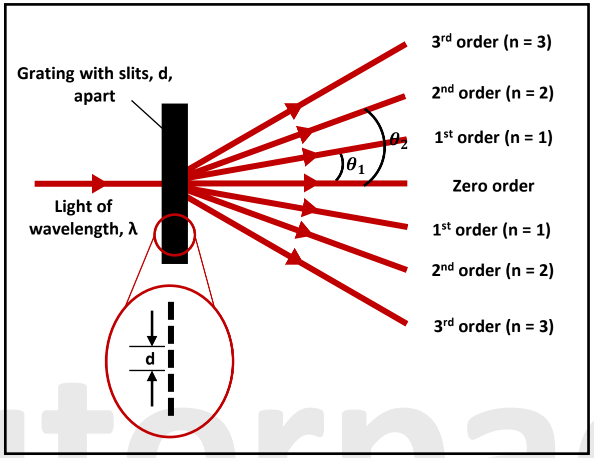
Different atoms have different spectral lines, which can be used to identify elements within stars.



Diffraction Grating

A diffraction grating has many equally spaced parallel slits that can diffract light. Different colours of light have different wavelengths, and so will be diffracted at different angles. The equation,

$$d\sin\theta = n\lambda$$



Where:

- **θ** = diffraction angle in degrees (θ_1 = first order angle, θ_2 = second order angel, θ_3 = third order angle, etc…)
- **n** = the diffraction order (e.g. n = 0, 1, 2, 3, etc…)
- **λ** = light wavelength in metres (m)
- **d** = grating spacing measured in metres (m)

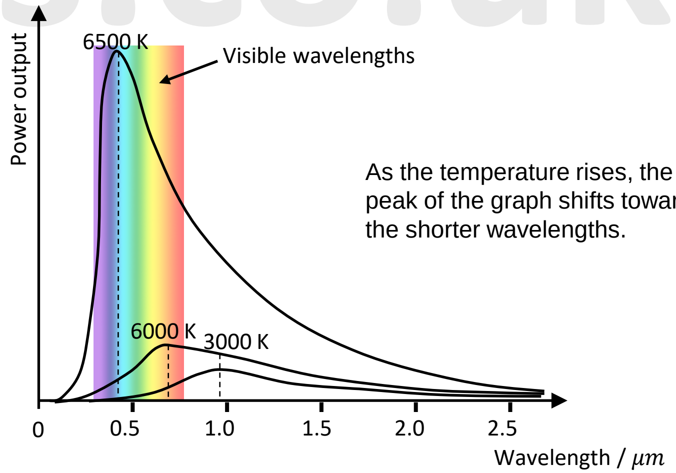
The wavelength of light may be calculated using the equation above.

Black Bodies

The colour of a star is determined by its surface temperature. At any temperature hotter than absolute zero $(0K)$ emits EM radiation due to their temperature. This radiation is largely in the infrared region of the spectrum (which humans can't see) at room temperature, but if you heat anything up enough, it will glow and emit visible light. This is because the wavelengths of radiation released depends on the object's temperature.

A black body is a body that absorbs all EM radiation of all wavelengths and can emit all wavelengths of EM radiation. It absorbs all incident light and is referred to as a "black body" because it does not reflect any light.

Since black bodies emit all wavelengths of EM radiation, they emit a continuous spectrum of EM radiation. It's known as black body radiation. The shape of a graph showing a black body's radiation power output against wavelength varies with temperature, but they all have the same overall shape (as shown below). They're known as black body curves:



Black Bodies

It's worth noting that the distribution is solely determined by temperature, not the material. As the temperature rises, the maximum intensity of a specific wavelength λ_{max} shifts to the left. At roughly 4000K and above, the maximum will move into the visible spectrum. This is why really hot objects, such as hot oven elements or a light bulb filament, appear to glow. In comparison, the human body emits $310\ K$, which is nowhere near the visible spectrum, thus we don't glow.

You also obtain a peak wavelength associated with a peak intensity (meaning when the star is at its brightest), but this is spread out over a wide range of wavelengths, making it impossible to determine the star's colour.

The temperature and other properties of an object can be estimated using black body radiation curves.

There is no such thing as a perfect body, yet stars (and some other astronomical sources) act as black bodies to a reasonable extent.

