ATARNotes

Physics Revision

ATARNotes September Lecture Series

Presented by:
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Overview

- 2 hour recorded lecture
- Live chat – feel free to ask any questions about the content, studying, or uni!
- Unit 4 content covered today:
    - Special Relativity
    - Quantum Theory & Standard Model

Overview

Goals of Today's Lecture

- Most schools will be finishing up unit 4 content by now, and will be heading towards mocks
- We will be revising unit 4 content and preparing for mocks
- We will go as in depth as time allows – make sure you have something to take notes with!
- We will go over a few worked examples and any tips that I have for particular content, things to look out for, common mistakes, common exam questions, etc – I've been where you are so I know the pain

A bit about me

- Graduated in 2021 with an ATAR of 99.55
- Currently studying a dual degree in Law and Economics at UQ
- Living in Brisbane
- Physics was one of my favourite subjects!

ATAR Notes

Special Relativity

Syllabus

Special relativity

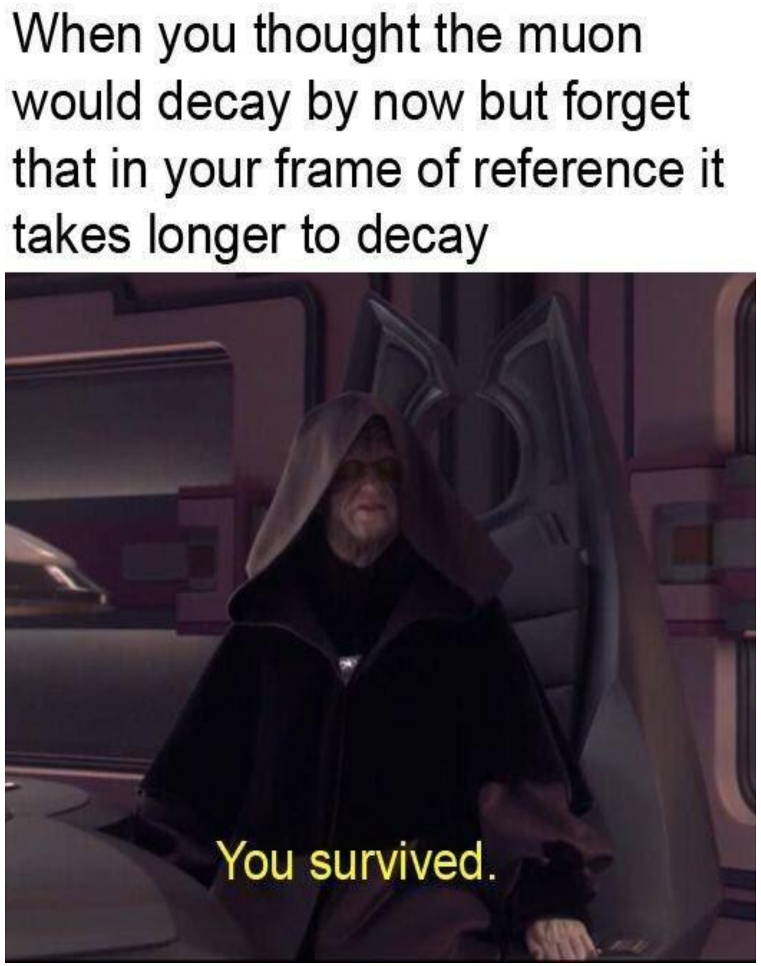
- describe an example of natural phenomena that cannot be explained by Newtonian physics, such as the presence of muons in the atmosphere
- define the terms *frame of reference* and *inertial frame of reference*
- recall the two postulates of special relativity
- recall that motion can only be measured relative to an observer
- explain the concept of simultaneity
- recall the consequences of the constant speed of light in a vacuum, e.g. time dilation and length contraction
- define the terms *time dilation*, *proper time interval*, *relativistic time interval*, *length contraction*, *proper length*, *relativistic length*, *rest mass* and *relativistic momentum*
- describe the phenomena of time dilation and length contraction, including examples of experimental evidence of the phenomena
- solve problems involving time dilations, length contraction and relativistic momentum
- recall the mass–energy equivalence relationship
- explain why no object can travel at the speed of light in a vacuum
- explain paradoxical scenarios such as the twins' paradox, flashlights on a train and the ladder in the barn paradox.

Muons

So … what's the deal with muons:

- Newton assumed space and time are constant, and that they are uniform and straight
- Muon - unstable particle created when high-energy cosmic rays interact with nuclei of oxygen atoms 15km above the surface of the Earth
- Lifetime of a stationary muon by atomic clock is 2.196 microseconds
- Muons travel at 99.97% the speed of light
  - So our friend Newton would tell us that the muon will end 8.41km above the surface of the Earth
  - After 10 lifetimes, can expect there to be no muons
  - ***WELL, MUONS CAN BE DETECED ON THE SURFACE OF THE EARTH!***

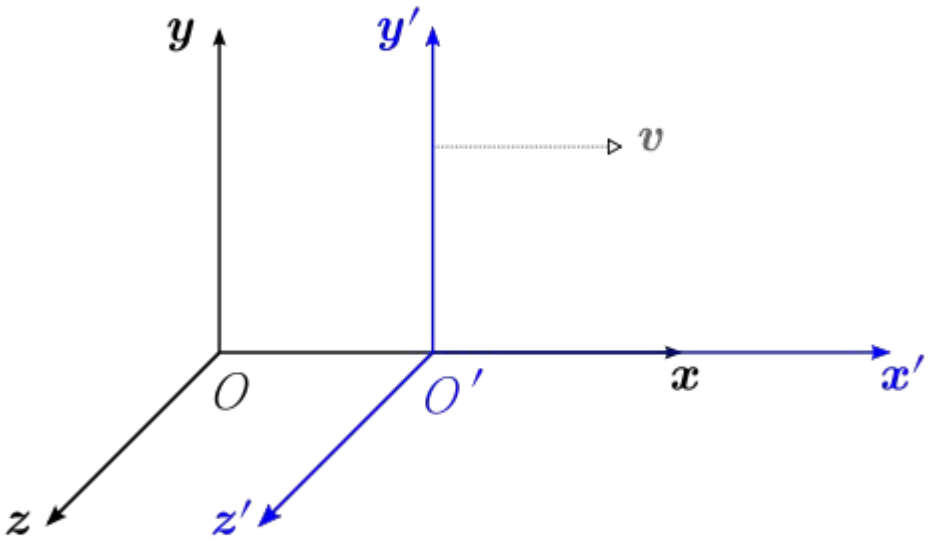
Muon lives 22.8 times more than predicted - they existed for longer time period than they should have…



Reference Frames

- Special relativity is based on the relativistic nature of motion
- Any motion that is observed is **relative** to the **reference frame** of the observer

- So we can say, a **frame of reference** = an abstract coordinate system and a set of physical reference points defined by the observer, used for observation and description (maths) of physical phenomena



