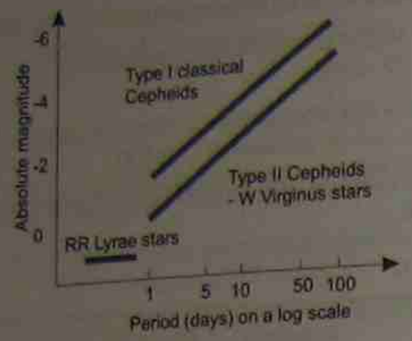


Figure 5.42

(f) This question refers to the information in Table 5.13.

Table 5.13

Star	Absolute magnitude	Spectral class
Sun	+4.83	G2
Antares	–4.50	M1
Sirius	+1.41	A1
Betelgeuse	–5.50	M2
Barnard's star	+13.25	M5

(i) Plot the position of each star on the Hertzsprung-Russell diagram in Figure 5.43 and predict its probable evolutionary state. (3 marks)

(ii) Which star is hottest? Explain your reasoning. (1 mark)

(iii) Identify the nuclear fuel in Betelgeuse. (1 mark)

(iv) Predict the colour of Antares. (1 mark)

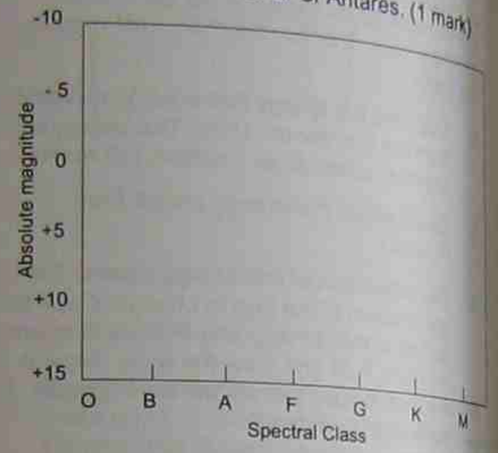


Figure 5.43

(g) Compare the H-R diagram of a globular cluster with that for an open (galactic) cluster, stating three major differences. (3 marks)

(h) (i) Define a protostar. (1 mark)

(ii) Recall how the mass of the protostar affects where it joins the main sequence and its final state. (1 mark)

Chapter Six

Quanta to Quarks

SECTION 1: MODELS OF THE ATOM

BIG IDEA:

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

OUTCOMES:

Students learn to:

1 Discuss the structure of the Rutherford model of the atom, the existence of the nucleus and electron orbits.
2 Analyse the significance of the hydrogen spectrum in the development of Bohr's model of the atom.
3 Discuss Planck's contribution to the concept of quantised energy.
4 Define Bohr's postulates.
5 Describe how Bohr's postulates led to the development of a mathematical model to account for the existence of the hydrogen spectrum for which $\frac{1}{\lambda} = R_H\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$
6 Discuss the limitations of the Bohr model of the hydrogen atom.

Students:

1 *Perform a first-hand investigation to observe the visible components of the hydrogen spectrum.*
2 *Process and present diagrammatic information to illustrate Bohr's explanation of the Balmer series.*
3 *Solve problems and analyse information using* $\frac{1}{\lambda} = R_H\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$
4 *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.*

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CONTEXTUAL OUTLINE

As we enter the twenty-first century it is of interest to reflect on the state of physics at the beginning of the twentieth century. Following the work of Newton in the seventeenth century on mechanics and gravity and the work of Maxwell in light and other electromagnetic waves in the nineteenth century, it was initially believed that physicists 'knew' all the laws of nature and that any changes would '… be in the fifth decimal place'. Classical physics—physics prior to 1900—was, however, unable to explain the behaviour of matter on the subatomic scale. *Black body radiation* (see p.112), the *photoelectric effect* (see p.113) and *line emission spectra* (see p. 186) defied explanation.

The first three decades of the twentieth century saw a change as revolutionary as the work of Newton some two centuries before. *Quantum mechanics* and *relativity* evolved to give a more accurate description of the behaviour of matter on the atomic and subatomic scale. This scientific revolution led to significant changes, both in the way we view the world around us and in our ability to manipulate matter for the benefit (and otherwise) of the human race.

This chapter commences with the *Rutherford model* of the atom. We then look at the *Bohr model*, both its successes and its failings. We then look at the wave nature of matter and its use in explaining the atomic model. Next we look at some practical applications of this new knowledge. We conclude with the current *standard model of matter* consisting of quarks, leptons and bosons.

THE ATOMIC THEORY

Today we believe that all matter is composed of tiny particles—*atoms*—and that these atoms are made up of even smaller *fundamental* particles—*protons*, *neutrons* and *electrons*[1]. The atomic theory is one of humankind's greatest intellectual achievements.

[1] We will see later that protons and neutrons are not truly fundamental as they are themselves made up of other particles—quarks.

The Beginnings

Democritus

Over 2000 years ago the Greek philosopher Democritus proposed that there was a limit to how small one could divide matter—this smallest indivisible particle was called an atom.

