9.8 Option – From Quanta to Quarks

Contextual Outline

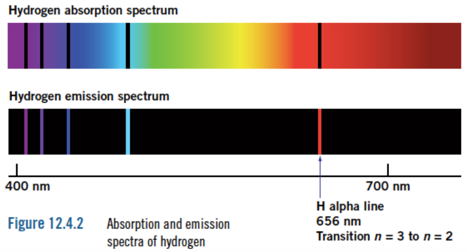
In the early part of the twentieth century, many experimental and theoretical problems remained unresolved. Attempts to explain the behaviour of matter on the atomic level with the laws of classical physics were not successful. Phenomena such as black-body radiation, the photoelectric effect and the emission of sharp spectral lines by atoms in a gas discharge tube could not be understood within the framework of classical physics.

Between 1900 and 1930, a revolution took place and a new more generalised formulation called quantum mechanics was developed. This new approach was highly successful in explaining the behaviour of atoms, molecules and nuclei. As with relativity, quantum theory requires a modification of ideas about the physical world.

This module increases students' understanding of the history, nature and practice of physics and the current issues, research and developments in physics.

1. Problems with the Rutherford model of the atom led to the search for a model that would better explain the observed phenomena

Students learn about:	*Notes:*
▪ discuss the structure of the Rutherford model of the atom, the existence of the nucleus and electron orbits	▪ **Earnest Rutherford** was the scientist that came up with the plum pudding model of an atom. ▪ Similarly, to JJ Thomson cathode ray experiment, Rutherford conducted an experiment where an alpha particle was fired into a metal foil. This experiment was known as the Thin Gold-foil Experiment. ▪ He could demonstrate and observe that: – Most of the alpha particles beam through the gold foil unreflected. – One in 8000 would get deflected at a slight angle and some deflect fully. – This rebound of electrons in the gold foil poses the idea that positive charged particle exists inside an atom. ▪ With this Rutherford proposed that the model of the atom was: – Required massive but tiny positively charged centre known as a nucleus. The nucleus would contain most of the atoms mass which was concentrated to the middle. – Electrons were placed on the outer region orbiting the nucleus. – And the rest would be composed of empty space. ▪ Hence Rutherford's model of the atom consists of a very dense and tiny nucleus which was positively charged and was small than the atomic radius. Electrons could be located outside orbiting the nucleus, with the rest of the space empty. ▪ However, this model has some limitations: – It wasn't very confirmed what the nucleus was made of, merely it exists at the centre. – How the orbits of the electrons were arranged and hence the path it followed. Fail to provide evidence for the spectra of a Hydrogen atom. – As the electrons was in centripetal motion around the nucleus, it is constantly accelerating, and hence Maxwell's electromagnetism, states that accelerating charges radiate EMR and energy, meaning that the electrons would lose energy and cause a spiral down to the nucleus. Hence it could explain the stability of the electrons as to way they are attracted to the nucleus.

