The Structure of The Atom

Line Emission Spectrum

The hot vapour (gas) of any pure element will emit light of discrete frequencies. When this light is viewed with a spectrometer, a line emission spectrum will be visible, since the spectrometer separates all the frequencies and spreads them out. There should be one line for each frequency.

The line emission spectra for any given element is unique; the combination of lines effectively acts as a code for that element.

Note that the hot vapour will give off frequencies of light in the infra-red and ultra-violet range – they just won't be visible to the human eye.

Energy Levels in Atoms

The presence of discrete frequencies in the spectra of atoms is evidence for the existence of discrete energy levels in atoms. Energy levels correspond to stable orbits in which electrons can be found.

Electrons are bound to the nucleus by electrostatic attraction, and since closer orbits will be more strongly held it follows that more work needs to be done on an electron to move it further away from the nucleus. Electrons in orbits further out from the nucleus will have more potential energy (like having farther to fall) than electrons in close orbit. So 'far' orbits correspond to *high* energy levels and 'close' orbits to *low* energy levels.

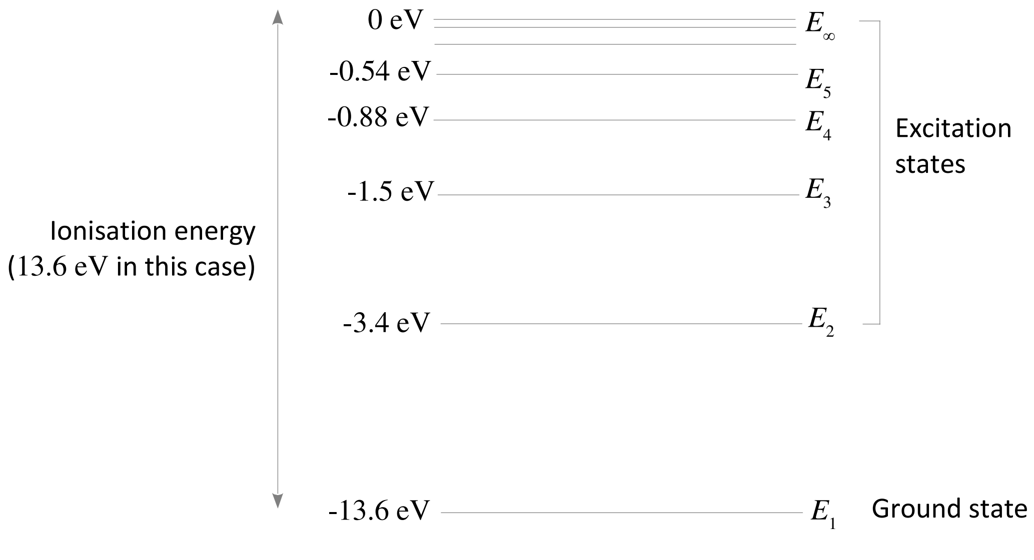
When an electron absorbs exactly the right amount of energy to make up the difference between its energy level and a higher one, it makes a transition to that energy level. It will not stay there (electrons are more stable in lower energy levels), very quickly it falls back to a lower energy level in the atom, and the energy is released as a photon.

While the electron is in the high energy level the atom as a whole has more energy, and therefore the atom can be considered to lose this energy as the photon is emitted.

The energy of the emitted photon is given by $E_n - E_m = hf$, where $E_n - E_m$ is the energy difference of the atom (since E_n is the energy of the higher level and E_m is the energy of the lower level), hf is the energy of the photon, and f is the frequency of the emitted light.
Note that this energy is the same as the energy that would be required to raise the electron from the lower to the higher energy level.

When performing calculations, be sure to convert eV to J first.

The energy levels for any given atom can be represented by an *energy level diagram*. These are essentially a series of lines (each representing a level) starting at 'ground state' (most tightly bound electrons) at the bottom and finishing at the highest energy level (least tightly bound electrons) at the top. The ground state of an atom is the lowest energy level that an electron can occupy. All the energy levels except the ground state of the atom are known as *excitation* states.