The Sun is assumed to be a black body. It absorbs nearly all of the light incident on it and emits the most intense radiation in the visible region of the electromagnetic spectrum.

Wien's Displacement Law

As you may know, stars can be modelled as idealised black bodies that emit radiation across a range of wavelength that corresponds to the star's colour.

A peak intensity can be found in all black body spectra. The wavelength that this peak occurs at is called the peak wavelength, λ_{max}. The higher the surface temperature of a star, the shorter the wavelength, λ_{max}.

This is because hotter stars release high energy radiation. The energy of a photon is given by $E = \frac{hc}{\lambda}$, therefore if it has a high energy, the radiation must have a shorter wavelength.

Wien's law is used to relate the temperature of the star with the peak wavelength λ_{max} of the EM radiation emitted by the star.

Wien's law states:

For different temperatures, the black body radiation curve peaks at a wavelength that is inversely proportional to the object's temperature.

$$\lambda_{max} \propto \frac{1}{T}$$
$$\lambda_{max}\, T = 2.9 \times 10^{-3}\ m\ K$$

Where:

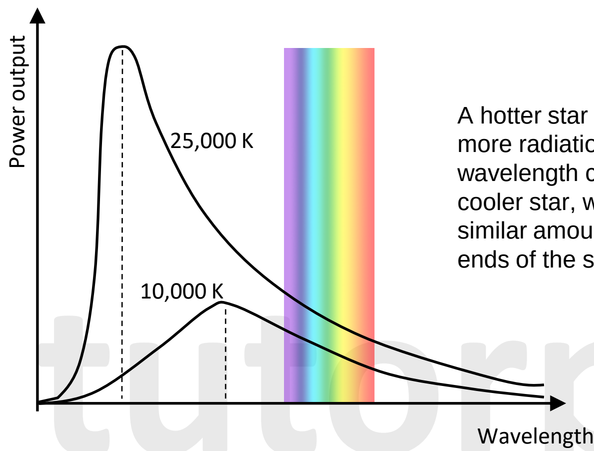
λ_{max} = peak wavelength associated with max. intensity in m

T = absolute surface temperature in K

$Wien\ constant = 2.9 \times 10^{-3}\ m\ K$

Wien's displacement law

A black body that is hotter emits more radiation than one that is colder, and its peak wavelength is shorter. It also produces more total power (assuming it has the same surface area).



A hotter star emits significantly more radiation near its peak wavelength compared to a cooler star, while emitting a similar amount of radiation at the ends of the spectrum.

If a star emits radiation that isn't visible region in the EM spectrum, a hotter star may appear less bright than a colder one. Therefore, a colder star will look brighter than a hotter star if it emits more radiation in the visible region.

When assuming that stars are black bodies, you must also assume that their surface temperature is uniform. Therefore, when you use the Wiens displacement law to calculate the surface temperature of a source, keep in mind that you're really calculating the source's black-body temperature. Since you assumed the star is a perfect black body, this temperature is simply an approximation of the surface temperature.

Stefan's Law

Stefan's law relates a star's temperature to its luminosity, L (in Watts, W). The luminosity is proportional to the star's surface area and represents the star's radiant power output.

The law states:

The total radiant heat energy emitted from a surface is proportional to the fourth power of the absolute temperature of a black body.

This gives:

$$L \propto 4\pi r^2 T^4$$

This can be expressed as:

$$L = 4\pi r^2 T^4 \sigma$$
$$L = AT^4\sigma$$

Where:

- L = luminosity of the star in watts, W.
- σ = Stefan's constant $5.67 \times 10^{-8}\ Wm^{-2}k^{-4}$.
- $A = surface\ area\ of\ a\ star = 4\pi r^2$ in m^2.
- T = Surface temperature of the star in kelvin.
- r = radius of the star in m.

If the star's colour and hence peak wavelength are known, Wien's law can be used to calculate the star's absolute temperature. We can calculate the luminosity of a star if we know its temperature. It's worth noting that luminous stars are hotter.

The radius of the star can be calculated if the luminosity and temperature of the star are known.

Please see '12.2.2 Electromagnetic Radiation from Stars worked examples' pack for exam style questions.

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