Some consequences:

- We can only measure motion **relative** to an observer
- There is **no** absolute (motionless) reference frame

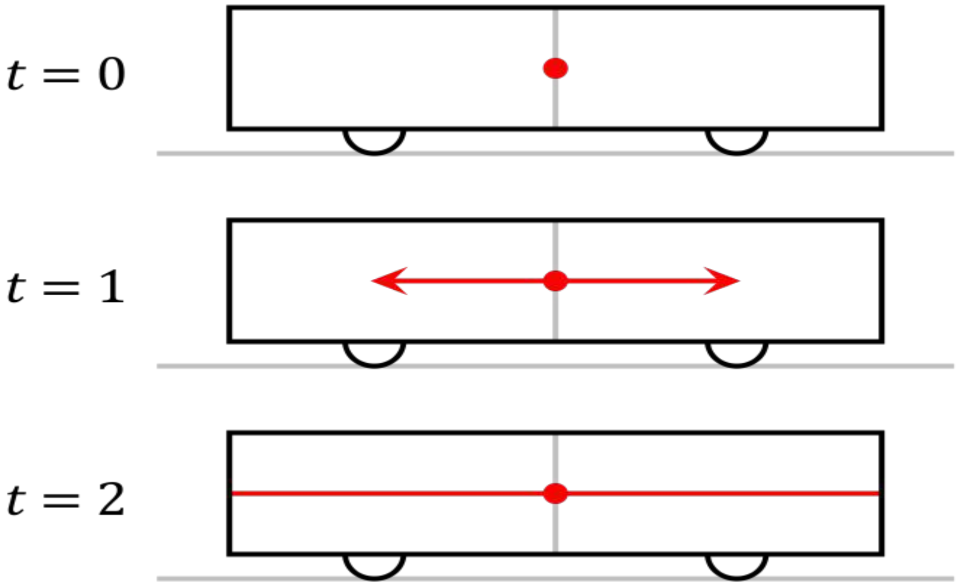
Postulates

- Einstein proposed two postulates for special relativity:
  - The laws of physics are the same and can be stated in their simplest form in all inertial frames of reference
  - The speed of light, *c*, is a constant, independent of the relative motion of the source
- We have already discussed the first postulate in some depth, evidence however for the second we have not demonstrated
  - Proof of the second postulate was shown by Michelson and Morley's 1887 experiment
  - Consequences of the second postulate will be further discussed in later classes

postulates of special relativity	the first postulate states that the laws of physics are the same in all inertial frames of reference; the second postulate states that the speed of light in a vacuum has the same value *c* in all inertial frames of reference

Simultaneity

- Events are considered simultaneous if they occur at the same time
- This can be difficult to determine if the events are occurring at distances from each other and the observer, and especially if these distances differ
- We can say instead that **two events are simultaneous if light signals from the events reach an observer who is midway between them at the same time**



Consider the train-car example:
- Light pulse from centre of carriage
- Light pulse opens the doors

Are the doors opening simultaneous?

Speed of Light

- The speed of light In a vacuum is a universal constant, we know that nothing with mass can travel faster than it
- Speed of light in a vacuum, c = 2.998×10^8m/s for our purposes
    - Generally simplify to 3×10^8m/s
- There are unusual phenomena that occur when an object with mass approaches the speed of light that explain this
- The phenomena of time dilation, length contraction, and the relationship between mass and velocity are some examples we will investigate

Suggestion 😊

Add the following terms to your glossary:

- time dilation
- proper time interval
- relativistic time interval
- length contraction
- proper length
- relativistic length
- rest mass
- relativistic momentum

Mass Effect

- Newton's second law of motion suggests that as long as there is an unbalanced force that an object will continue to accelerate
- We know the above to not be true

F = ma is still true however

- How is this so? □ Mass increases, however we know that mass is an intrinsic property

- Mass is also a relativistic property

- m_0 = rest mass or invariant mass (this is the same in all reference frames)
- m = relativistic mass (the mass in the frame at which the object is moving at a velocity, v)

Mass Effect

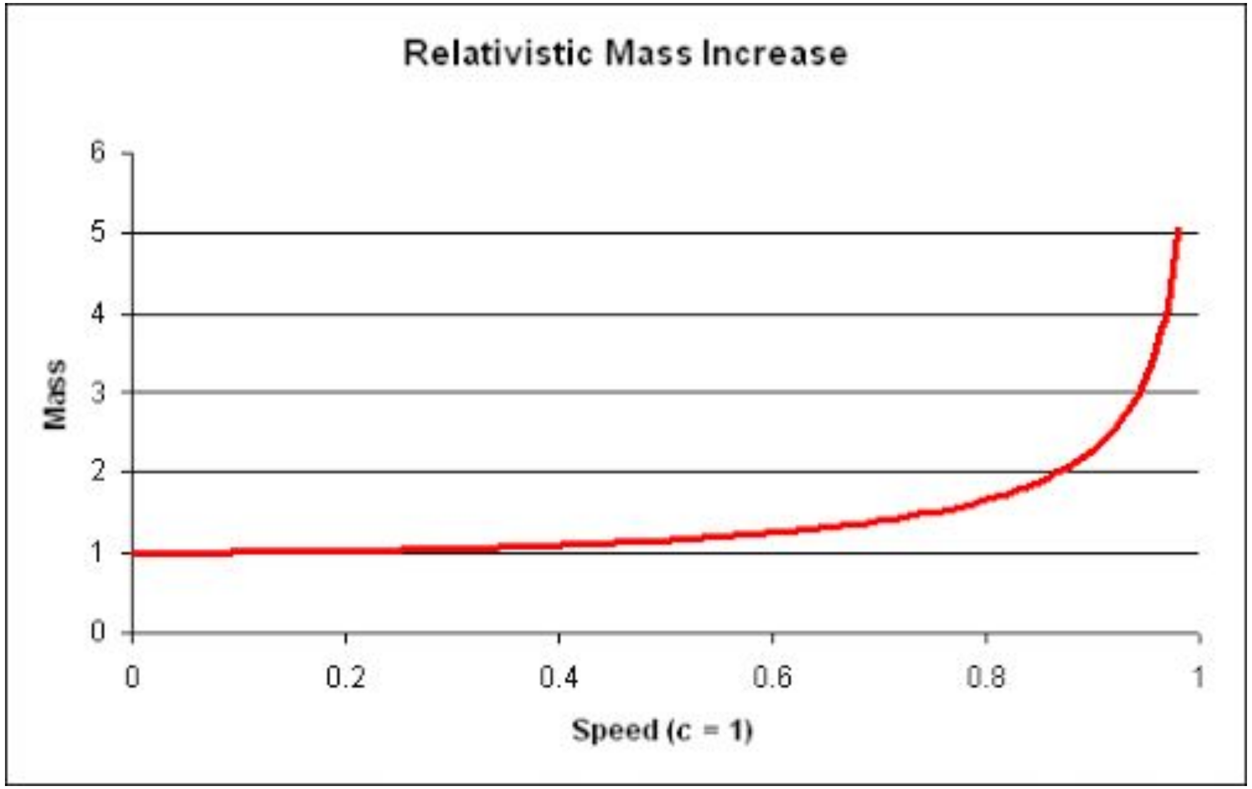
- There is a formula for determining the mass effect based on the relative velocity of the object compared to the speed of light:

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c_2}}}$$

- Clearly the relativistic mass is always greater than the invariant mass
- The relationship of mass increase as velocity approaches the speed of light is exponential

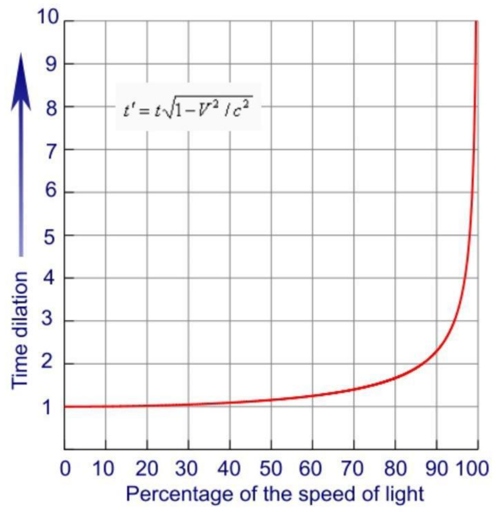
Mass Effect

As the velocity of the object approaches the speed of light, its mass approaches infinity



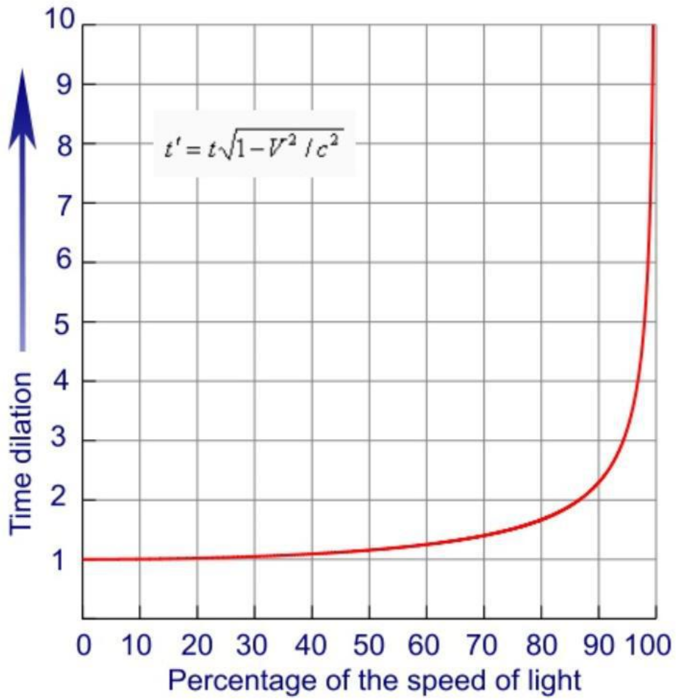
Time Dilation

- The cause of the ‘moving clocks run slow’ phenomena
- Time is relativistic, i.e., the time interval between two events cannot be the same for two observers that are in motion with respect to one another
- Gravity bends space time, therefore time moves slower in regions of increased mass
- The mass of an object will increase significantly as its velocity approaches the speed of light, hence its gravity increases, and elapsed time slows



Time Dilation Formula

- The relationship between relative velocity and time dilation is similarly exponential
- The time dilation is maximal when the velocity = c
- The elapsed time of an object with mass travelling at the speed of light is 0
- t_0 = proper time interval
- t = dilated/relativistic time
- If a rocket were to take off, the clock on the rocket would be measuring proper time (two events were measured in the one place by one clock that is at rest with respect to **both events**



$$t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Length Contraction

- Consider the astronaut/rocket ship example again
- The elapsed time in the rocket is t_0, the elapsed time on earth is t
- The velocity is considered to be consistent for both frames of reference
- Thus, in order for this to be possible, the length travelled must be different for the two observers

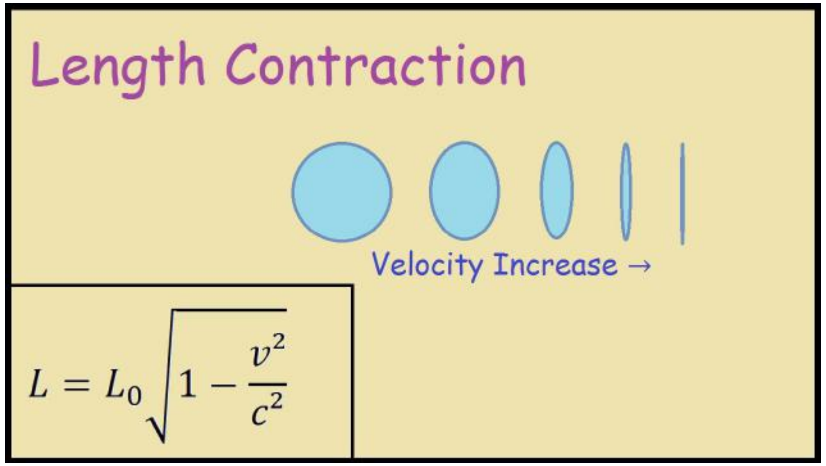
- L_0 = the length for those on earth/not moving (proper length) – length in stationary reference frame
- L = the length for those in moving frame of reference (relativistic/dilated length)

Frame of Reference	Earth-Rigel	Spacecraft
Distance Travelled	L_0	L
Time for Journey	t	t_0
Velocity	v	V

Length Contraction

- So in summary, the relationship between velocity, length contraction, and time dilation:

$$v = \frac{L}{t_0} = \frac{L_0}{t}$$



- The relativistic length can be determined by the following formula, the contracted length too exhibits an exponential relationship with the time

$$L = L_0\sqrt{1 - \frac{v^2}{c^2}}$$

Light as the Universal Speed Limit

- It should be very apparent now why light acts as the universal speed limit, why nothing with mass can travel faster than the speed of light in a vacuum (*c*).
- As an object approaches the speed of light, its mass approaches infinity, its length approaches 0, and the elapsed time for a given period approaches 0.

$$\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$t = \frac{t_0}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$L = L_0\sqrt{1-\frac{v^2}{c^2}}$$

$$m = \frac{m_0}{\sqrt{1-\frac{v^2}{c_2}}}$$

Mass-Energy Equivalence

- Anything with mass has an **equivalent** amount of energy, anything with energy, an **equivalent** amount of mass
- Equivalent energy calculated as mass (m) x c^2 $(2.998 \times 10^8\ m/s)^2$
- *Anything with energy exhibits a corresponding mass (m), derived from its energy (E) divided by c^2
- Primary consequence of this relationship is that an object at rest has intrinsic energy (rest energy) that corresponds to its rest mass
- When the body is in motion (kinetic energy), its relativistic mass > its invariant mass

$$E = mc^2$$

Twins Paradox

- Say we have two identical twins, one of which makes a journey into space in a high speed rocket. Upon returning he notices the twin on earth has aged more.
- Consider an application if inertial reference frames and time dilation – each twin has observed the other in motion, and so should have find the other to have aged less, but this is not so.