The levels are sometimes denoted $n = 1$, $n = 2$, etc instead of E_1, E_2, etc

Along the side of the diagram are labels, negative values given in eV. These values represent how 'deep' the electron is in the atom. For example at an energy level of -13.6 eV, an electron would need to be given 13.6 eV in order to escape the nucleus. The minimum energy required to *transition* (the word for changing the energy level) an electron from the ground state to freedom from the nucleus is known as the *ionisation* energy.

Notice that the energy levels get closer together the closer you get to 0 eV. This is the highest excited state (the electron has left the atom) and is denoted E_∞ ($E_{infinity}$) because there are infinite energy levels between the ground state and it. As electrons go further out from the nucleus, they are not as strongly bound and therefore the transition between levels is less and less, allowing for infinite levels.

The set of frequencies in the line emission spectrum is unique for each element because each has a different amount of charge in the nucleus, and has its own set of energy levels, allowing a unique set of transitions to take place.

Notice that increasing the temperature of the atom (giving it more energy) will not change the frequencies of light already being emitted because the energy levels don't change. The increase will however allow for larger transitions, meaning that higher frequencies of light will start being emitted along with the lower ones.

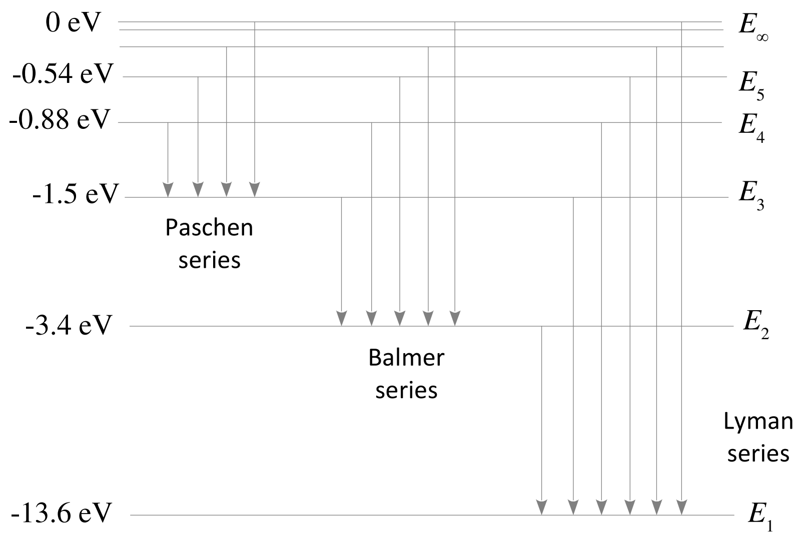
Emission Spectrum of Atomic Hydrogen

The emission spectrum of atomic hydrogen consists of several series of lines, each of which converges to a series limit (maximum frequency for that series).

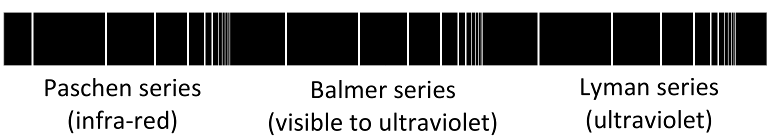
The three series are called the Paschen, Balmer and Lyman series and correspond to electrons dropping from some higher level to the E_3, E_2 and E_1 series respectively.

There are an infinite number of levels which can drop down for each series, and since the higher levels are closer together (in terms of energy) it is expected that the spectral lines are closer and closer together as they approach the series limit.

A few lines from each series are shown below. The horizontal placement of the transitions does not mean anything.



The resulting spectrum is shown below:



The larger the transition, the greater the frequency of light emitted.