▪ analyse the significance of the hydrogen spectrum in the development of Bohr's model of the atom  Figure 12.4.2 Absorption and emission spectra of hydrogen	▪ When white light is passed through a triangular prism and is diffraction a spectrum of colours is broken up into, Red, Orange, Yellow, Blue, Indigo, Violet. [ROYBIV] This was the continuous spectrum. ▪ **Bohr** heightened the understanding of Rutherford's model of the atom, solving the instability of electrons in an atom. He applied quantum theory to explain for nature of electrons and explained the quantisation of electrons. ▪ There are two type of spectrum: – **Absorption Spectrum** ▪ Absorption Spectra can be produced by passing white light through cool gas. ▪ **Atoms** and molecules will absorb specific type of wavelength and hence the it corresponding colour. ▪ The absorbed atoms are now in an excited state, where they emit photon of light, usually in a different direction. ▪ Hence, were observed on the continuous spectrum, there will be certain wavelength depletion which are replaced with dark lines. – **Emission Spectrum** ▪ **Emission Spectra** was produced with excited gas. This can be done by heating up the molecules or passing an electrical current. ▪ As a result, the colours that are absorbed are displayed with a dark background. ▪ This was used to determine the emission spectrum of other elements, as every element has it unique spectrum line and was used to identity new elements. ▪ Bohr could produce emission spectrum will the simplest element, Hydrogen, where electrons could be spotted at different spectral line indicating that they are located at different energy level.
▪ define Bohr's postulates	▪ **Bohr's Postulates [On the Rutherford-Bohr Model of Atom]:** – Electrons in an atom exist in stable circular orbits without emitting radiation. They can make quantum jumps from one to another. The energy level, can be known as their stationary state. – Electrons absorb and emit quantised energy, when they transition from their stationary states. This is with the used of Plank's Quantum Theory. – An electron in a stationary state has an angular momentum that is quantised and is a multiple of h/2pi.
▪ discuss Planck's contribution to the concept of quantised energy	▪ **Plank's** contributed in the concept of solving the violation of classical physic in black body radiation. He could explain the cause of the ultraviolet catastrophe and hence deduce that energy was given in discrete packets. ▪ **Energy** was now known to be quantised and hence the development of quantum theory was established. ▪ With this Einstein, could reassess the photoelectric effect and it model of light. ▪ Bohr could his model of the atom.

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- describe how Bohr's postulates led to the development of a mathematical model to account for the existence of the hydrogen spectrum:

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

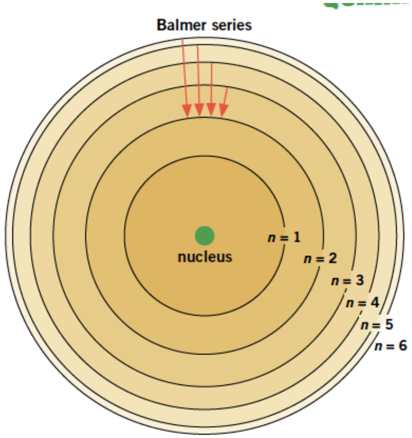

Figure 12.6.1 Diagrammatic representation of Bohr's explanation of the Balmer line series for the hydrogen spectrum

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- **Bohr** could derive the Balmer's series, using the Plank's quantum theory and hence stated that:
  - When an electron absorbs energy, it moves up in energy level to a higher orbit.
  - When energy from an electron is emitted, it moves down to a lower orbit and emit EMR.
  - With the help of Bohr's 2nd postulate, an equation can be derived with Balmer's trial and error and Rydberg's constant.
- With this Bohr was able to explain his model, by predicting the wavelengths for a hydrogen spectra line. In a hydrogen atom, the energy difference from the quantum jump can be calculated.
- The equation could be derived from:

$$E_n = \frac{1}{n^2} \times E_1$$

$$\text{Therefore, the difference in the energy from one stationary state to other is given by}$$

$$\Delta E = hf = E_i - E_f$$

$$hf = \frac{1}{n_i{}^2}(E_1) - \frac{1}{n_f{}^2}(E_1)$$

$$h\frac{c}{\lambda} = -E_1\left(\frac{1}{n_f{}^2} - \frac{1}{n_i{}^2}\right)$$

$$\frac{1}{\lambda} = \frac{-E_1}{hc}\left(\frac{1}{n_f{}^2} - \frac{1}{n_i{}^2}\right)$$

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

$$\text{where } R = \text{Rhdberg's constant} = \frac{-E_1}{hc}$$

With this equation, the wavelength that the electrons emitted could be calculated.

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- discuss the limitations of the Bohr model of the hydrogen atom

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- **Limitations** Bohr's model possess:
  - **Multi-electron Atoms:** Bohr couldn't account for atoms larger than Hydrogen. Since Hydrogen consist of one electron in planetary orbit, it didn't have to interact with other electrons in complex ways. When the **spectra of larger atoms** were observed, there multi-electrons orbiting the nucleus interacted in a different manner, as supposed to Hydrogen, Helium ion and Lithium ion.
  - **Relative intensities in spectra lines:** Bohr couldn't explain the varying intensities given to a spectra line. Some of the line were thicker and brighter than other, meaning that some transition were preferable.
  - **Existence of Hyperfine Spectra lines:** When observed closer in the supposed single line spectra lines, it was noticed that many layers of thicker spectra line existed with distance of .1 - .5 nm. This was the reason that electrons have a spin magnitude and that electrons have many energy states that states.

