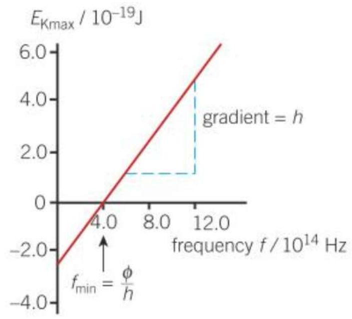
3.2.2 Electromagnetic radiation and quantum phenomena

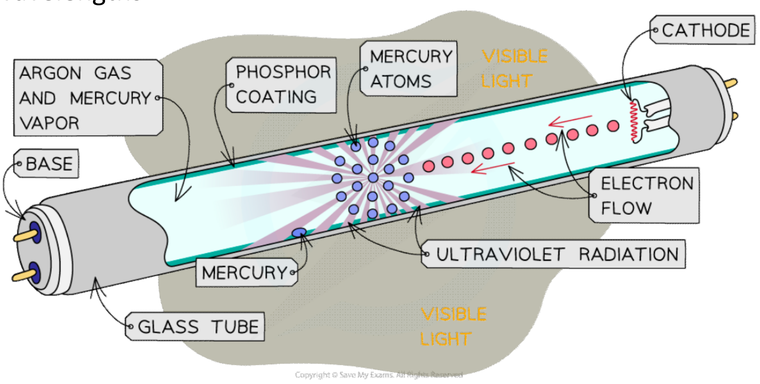
3.2.2.1 The photoelectric effect

- The photoelectric effect
  - Photoelectrons are emitted from the surface of a metal after light above a certain frequency (threshold frequency) is shown on it
- Work function
  - The minimum energy to remove an electron from the metal surface when the metal is at **zero potential**
  - Denoted by ϕ
- Stopping potential (V_s)
  - The PD needed to apply across the metal to stop the photoelectrons with the maximum KE ($E_{\mathrm{k(max)}}$)
  - Minimum energy needed to stop photoelectric emissions
  - $E_{k(\max)} = e \times V_s$
- Threshold frequency
  - The minimum frequency of the radiation / light / photon needed to liberate an electron from the surface of a material
  - $hf > \phi$
  - $f_{\min} = \dfrac{\phi}{h}$
- Why wave theory doesn't work
  - There is no photoemission below the threshold frequency even with bright light
    - Wave theory would allow gradual accumulation of energy to cause emission
    - Any frequency of light should be able to cause electron emission
  - Electrons are emitted with no noticeable decay
    - In wave theory time would elapse while an electron gains sufficient energy to leave the surface
  - Intensity of the light does not affect the KE of the emitted electrons
    - High intensity waves would be expected to give higher KE to an electron
- Explanation with the photon model
  - When light is incident on a metal surface an electron at the surface absorbs **a single photon** from the incident light and gains energy equal to hf
  - An electron can leave the metal surface if the energy gained > the work function of the metal
  - Excess energy gained becomes KE of the photoelectron
- Effect of increasing the intensity of light
  - There are more photons striking the surface per second
  - Current increases as the number of electrons emitted per second increases
- Photoelectric equation
  - $E = hf = \phi + E_{\mathrm{k(max)}}$
  - $E_{\mathrm{k(max)}} = hf - \phi$
  - Graph
    - 

    - Gradient = h
    - y-intercept = $-\phi$
- Energy level of emitted electrons

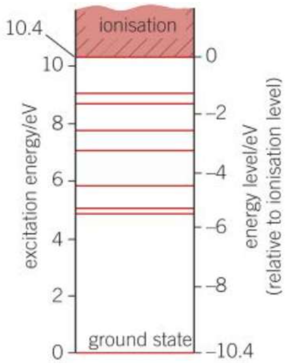
- There exists a maximum value of energy
- Energy of photons are constant ($E = hf$)
- One to one interaction between photon and electron so a fixed amount of KE is transferred
- The energy required to remove an electron varies so the KE of electrons varies
  - Max KE = photon energy - work function
  - Deeper electrons require more energy to remove than ϕ

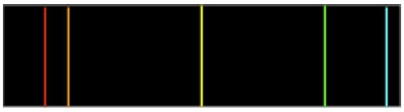
3.2.2.2 Collisions of electrons with atoms