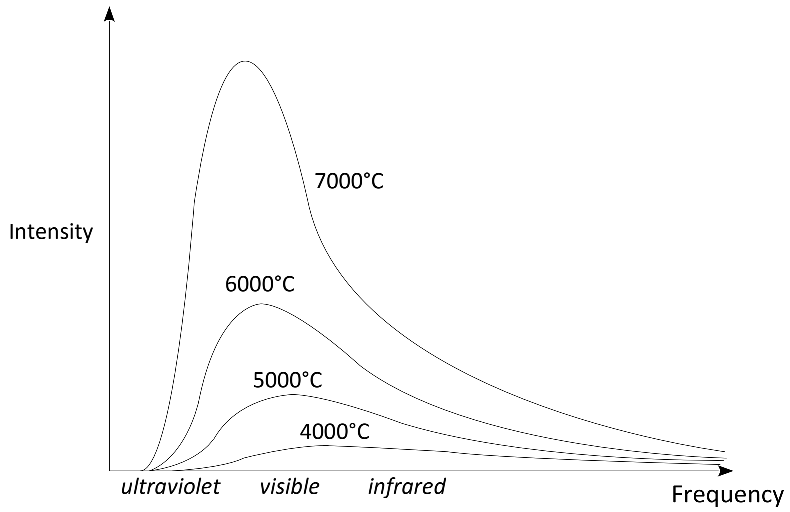
Continuous Spectrum

If a solid or liquid is heated (or gas if dense enough) then a continuous spectrum (infinite frequencies) is produced instead of discrete lines. This is because the energy contained in the substance is not just in individual molecules or atoms exciting electrons, it is also contained in the oscillation of the particles along bonds between them. Heat gives the particles kinetic energy causing them to move around but the bonds are holding them together, so they oscillate.

The atoms, molecules and electrons in the hot dense substance are vibrating at an infinite range of frequencies not dependent on the energy levels in the atoms. It is expected then that the frequencies of light emitted will be infinite, therefore covering a continuous range.

The relative amounts of the various frequencies emitted depends on the temperature of the substance – the hotter it is, the more kinetic energy the particles have, so the range of emitted frequencies will be higher.

Continuous spectra for different temperatures



Note that as the temperature increases, more high frequency light is emitted but the lower frequencies still continue to be emitted (though not as much). The most common frequencies for a substance for a given temperature are called the *dominant* frequencies.

For example, room temperature substances tend to emit more infra-red light, hotter substances emit an obvious amount of red light as well, increasing the temperature more leads to white light (all colours of the visible spectrum), and increasing further still will mean that ultra-violet is emitted as well.

Another example that shows this effect is the continuous spectrum of a filament globe. The visible light emitted by a low temperature filament globe tends to be down the red end of the spectrum, while the light emitted by a high temperature filament globe tends to emit light covering a much larger range (that is, it includes higher frequencies) of the visible spectrum, and hence its light will have an appearance much closer to white.

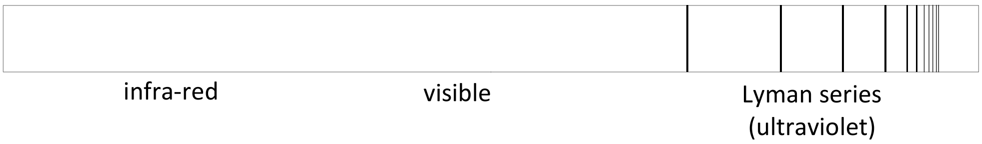
Line Absorption Spectrum

When light with a continuous spectrum is incident on a gas of an element, discrete frequencies of light are absorbed, resulting in a line absorption spectrum. Most of the spectrum is not absorbed but passes through the gas and therefore the continuous bright pattern is seen, but where the light was absorbed it is re-emitted in random directions, meaning not many photons of those frequencies make it to the observer and dark lines are seen.

The only frequencies absorbed are those which correspond to energy jumps electrons are able to make in the atoms of that element – frequencies from the emission spectra. Only a *subset* of the lines from an emission spectra will be present, however, not all of them. This is because the lines present on an absorption spectra are those produced by a transition from the ground state to some excited state (since most atoms are in the ground state before they absorb the incident photon).

Absorption Spectra of Atomic Hydrogen

The line absorption spectrum for atomic hydrogen at room temperature has dark lines corresponding to the Lyman emission series (UV) since these are the only frequencies with energy transitions from the ground state.