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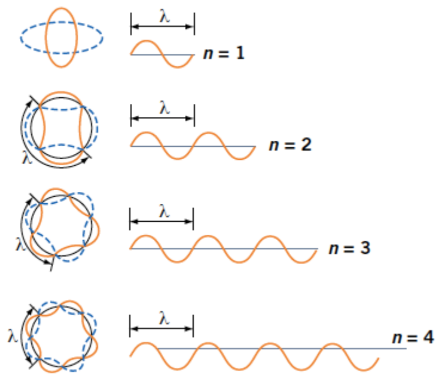
	– **The Zeeman Effect:** The splitting of spectra line when a strong magnetic field is applied. The spectra line further split in triplet and hence classical physic and Bohr couldn't explain for that. It showed that electron has further sub-states.

Students learn to:	*Notes:*
▪ perform a first-hand investigation to observe the visible components of the hydrogen spectrum	▪ A
▪ process and present diagrammatic information to illustrate Bohr's explanation of the Balmer series.	▪
▪ solve problems and analyse information using: $\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$	▪
▪ analyse secondary information to identify the difficulties with the Rutherford-Bohr model, including its inability to completely explain: – the spectra of larger atoms – the relative intensity of spectral lines – the existence of hyperfine spectral lines – the Zeeman effect	▪

2. **The limitations of classical physics gave birth to quantum physics**	
Students learn about:	*Notes:*
▪ describe the impact of de Broglie's proposal that any kind of particle has both wave and particle properties	▪ Like **light having a particle and wave properties, De Broglie**, proposed that **particle too can also possess a wave like nature**, believing the idea that **photon can have momentum**. ▪ Mathematically: $$E = hf = mc^2$$ $$p = mv$$ $$\text{the moementum for ligth will travel at c}$$ $$\therefore p = mc$$ $$pc = mc^2$$ $$pc = E$$ $$p = \frac{E}{c}$$ $$= \frac{hf}{c}$$ $$= \frac{E}{c}$$ $$\text{from } c = f\lambda$$ $$f = \frac{c}{\lambda}$$ $$\text{Hence by substituting f into p}$$ $$p = \frac{h}{\lambda}$$ $$\text{This is the equation of momemtum of photon in terms of its wavelength}$$ $$\text{Hence to found its wavelength}$$ $$\lambda = \frac{h}{mv}$$ $$\text{where } \lambda = \text{Wavelength (m)}$$ $$h = \text{Plank's Constant } (6.63 \times 10^{-34})$$ $$m = \text{Mass (kg)}$$ $$v = \text{Velocity (m/s)}$$ ▪ This impacted the stability of an atom where it could explain Bohr's model for all elements not just Hydrogen.

	▪ De Broglie showed that in Bohr's model of stability in electrons, it corresponded with the circumference of the shell. nλ [Standing Waves] ▪ All electrons (particle) will possess a wavelength nature, which either creates a constructively or destructively superposition. – If the electrons wavelength creates a constructive interference, then a location exists. – If the electrons wavelength creates a destructive interference, then that location is empty.
▪ define diffraction and identify that interference occurs between waves that have been diffracted	▪ **Diffraction is the spreading of waves around corners, of through small openings.** ▪ All waves that diffract will experience an interference. Interference can only occur in small gaps will large wavelength, for it to be visible and effective. ▪ When two wave pass through different slits or gaps and create a diffraction. When there diffraction collides, they an interference patterns can be observed.
▪ describe the confirmation of de Broglie's proposal by Davisson and Germer	▪ **Davisson** and **Germer** used electron scattering to experimentally confirm De Broglie concept of wavelike properties on particles. The electrons could diffraction. ▪ **Davisson and Germer's Experiment** – A beam of low energetic electrons was fired onto the surface of a nickel crystal. This was done in a vacuum tube with a heating filament to supply the electron beam. – The electrons striked were scattered and diffracted to form a diffraction pattern. This could be determined by the different intensity pattern that electrons reflected. – The diffraction consists of a maximum and minimum angle of around 50 degrees, and hence an interference made by the scattering electron suggested the wave-nature of electrons.