Can anyone explain?

Twins Paradox

Essentially:

- One twin goes out in space, comes back **and is younger**
- The twins were in constant motion relative to each other, both see each other aging quicker
- ***THE KEY!*** only one twin spent time the entire time in an inertial frame of reference.
    - Spaceship twin accelerated away from earth, then slowed back down etc.
- Einstein's theory deals with <u>constant</u> motion only
    - Special relativity does not encompass accelerated frames of reference

Flashlights on a Train Paradox

- Imagine a person on a train in constant motion with a torch, he shines it at a mirror on the other side of the carriage, the distance that the light beam travels
- From the frame of reference of someone on an embankment watching the train go by, the light travels a shorter distance
- How is this possible, knowing the light cannot travel faster than c?

Can anyone explain?

Hint: simultaneity

Flashlights on a Train Paradox

Essentially:

- Consider time dilation and simultaneity
- Speed of light remains constant
- Events simultaneous to one viewer isn’t simultaneous to other, distance the light had to travel depends on your **reference frame**
  - Train moving close to speed of light

Ladder in a Barn Paradox

- A ladder (or pole) parallel to ground is moving horizontal to the ground at a relativistic speed (near speed of light)
- It is undergoing a length contraction, and moves through a barn that's length is shorter than the ladders rest length
- To a stationary observer the ladder can fit inside
- To an observed moving with the ladder, there is no length contraction of the ladder, and it is instead **the barn** that is contracting (the ladder can't fit)

Can anyone explain?

Ladders in a Barn Paradox

- Simultaneity is relative!
- Just because two events are simultaneous as measured from one frame of reference, does not mean they are simultaneous from another frame of reference!
- The doors being opened and closed are not simultaneous events from the frame of reference of the pole!

ATAR Notes

Quantum Theory

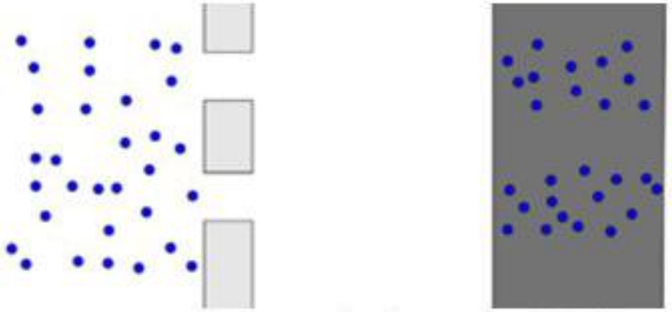
Syllabus

Quantum theory

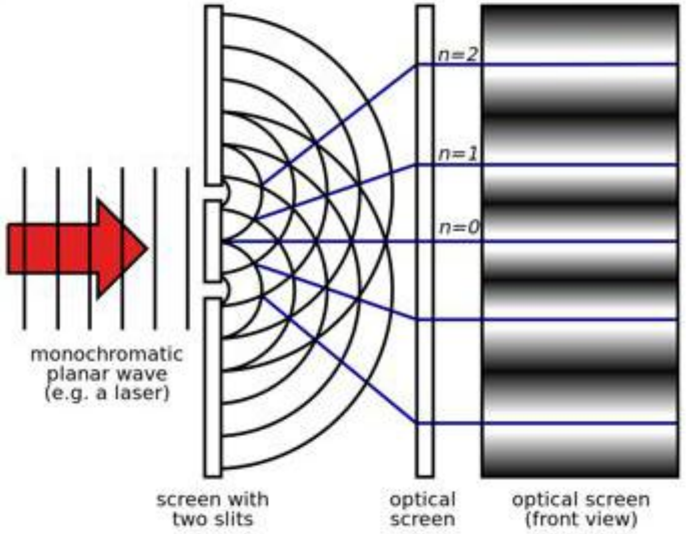
- explain how Young's double slit experiment provides evidence for the wave model of light
- describe light as an electromagnetic wave produced by an oscillating electric charge that produces mutually perpendicular oscillating electric fields and magnetic fields
- explain the concept of black-body radiation
- identify that black-body radiation provides evidence that electromagnetic radiation is quantised into discrete values
- describe the concept of a photon
- solve problems involving the energy, frequency and wavelength of a photon
- describe the photoelectric effect in terms of the photon
- define the terms *threshold frequency*, *Planck's constant* and *work function*
- solve problems involving the photoelectric effect
- recall that photons exhibit the characteristics of both waves and particles
- describe Rutherford's model of the atom including its limitations
- describe the Bohr model of the atom and how it addresses the limitations of Rutherford's model
- explain how the Bohr model of the hydrogen atom integrates light quanta and atomic energy states to explain the specific wavelengths in the hydrogen line spectrum
- solve problems involving the line spectra of simple atoms using atomic energy states or atomic energy level diagrams
- describe wave–particle duality of light by identifying evidence that supports the wave characteristics of light and evidence that supports the particle characteristics of light.
- **Mandatory practical:** Conduct an experiment (or use a simulation) to investigate the photoelectric effect. Data such as the photoelectron energy or velocity, or electrical potential difference across the anode and cathode, can be compared with the wavelength or frequency of incident light. Calculation of work functions and Planck's constant using the data would also be appropriate.

Young's Double Slit Experiment

If you project a beam of particles at two slits, the resulting projection on a wall behind those slits appears as so:

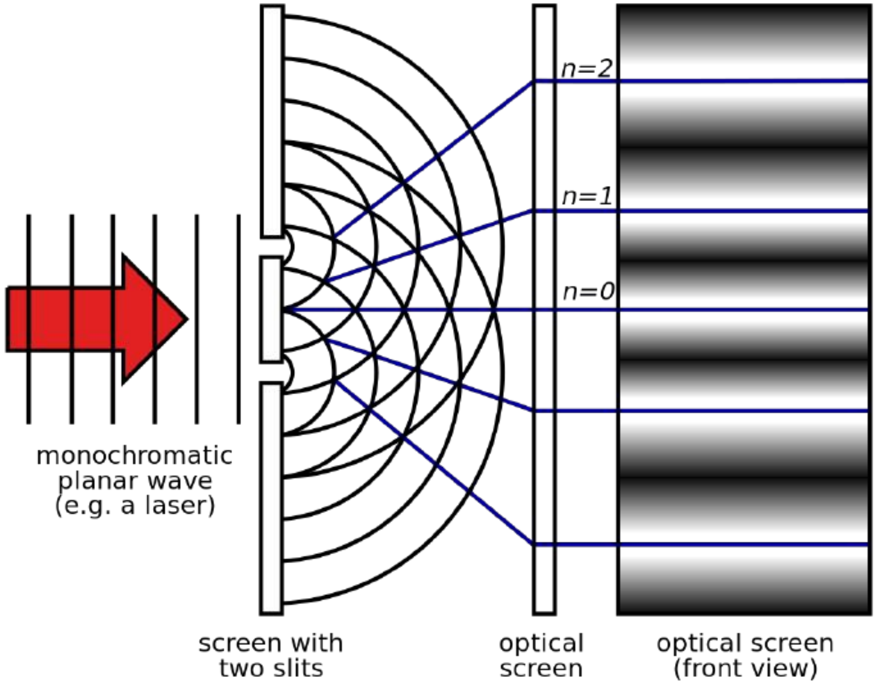


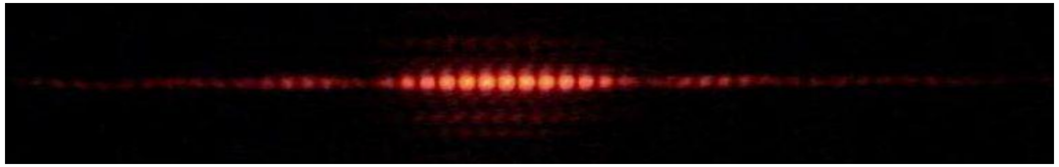
If you project a monochromatic beam of light towards the same two slits, the projection on the wall behind looks far different



Young's Double Slit Experiment

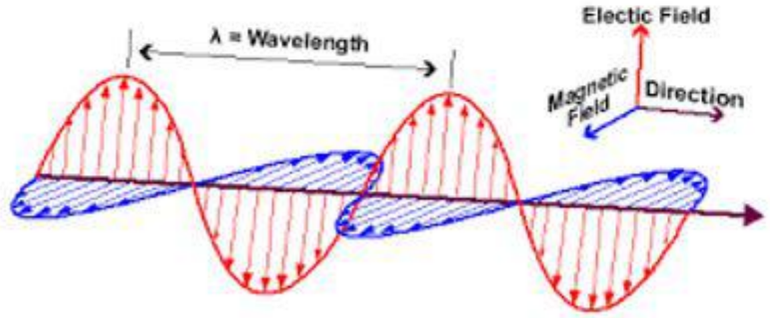
- This is occurring as the distance between the slits is approximately the same as the wavelength of light, causing the splitting into two new light waves
- These waves interfere, either **constructively** (yielding bright spots), or **destructively** (yielding dark nodes)





Light as a Wave

- Characteristics of electromagnetic radiation:
  - Consist of **oscillating** electric and magnetic fields
  - These fields are at right angles to one another
  - The speed of the wave is dependent on the **magnetic** and **electric** properties that it is travelling in (speed of light differs in different substances – refractive index)

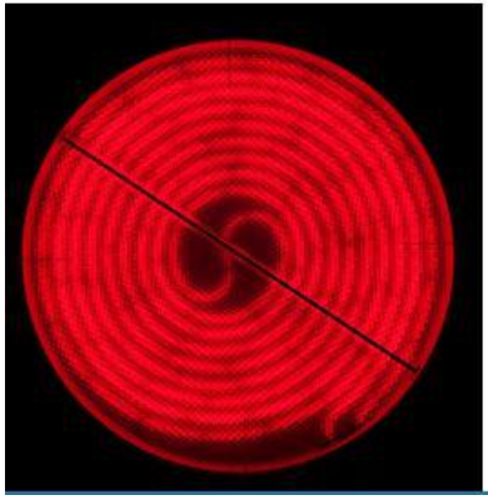


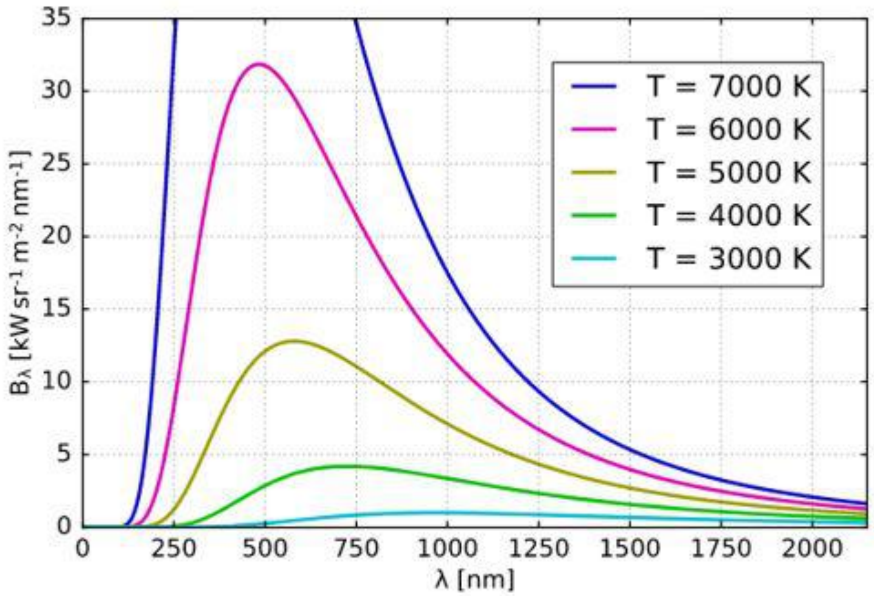
$$E = hf$$

- Where,
  E = energy (Joules)
  h = Plancks constant
  (6.62607004x10^{-34} m^2kg/s
  f = frequency (Hz)

Black Body Radiation

- In the late 1850's experiments were being performed on completely black metal objects called 'black bodies' – will not reflect any light
- Radiation is emitted purely by the energy from within itself. e.g. a hotplate glowing red ▯▯ orange ▯▯ white
- Distribution between intensity and frequency (with relation to temperature) is given below