Note: The white areas shown above would not appear white, they would be the respective colours of the spectrum, from infra-red on the left through to ultra-violet on the right.

The energy level diagram for the absorption spectra of hydrogen is similar to that for the emission spectra. The differences are that only the Lyman series is present and any transitions shown point upwards on the diagram (since the energy is being absorbed so the electron is gaining energy).

Notice that there are no lines for visible or infra-red light, since their transitions would need to start at the first excited state, and at room temperature atoms tend to be at ground state.

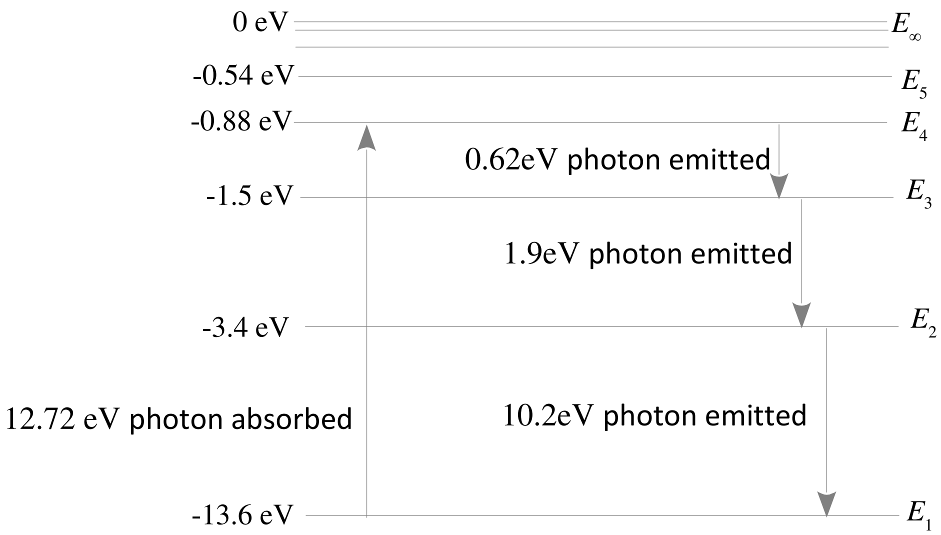
Dark lines can be found in the visible part of the Sun's spectrum (these are called *Fraunhofer lines*). These exist because the hydrogen gas in the Sun's atmosphere is very hot and can be excited above the ground state. Transitions from the n = 2 state upwards correspond to absorption of frequencies of visible light.

Fluorescence

When an atom absorbs high-energy photons, sometimes it can re-emit the energy in a number of steps as photons of lower energy.

This effect takes place because atoms are elevated to 'excited states' (energy states above the ground state). Excited states are generally short-lived and so the atom quickly returns to its ground state, often by emitting a series of lower-energy photons. This process of converting high-energy photons into a larger number of lower-energy photons is called 'fluorescence'.

An example of fluorescence is shown below: an energy level depicts UV light being absorbed (12.72 eV) and re-emitted in three steps, including one step of visible light (1.9 eV)



Stimulated Emission

When an atom is excited by absorbing a photon and quickly emits the energy by returning to a lower state, this is called *spontaneous emission.*

If an atom is already in an excited state and a photon of the right energy (the same energy as the transition from that excited state to ground state) interacts with it, it can experience *stimulated* emission. That is, the interacting photon causes the atom to return to ground state, emitting a photon of the same frequency.

Photons from stimulated emission travel in the same direction and are in phase with the photon that stimulated their emission, whereas photons from spontaneous emission go in any random direction and are not necessarily in phase with anything.

Population Inversion and Metastable States

Whenever there are more atoms in a higher-energy state than in a lower-energy state in some given set of atoms, the set is said to be in a 'population inversion'. Photons with energy corresponding to the transition from the higher-energy state to the lower-energy state will produce more stimulated emissions than absorptions under such conditions.