▪ explain the stability of the electron orbits in the Bohr atom using de Broglie's hypothesis  Figure 13.5.1 Comparison of standing waves wrapped in a circle and on a rope. For a standing wave to be produced in a circle, a whole number of matter waves must fit into the circumference.	▪ Since De Broglie showed that particle have wavelike properties or known as matter waves. Electrons could be suggested to orbit around the nucleus in a form of a standing wave. ▪ This orbit was made up of an integral number of wavelengths that fitted the circular orbit. This relates back to Bohr's 3rd postulate about angular momentum. $$\text{Stansing wave} = \text{Circumference of orbit}$$ $$n\lambda = 2\pi r$$ ▪ **Standing wave: A wave that doesn't propagate, rather vibrate between two boundaries.** ▪ By substituting, $$\lambda = \frac{h}{mv}$$ $$mvr = \frac{nh}{2\pi}$$ Since angular momentum exist as whole integers, due to quantum theory, it provide support for Bohr's 3rd postulate of quantisation of angular momentum. ▪

Students learn to:	*Notes:*
▪ solve problems and analyse information using: $$\lambda = \frac{h}{mv}$$	▪
▪ gather, process, analyse and present information and use available evidence to assess the contributions made by Heisenberg	▪

and Pauli to the development of atomic theory	

3. **The work of Chadwick and Fermi in producing artificial transmutations led to practical applications of nuclear physics**	
Students learn about:	*Notes:*
▪ define the components of the nucleus (protons and neutrons) as nucleons and contrast their properties	▪ This topic is based of Neutrons, Nuclear Physic and Transmutation. ▪ nucleon: a term used to describe a group of neutrons and proton. Only the particle not the energy that binds them. ▪ Neutrons was further discovered with the use of beta decay. ▪ James Chadwick was involved in founding the neutrons by knocking neutrons out of the nucleus ▪ Properties of atoms in the nucleus: – Proton: Charge ➔ + 1.6 x 10 ^-19 C, Mass ➔ 1.673 x 10 ^-27 kg The number of proton will determine the number of electrons, and hence allow for the arrangement of electrons to determine its element or chemical identity. – Neutrons: Charge ➔ 0 C, Mass ➔ Slighter heavily than protons. The neutrons are what hold the nucleus together. As they are heavier than protons, it provide theory that they were protons plus electrons combined to create a neutron charge and determine its weight.
▪ discuss the importance of conservation laws to Chadwick's discovery of the neutron	▪ **History** – 1920 Rutherford proposal a tiny dense nucleus existed at the centre of an atom comprising of protons and neutrons. – 1930 German scientists Bothe and Becker discovered that bombarding Beryllium with alpha particles resulted in an unknown radiation. Scientists Joliet and Currie discovered with an added layer of Paraffin wax, that protons were knock out. ▪ **Problem** – The **protons energy measured 5 MeV**, however if the radiation **was gamma ray. It would have energy of 50 MeV, violating the law of conservation.** ▪ **James Chadwick's Discovery**

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James Chadwick conducted an experiment where he fired alpha particles to a Beryllium target. By calculation with the velocities and the law of conservation of energy and momentum, he hypothesized that the unknown radiation were neutrons, which could account of the energy difference.
He also taken account that these neutrons had slightly larger mass than protons.
The work of Rutherford and Chadwick confirmed that the nucleus consisted of protons and neutrons collectively known as nucleons.