Black Body Radiation

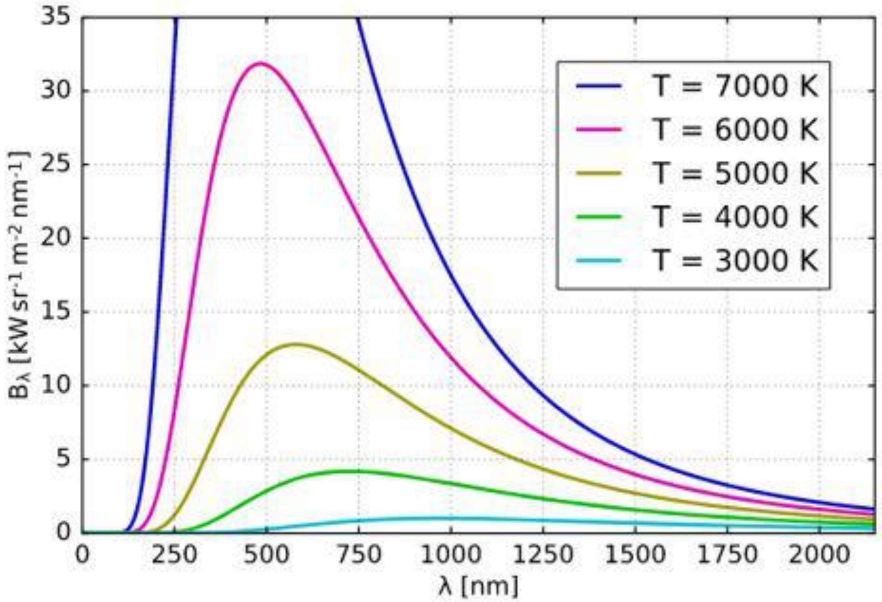
- The explanation of the distribution curves eluded scientists until Max Planck proposed that the energy emitted by black bodies was from the **vibration of atoms** limited to **certain frequencies** that were multiple of **some value**
- Light in this situation is emitted as packets (quanta)
- The frequency of light emitted by the vibration of an atom is proportional to the change in energy of the atom, related by the Planck's constant

- Proof that light exists as a quanta!!

$$E = hf$$

$$c = \lambda f$$

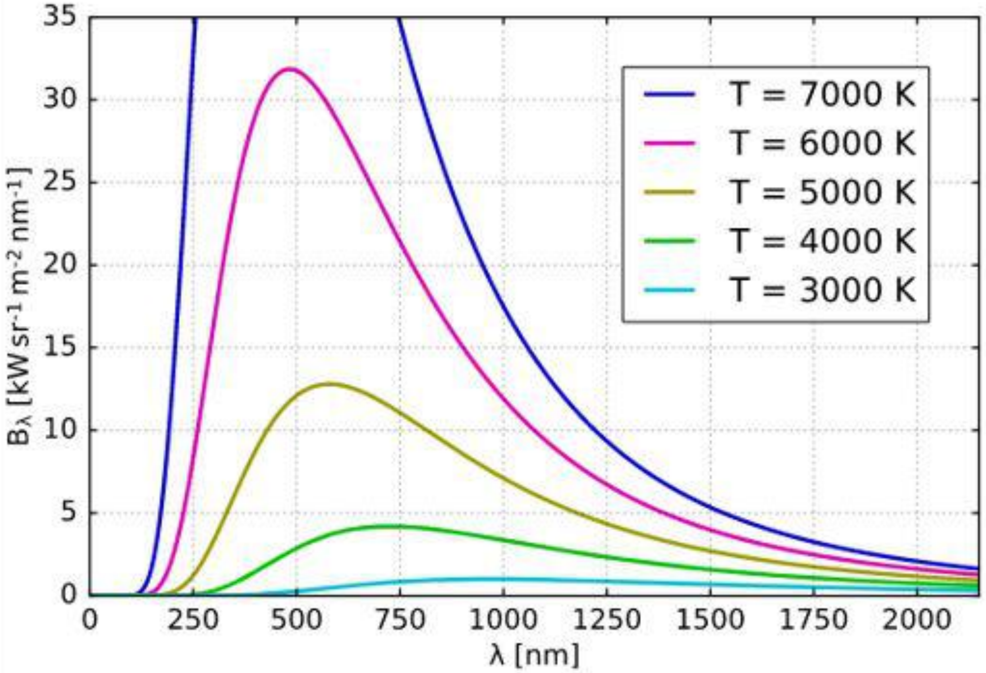
$$E = \frac{hc}{\lambda}$$



Blackbody Radiation

- Wien's displacement law describes the relationship between the temperature and peak wavelength of black body radiation curves (like those you see below)

$$\lambda = \frac{b}{T}$$



T = temperature (K)
b = Wien's displacement constant = 2.897772×10^{-3} mK

A nice breakdown

$$E = hf$$

- The **energy, E,** in a single quanta of light of a **frequency, *f*,** related by **Planck's constant, *h***

$$c = \lambda f$$

- The **frequency, *f*,** and **wavelength, *λ*,** of light, is related to its **velocity** in a **vacuum, c,** by wave equation

$$E = \frac{hc}{\lambda}$$

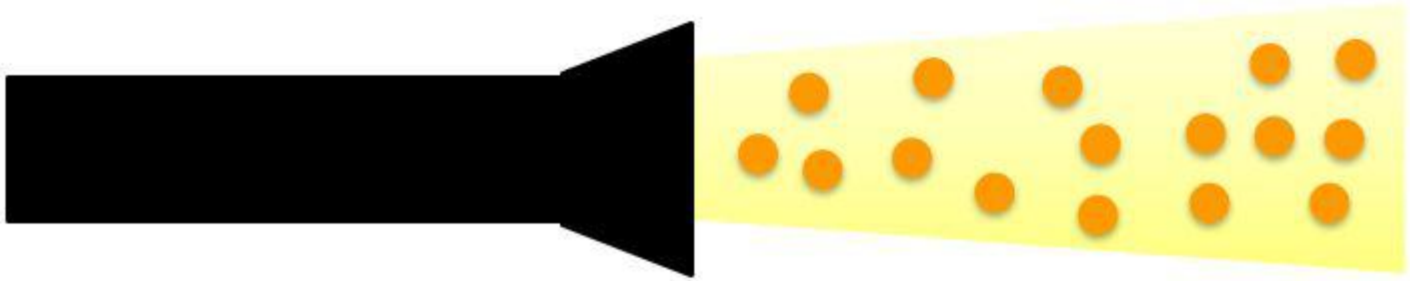
- Thus, the **energy, E,** of a single quanta of light can be related to the **wavelength, *λ*,** by **velocity, c,** and **Planck's constant, *h***

E = energy (Joules)
f = frequency (s^{-1} or Hz)
h = Planck's constant (6.63×10^{-34})
c = speed of light in a vacuum (3×10^{8} m/s)
λ = wavelength (m)

Photon Model of Light

- Photon model or particle model of light deals with the particle light behaviour we observe of subatomic particles
- Light exists as numerous photons
- Photons (light particles):
  - Have **no rest energy** (recall special relativity)
  - Have **no mass**
  - Have **kinetic energy**