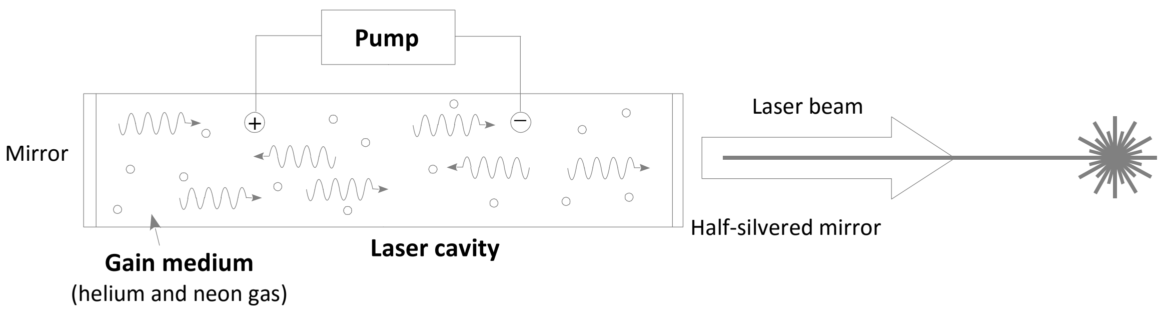
Some atoms can experience excited states which last for a relatively long time before the atom undergoes spontaneous emission and transitions to a lower-energy state (emitting a photon). These long-lasting excited states are called 'metastable' states.

The higher-energy state must be a metastable state if a population inversion is to be produced.

Lasers

The word 'laser' is an acronym for **l**ight **a**mplification by **s**timulated **e**mission of **r**adiation. A population inversion is maintained, causing *stimulated emission to predominate over absorption* (more photons are created than absorbed) therefore light is *amplified* (number of photons increased).

A common kind of laser is the helium-neon gas laser, which consists of three main components.



<u>Laser cavity</u>
The 'cavity' refers to the space inside the tube containing the laser medium. At each end of the tube are mirrors that allow the light produced by stimulated emission to reflect back and forth many times, stimulating more emissions and constructively interfering to produce a large amplification. The mirror at one end reflects some of the light and allows the rest to pass through, so some of the amplified light is able to pass out of the laser cavity and produce a laser beam.

<u>Pump</u>
The purpose of the pump is to elevate ('pump') atoms in the gas from the ground state to a higher-energy excited state. In the case of a helium-neon laser, the pump is a high potential difference applied across the tube. Free electrons are caused by the potential difference to travel at high speeds across the tube, and on colliding with helium or neon atoms may elevate them to their excited state.

<u>Gain medium</u>
This is the substance contained within the laser cavity. It must contain atoms that have a metastable state so that a population inversion can be achieved. In the case of a helium-neon gas laser, the gain medium is a mixture of neon gas (has a metastable state and therefore produces the laser photons through stimulated emission) and helium gas (makes the process more efficient as collisions between excited helium and unexcited neon can produce metastable neon).

Useful Properties of Laser Light

Laser light is coherent and monochromatic.

Photons produced by stimulated emission are in phase and of the same wavelength as the photons which stimulate the emission.

The beam may be nearly unidirectional and of high intensity.

The photons bounce back and forth between the parallel mirrors at the ends of the tube and any stimulated photons will be emitted in the same direction. The beam diverges only slightly, so high intensity laser light will not decrease significantly over a distance.

Safe Handling of Lasers

Laser beams can have a high intensity, so safety is very important:

- Avoid exposing the skin to the laser beam
- Avoid exposing the eyes to the laser beam (safety glasses matched to that frequency are one way to avoid exposure)
- Beware of reflecting surfaces
- Some lasers have a very high potential difference so there is a danger of electrical shock
- Some laser beams may be invisible (e.g. infrared or ultraviolet) but are no less dangerous

Uses of Lasers

Lasers have many uses, some of which are listed below.

- Manufacturing (e.g. cutting)
- Communications (e.g. fibre optics)
- LADS
- Compact discs
- Surveying and rangefinding
- Barcode scanning
- Surgery
- Holography