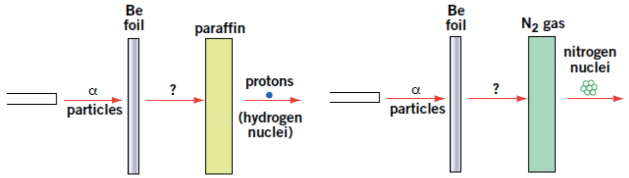

Figure 14.1.2 Chadwick's two main experiments
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<td>▪ define the term 'transmutation'</td>
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▪ Transmutation

The process where one element changes to another due to the emission of radioactive decay.

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<tr><th>Natural Transmutation</th><th>Artificial Transmutation</th></tr>
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– Natural Transmutation take in form of alpha and beta decay.
– When an atom contains an unstable neutron to proton ratio, they will undergo natural transmutation
– High neutron to proton ratio leads to beta-minus decay.
– Low neutron to proton ratio leads to beta-plus and alpha decay.
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– Artificial Transmutation is the manipulation into a transmutation.
– The first artificial transmutation was Chadwick's neutron experiment.
– Takes in two states
Fission: Splitting of the nucleus
Fusion: Bombardment of two high speed atoms to form a heavy single atom
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- describe nuclear transmutations due to natural radioactivity

- Natural radioactivity causes an element to change to another element by emission of alpha, beta and gamma rays.

Radiation	Symbols	Charge	Nature	Ionising Power	Deflection by B- field
Alpha	α	+2	Helium Nucleus	Weak	Yes
Beta	β	-1	Electron	Medium	Yes
Gamma	γ	0	Electromagnetic Radiation	Strong	No

- Alpha
  - Occurs in unstable nucleus
  - In forms of alpha particles [Energetic Helium Nucleus]
  - When an alpha decay occurs, the element will lose 2 neutrons and 2 protons resulting a loss of a 4 atomic mass.

$${}_{92}^{238}U \rightarrow {}_{90}^{234}Th + {}_{2}^{4}He$$

$$\alpha \text{ decay: } {}_{Z}^{A}X \rightarrow {}_{Z-2}^{A-4}X + {}_{Z}^{4}He$$

- Beta
  - In forms of beta particles [Electrons]
  - Beta (minus) decay
    - Occurs when there is too neutron compared to protons.
    - A neutron is converted into a proton, electron and an antineutrino.
    - The electrons and antineutrinos are then emitted resulting in same atomic mass but an increase in 1 atomic number.

$$n \rightarrow p + {}_{-1}^{0}e + {}_{0}^{0}v -$$

$$\beta \text{ decay: } {}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}e$$

  - Beta (positive) decay
    - Occurs when there are too many protons compared to neutrons.
    - A proton is converted in to neutrons, a positron and a neutrino.
    - The positron (positive electron) is emitted resulting in same atomic mass but a decrease in 1 atomic number.

$$p \rightarrow n + {}_{+1}^{0}e + {}_{0}^{0}v$$

  - Gamma
    -

$$\gamma \text{ decay: } {}_{Z}^{A}X \rightarrow {}_{Z}^{A}X + {}_{0}^{0}\gamma$$

▪ describe Fermi’s initial experimental observation of nuclear fission	▪ Enrico Fermi’s Observation – Fermi conducted experiments on bombarding neutrons with various elements. This was achievable due to the neutral state, being unaffected by electrostatic attraction and repulsion. – Using U-235 (heaviest element, 92) the bombardment of the neutron was though to undergo beta decay transmutation into a proton, increasing its atomic number to 93; a transuranic element.
▪ discuss Pauli’s suggestion of the existence of neutrino and relate it to the need to account for the energy distribution of electrons emitted in β-decay	▪ Wolfgang Pauli’s Discovery of The Neutrino – Beta decay were initially through to have eject beta particle. However, one beta decay’s emission of energy on two similar nuclei will have two different results. Along with beta decay, these must exist another penetrating particle to account for the missing energy. Pauli suggested that the particle had no charge and very weakly interacted with matter. ▪ Fermi’s contribution – Fermi and Pauli both accounted for the neutrino as an undetectable neutral particle, due to it lightweight travelling at near c and no electrical charge. ▪ Beta-minus – ${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + {}^{0}_{0}\bar{\upsilon}$ – Neutron ==> Proton + Electron + Antineutrino ▪ Beta-plus – ${}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{-1}e + {}^{0}_{0}\upsilon$ – Proton ➔ Neutron + Positron + Neutrino ▪ Problems for detection – Virtually no mass meaning and hence can’t collide into other particles. – Has no charge and no ionisation. – Invisible
▪ evaluate the relative contributions of electrostatic and gravitational forces between nucleons	▪ When Gravitational force and Electrostatic force are compared, the force of gravity is very small in comparison with the electrostatic repulsion of protons. Hence, there must exist another force known as ‘Strong Nuclear Force’. This force holds the nucleons together.
▪ account for the need for the strong nuclear force and describe its properties	▪ **Strong Nuclear Force (SNF)** – Strong nuclear are there to **hold the nucleon**s, and act against the electrostatic repulsion of protons. ▪ **Properties** – They are **independence of charge**, meaning that they act equally weather proton-proton, proton-neutron, neutron-protons. – Are much **stronger than the electrostatic repulsion of protons**.