- The electron volt
  - The work done when **1 electron** is moved through a **potential difference of 1 V**
  - $\text{work done} = \text{charge} \times \text{potential difference moved through} = qV$
  - **1 eV = 1.6 × 10^{-19} J**
- Electron energy level
  - Electrons in atoms can only exist in **discrete energy levels**
  - These electrons can gain energy from collisions with free electrons
  - Excitation
    - Electrons move up in energy level
    - It will quickly return to its original energy level (the ground state) and release energy gained as a photon
  - Ionisation
    - Electrons gain enough energy to be removed from the atom entirely
    - Occurs if **the energy of the free electron is greater than the ionisation energy**
- Excitation energies
  - The energy values at which an atom absorbs energy
- Flourescent tube
  - Filled with mercury vapour
  - High voltage applied which accelerates free electrons through the tube
  - Free electrons collide with the mercury atoms
  - Electrons in the mercury atoms are raised to a higher level
  - The mercury atom become ionised → release more free electrons
  - The new free electrons collide with the mercury atoms, causing them to become excited
  - Mercury atoms de-excites and relaxes to a lower energy level
    - They release photons of energy equal to the energy difference between the levels
    - Frequency is mostly in the **UV range**
  - The fluorescent coating on the inside of the tube absorbs these UV photons and therefore electrons in the atoms of the coating become excited and de-excite releasing photons of **visible light**
  - Emitted radiation consists of (a range of) lower photon energies / frequencies or longer wavelengths
  - 

3.2.2.3 Energy levels and photon emission

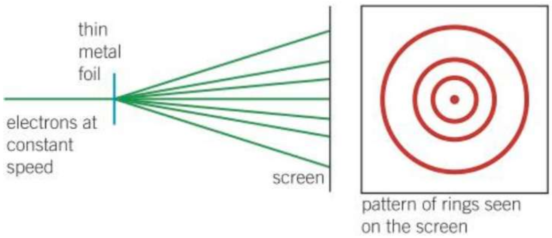
- Ground state
  - When electrons / atoms are in there **lowest energy state** / most stable state
- Excited state
  - **Electron** (in ground state) has moved to higher energy level / shell

- Ionisation energy
    - The minimum energy to remove an electron from an atom from the **ground state**
- Possible energy level of atoms
    - An atom can **only have certain levels** of energy
    - Each allowed energy level = a certain electron configuration of the atom
    - 

- Line spectrum
    - Obtained by passing the light from a fluorescent tube through a diffraction grating or prism
    - Each line = different wavelength of light emitted by the tube = corresponding to the different photon energies emitted
    - Show that electrons in atoms can only transition between discrete energy levels
    - 
- Line absorption spectrum
    - Continuous spectrum with black lines at certain intervals
    - Obtained by passing white light through a cooled gas
    - Black lines represent the possible differences in energy levels
        - The atoms in the gas can only absorb photons of an energy equal to the exact difference between two energy levels
- Why only certain frequencies of light can be absorbed
    - Electrons occupy discrete energy levels
    - They need to absorb an exact amount of energy to move to a higher level
    - Photons need to have certain frequency to provide this energy ($E = hf$)
    - Energy required is the same for a particular atom
    - All energy of the photon is absorbed in **1 to 1** interaction between photon + electron
- De-excitation
    - The electron configuration in an excited atom is unstable due to a vacancy in the shell that the excited electron left
    - The vacancy is filled by an electron from an outer shell transferring to it
- Energy level difference
    - Difference between two energy levels in line spectrum = a specific photon energy emitted by a fluorescent tube / absorbed in a line absorption spectrum
    - Energy of photon emitted = energy lost by the electron = energy lost by the atom
    - Energy of the emitted photon $hf = E_1 - E_2$

3.2.2.4 Wave-particle duality

- Evidence for wave-particle duality of light / EM waves
    - Acting as wave: diffraction and interference
    - Acting as particle: photoelectric effect
- De Broglie hypothesis
    - Matter particles have a dual wave-particle nature
- Evidence for de Broglie hypothesis
    - Collisions by incident electrons move electrons in atoms between energy levels
    - Photon emitted when atoms de-excite or electrons move to lower energy levels
    - Wave properties of electrons
        - Electrons can be **diffracted**, shown as concentric rings on scree (also diffraction of

electrons by a metal crystal)
    - Foil causes electrons to travel in particular directions
    - Bright rings / maximum intensity occurs where waves **interfere constructively**
    - Particle behaviour would only produce a circle of light as particles scatter randomly
    - **Only waves can experience diffraction** → electrons also have a dual wave-particle nature
  - Particle properties of electrons
    - Electrons must provide enough kinetic energy for light to be emitted
    - Instant light as electron can provide the energy in discrete amounts
    - Waves → energy will accumulate gradually so time is needed until light is emitted & light will always be emitted no matter how low the energy is
  - Property later also shown for other particles
  - 

- De Broglie wavelength
  - The wavelength of the wave-like behaviour of a matter particle
  - $\lambda = \frac{h}{p} = \frac{h}{mv}$
  - Higher particle momentum = shorter wavelength = less diffraction = concentric rings of the interference pattern become closer
- Change in understanding of matter
  - Knowledge and understanding of the nature of matter changes over time in line with new experimental evidence gathered
  - Such changes need to be evaluated through peer review and validated by the scientific community before being accepted