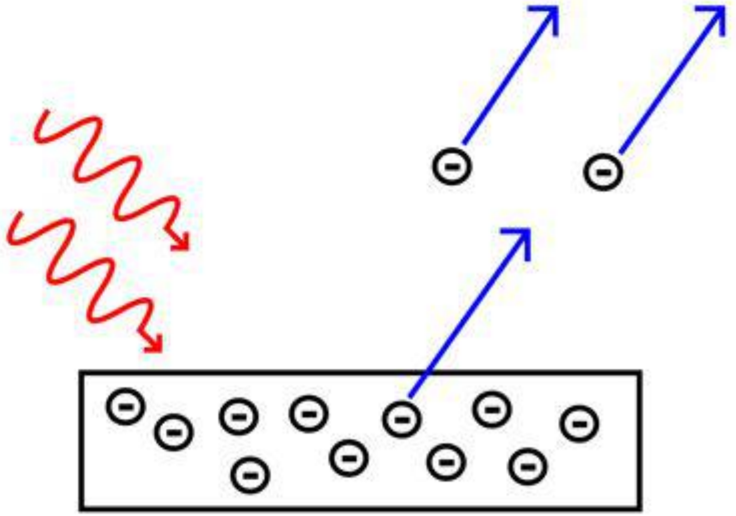
$$e = mc^2$$



Photoelectric Effect

- When a metal surface is illuminated by **electromagnetic radiation** of a high frequency, **electrons** are **ejected** from the metal surface as a **photocurrent**
- This ejection only occurs if the frequency exceeds the **ejection frequency, f_0**
- The ejection frequency differs depending on the metal

- Some photocurrent characteristics
  - When a photocurrent is registered, increasing the intensity of incident light will increase the magnitude of photocurrent
  - Light with a higher frequency than the ejection frequency will increase the kinetic energy of the ejected electrons



Photoelectric Effect

- This phenomena cannot be explained by the standard wave model of light, and instead supports the theory of the particle model
- A single photon ejects a single electron, giving all of its energy to the electron, or none of it
- The collisions are **completely elastic** and abide by the **law of conservation of energy**

- Three forms of energy in this system can be defined:
  - Photon energy: $\boldsymbol{E = hf}$
  - Energy of electron binding to metal: $\boldsymbol{W = hf_0}$
  - Maximum kinetic energy of ejected electrons: $\boldsymbol{E_{K(max)}}$

- This yields the formula:

$$\boldsymbol{E_{K(max)} = hf - W}$$

Photoelectric Effect

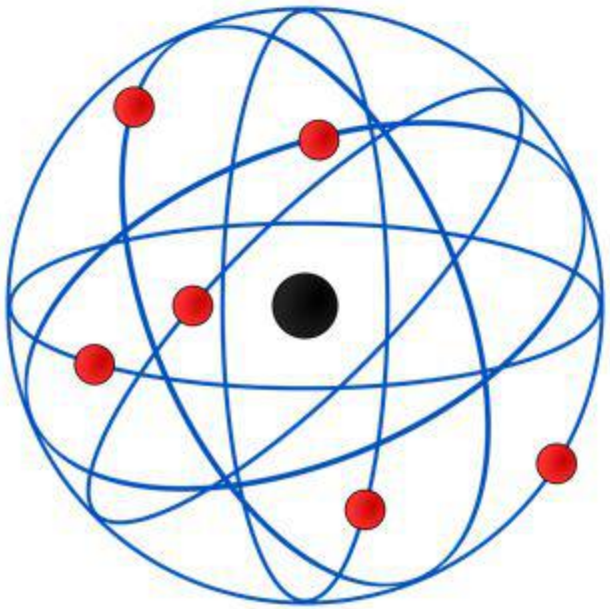
- We can physically measure photocurrent with a negatively charged collector plate
- Negative potential reflects the incident electrons, and eventually this potential becomes large enough to deflect the entire photocurrent
- The voltage that this happens is the **cut-off voltage, V_c**, or 'stopping potential'
- Thus, the kinetic energy of the ejected electrons can also be determined by:

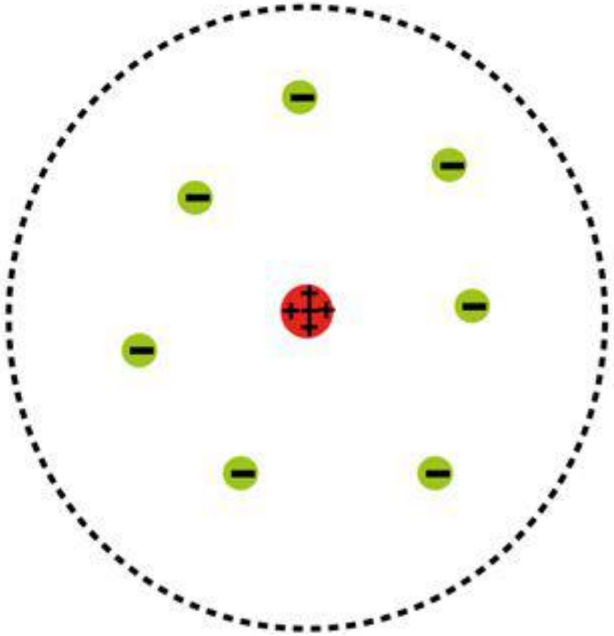
$$\left(\frac{1}{2}mv^2\right) = hf - hf_0 = qV_c$$

V_C = cut-off voltage
v = ejection velocity of the electron (kg)

Rutherford's Model

- Rutherford's model of the atom is the 'stereotypical' atom model
- It denotes an atom as mostly empty space
- The positively charged nucleus is set in space
- The negatively charged electrons orbit in predictable paths





Rutherford's Model - Limitations

Atom stability:

- In the model electrons ordered in a fixed orbit at a high speed. George Maxwell explained, however, that these accelerated (the direction is changing) particles will release electromagnetic radiation
- This electromagnetic radiation has energy, so the KE of the particles will decrease. As the velocity decreases, the orbit will decrease, and the electrons will collapse into the nucleus
- Thus, Rutherford's model is challenged by the stability of **his** atom

Electron location:

- The model was inherently incomplete, as it gave no mention to the arrangement of electrons within their orbit. This is addressed by Bohr's model

Bohr Model

- In 1913 Niels Bohr approached the issues of atom stability and electron location using quantum concepts to propose the Bohr Model of the atom

- Electrons only radiate energy in **exact quanta** (definite amounts of energy)
- As electrons radiate energy they move **inward** towards the **nucleus** in definite **quantum orbitals** until a stable orbital is reached

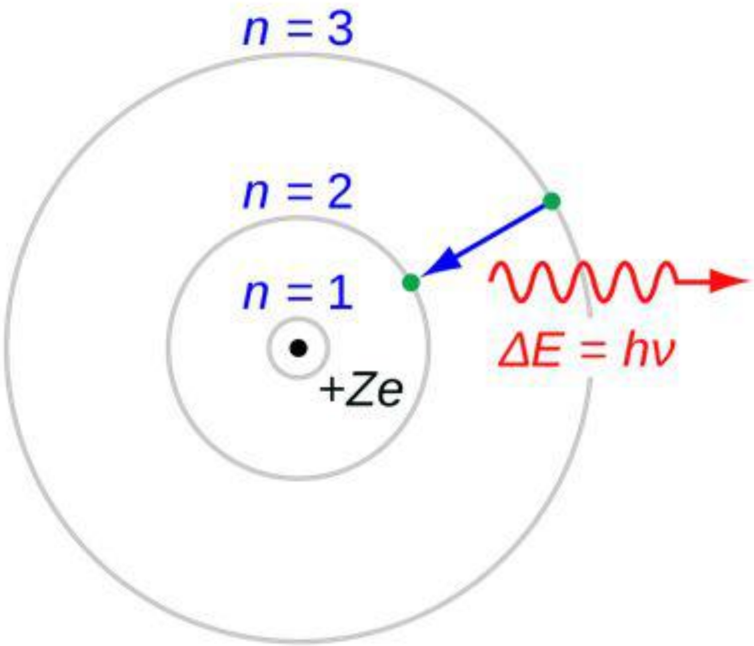
Given this information, how does the Bohr model address the issues of the Rutherford model?