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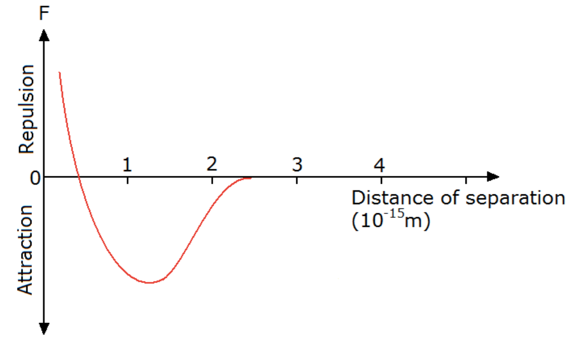
– Acts in very short range.
▪ Graph
– Distance > 2, SNF become 0
– Distance < 0.5, SNF is repulsive
– 0.5 < Distance < 2, SNF is attractive.


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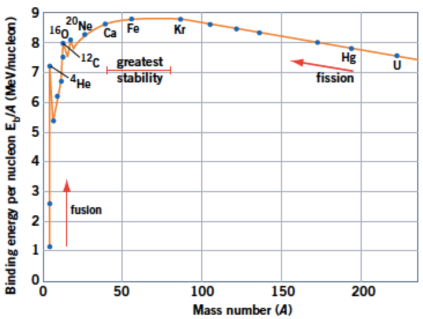
▪ explain the concept of a mass defect using Einstein's equivalence between mass and energy


Figure 14.7.1 Binding energy is greatest for elements with atomic mass numbers between 40 and 80.
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▪ Einstein's Equivalence Between Mass and Energy
– Einstein suggests that mass and energy are interchangeable using the equation
$$E = mc^2$$
▪ Mass Defect
– The actual mass of a nucleus is heavier than the sum of its constituents (protons, neutrons). This means that the is a missing mass that accounts for the imbalance of the same atom.
– Mass Defect is the difference between the mass of nucleus minus the sum of its nucleons.
▪ Binding Energy
– Binding Energy is the energy required to separate the nucleons apart. This allowed for the existence of strong nuclear force that hold the nucleus together.
– This is with the use of Einstein's E=mc^2.
▪ Graph
– (Fe) Iron-56 is most stable.
– Measured in Binding Energy / Nucleon.
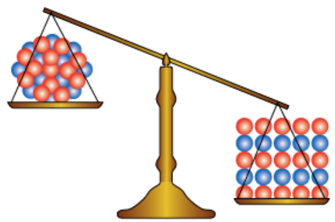
Figure 14.6.1 The mass of constituent parts is greater than the mass of the whole nucleus.
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- describe Fermi's demonstration of a controlled nuclear chain reaction in 1942

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- **Nuclear Fission**
  - When a **heavy unstable atom is hit by a neutron**, which **splits into two or more light nuclei**. Will this, it releases neutrons and energy.
- **Nuclear Fusion**
  - When two
- **Fermi's Demonstration of a Controlled Nuclear Chain Reaction (Chicago 1942)**
  - **Enrico Fermi's** created the first nuclear reactor using **Uranium** to demonstrate a controlled nuclear chain reaction.
  - **50 tonnes of Uranium** were used as **fissile material**.
  - **Layers of graphite blocks acted as moderators** to **slow down the energetic neutrons**. This was down because slow neutrons were more effective and easier to obtain.
  - **Cadmium rods acted as control rods** to **control the rate of neutrons**, by harmlessly **absorbing them**. As the cadmium rods were withdrawn, the activity of neutrons increase, and completely stopped when it was inserted, indicating it can be **self-sustaining, giving of heat, and not out of control**.

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- compare requirements for controlled and uncontrolled nuclear chain reactions

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- Critical Mass
  - The minimum fissile material required to sustain a nuclear reaction.

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<tr><th>Controlled Nuclear Chain Reactions</th><th>Uncontrolled Nuclear Chain Reactions</th></tr>
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- Only one neutron is contained from the fission splitting.
- From the fission, the chain reaction is controlled by absorbing and slowed down, by control rods and moderators.
- One for one capture of neutrons.

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- From one neutron undergoing fissions split into two or more fission.
- The rate of these growth is exponential and hence goes at a rapidly rate.

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- perform a first-hand investigation or gather secondary information to observe radiation emitted from a nucleus using Wilson Cloud Chamber or similar detection device

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<tr><td>▪ solve problems and analyse information to calculate the mass defect and energy released in natural transmutation and fission reactions</td><td>▪</td></tr>
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<tr><td colspan="2">4. An understanding of the nucleus has led to large science projects and many applications</td></tr>
<tr><td>Students learn about:</td><td>Notes:</td></tr>
<tr><td>▪ explain the basic principles of a fission reactor</td><td>

▪ Fission Reactors

– Operates like an atomic bomb, however its energy released is controlled. In Nuclear Fission reactors, extremely large amount of energy is emitted over a short time.

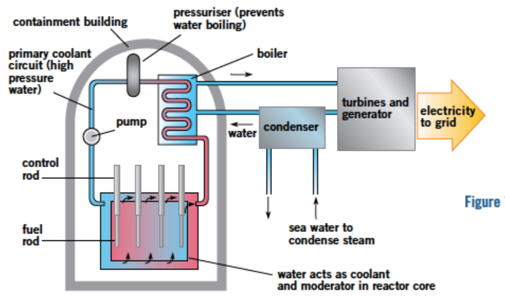

Figure 15.2.1 A schematic diagram of a pressurised water reactor. A typical 1000 MW power plant consumes about 6 000 000 tonnes of black coal each year, or about 25 tonnes of enriched uranium that has been obtained from around 75 000 tonnes of ore.

▪ Components

– Controls Rods (Boron / Cadmium)
Control rods are made from neutron absorbing materials to increase and decrease the rate of fission. The control rods, when placed at the top will absorb neutrons at an increasing rate, hence increase
When they are lowed or fully inserted in the reactor, they will decrease the rate of neutron ejection, or completely shut down.

– Coolant
Coolants are made from heavy water, turbine or helium gas, to reduce the heat in the reactor. Since the core, releases high kinetic energy, they produce thermal energy, which need to be maintained.

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<tr><td>▪ describe some medical and industrial applications of radio-isotopes</td><td>▪</td></tr>
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▪ describe how neutron scattering is used as a probe by referring to the properties of neutrons	▪
▪ identify ways by which physicists continue to develop their understanding of matter, using accelerators as a probe to investigate the structure of matter	▪
▪ discuss the key features and components of the standard model of matter, including quarks and leptons	▪

Students learn to:	*Notes:*
▪ gather, process and analyse information to assess the significance of the Manhattan Project to society	▪ Manhattan Project – Manhattan Project consist of US scientists produce the first nuclear weapons. – Led to new nuclear technology. –
▪ identify data sources, and gather, process, and analyse information to describe the use of: – a named isotope in medicine – a named isotope in agriculture – a named isotope in engineering	▪