Bohr Model – Emission & Absorption

- Each jump down results in the emission of a **photon** with **energy** a definite a predictable value (relative to the difference in energy between the orbitals)
- The absorption of a photon with energy equal to the difference in energy between an electrons **stationary state** and **excitation energy** state will cause the incident electron to move to the **excitation state**

- Every **change in electron orbit** corresponds to the **absorption** (orbital up) or **emission** (orbital down) of **electromagnetic radiation**

- If the **electromagnetic radiation** is high enough energy it will knock of the electron **ionising** the atom (the limit = **ionising energy**)



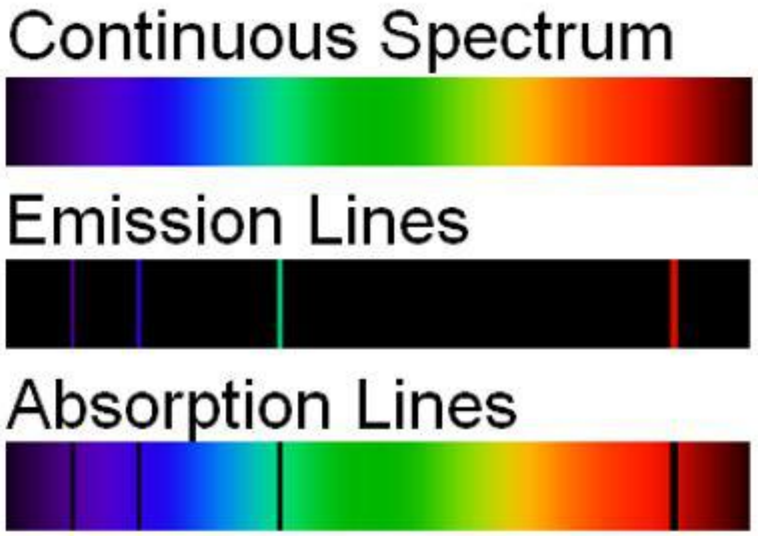
Bohr Model - Evidence

- The orbitals of electrons cause the emission/absorption of photons of definite and specific energy levels. Which as we know is related to the frequency.
- The emission of energy and jump back down orbitals is stepwise

- If we pass light emitted from an atom through a **prism spectrometer** it will split the light into the spectral components
- The absorption and emission values are equal and opposite!

$$E = hf$$

E = energy (Joules)
h = Planck's constant (6.626×10^{-34})
f = frequency (Hz or s^{-1})

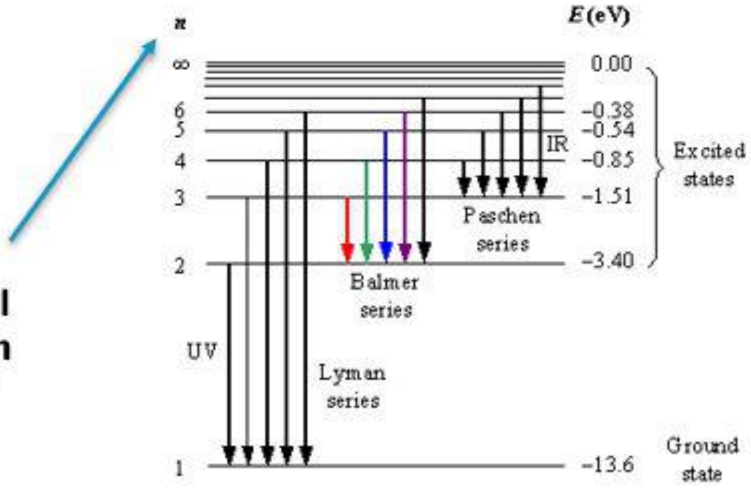


Balmer Series

- In 1885 Johann Balmer determined the mathematical relationship between the light colours emitted by excited Hydrogen gas atoms
- Bohr determined the orbits for the hydrogen atom electrons based on the wavelengths for the spectral lines, giving the Balmer equation:

$$\frac{1}{\lambda} = R_H\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

Principal quantum number



Energy levels of the hydrogen atom with some of the transitions between them that give rise to the spectral lines indicated

De Broglie’s Justification of Bohr Model

- Applied the theory of wave-particle duality to the Bohr model of the atom
- This allowed the explanation of why only certain orbits are facilitated in the atom
- The circumference of the orbit must be an integral multiple of the electron wavelength
- This gives the below formula:

$$n\lambda = 2\pi r$$

Final Study Tips

- Work up to doing practice questions/homework in exam conditions
  - Timed
  - Formula sheet
  - Graphics calculator

- Spaced retrieval will *save you*
- Mark all your work
- Create a feedback/mistakes log
  - Reflect on this
- Variety in your notes – add from multiple sources but keep it focused to what you need

Final Study Tips

- Take mocks seriously (but don't push yourself to the edge for them, Year 12 is a marathon NOT a sprint)

- Glossary/definition bank
  - Start practicing these now, you have 30+ definitions to know
  - **USE THE QCAA DEFINITIONS, NOT YOUR TEXTBOOK DEFINITIONS**

- Steal some friends and make a study group
  - Or better yet, make a study group with people from your class you typically don't spend a lot of time with – we're all in this together!

Final Study Tips

- Know how to use your calculator

- Regular physics study – even on the holidays
- Do rest though
- Be friends with your teacher (or a different teacher if yours isn't A1)
- Seek help and clarification
  – Keep a note if it distracts you during your study or if you forget

- Break down the formula sheet without using your notes or looking anything up

Summary

Key skills

- Special Relativity
  - Einstein's Postulates
  - Time dilation, length contraction, change in mass
  - Mass-energy equivalence
  - Paradoxes
- Quantum Theory
  - Young's double slit experiment
  - Blackbody radiation
  - Photoelectric Effect
  - Rutherford's and Bohr's model

Reminders

- Study consistently for your externals
- Don't stress too much
- Do lots of practice questions & check your answers
- Do all of the past exams on the QCAA website

ATAR Notes

Good luck & thank you for listening 😊