Aristotle (~340 BC)

The atomic theory of Democritus was criticised by Aristotle who proposed an alternative model based on four basic 'elements'—*earth*, *air*, *fire* and *water*. Aristotle's view held prominence for the next two thousand years as it better fitted with the religious beliefs of the time.

Dalton

In 1801, as a result of his studies in chemistry, James Dalton, a Scottish teacher proposed his atomic theory which stated that:

1 Matter is composed of small *indivisible* atoms.
2 Elements contain only one type of atom. Different elements contain different atoms.
3 Compounds contain more than one type of atom.

Thomson's 'Plum Pudding' Model

As discussed in the HSC Core Topic *From Ideas to Implementation* we saw how the British physicist JJ Thomson and others showed that cathode rays—*electrons*—were present in all matter.

In 1904, Thomson proposed that the atom was a sphere of positive charge in which were embedded rings of negative charges (electrons), like 'plums in a pudding' (Figure 6.1).

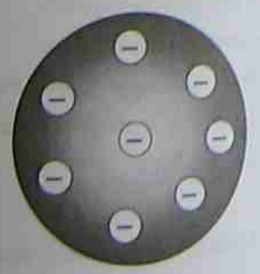


Figure 6. 1 Thomson's 'plum pudding' model

Radiation and the Atom

The discovery of radiation in the late nineteenth century by Henri Becquerel proved vital in the progress of physics in at least two areas:

1 The fact that certain elements were known to emit radiation (that is α, β and γ rays) suggested that the atom was divisible and not indestructible, as proposed in Dalton's atomic model; and
2 Radiation provided an important tool for the study of matter. Rutherford first suggested the use of alpha particles to probe the internal structure of the atom in 1911. As a result of this experiment the nucleus and its protons were discovered.

RUTHERFORD'S SCATTERING EXPERIMENT[2]

In 1911 Geiger and Marsden, at the instigation of Ernest Rutherford, performed an experiment in which the newly discovered alpha particles were fired at a thin gold foil (Figure 6.2). Most of the alpha particles passed through with only small deflections, as would have been expected on the Thomson model of the atom current at the time. About 1 in 8,000, however, were deflected through angles greater than 90°.

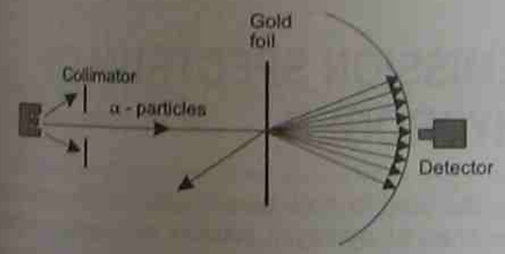


Figure 6. 2 Rutherford's scattering experiment

The results obtained by Geiger and Marsden were so unexpected that Rutherford was prompted to write *'… it was almost as incredible as if you fired a 15 inch shell at a piece of tissue paper and it came back and hit you …'*.

[2] http://micro.magnet.fsu.edu/electromag/java/rutherford/ A virtual Rutherford experiment.

Rutherford proposed that the only way that the alpha particles could be deflected through large angles was if *all* the atom's positive charge and nearly all its mass was concentrated in a small dense *nucleus* with the electrons some distance away, as indicated in Figure 6.3. Most of the atom is empty space.

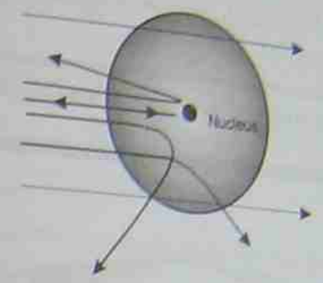


Figure 6.3 The Rutherford atom (not to scale)

The Nucleus

From the results of the alpha particle scattering experiment, Rutherford was able to estimate the size of the atom and its nucleus. He estimated the atom to have a diameter of $\sim 10^{-10}$ m and the nucleus a diameter of $\sim 10^{-14}$ m.

Inadequacies of Rutherford's Atom

For all of its success in explaining alpha particle scattering, Rutherford's interpretation still left many questions unanswered. These included:

1 What is the nucleus made up of?
2 What keeps the negative electrons from being attracted into the positive nucleus?
3 How are the electrons arranged around the nucleus?

If the electrons circled the atom like planets around the Sun (which could explain why they did not fall into the nucleus), they would be accelerating. Accelerated charges, however, are known to emit electromagnetic radiation, so the electrons should *continuously* lose energy and spiral into the nucleus and hence the atom should collapse.

The fact that atoms are stable and elements emit *line spectra* (see p.224), rather than *continuous spectra*, showed that electrons had none of these characteristics.

SPECTRA

When white light is passed through a triangular prism as in Figure 6.4, the light is broken up into its constituent colours—*red, orange, yellow, green, blue and violet*. There is a continuous spread of colours and hence wavelengths. Such a spectrum is called a *continuous spectrum*. It can be viewed with a *spectroscope*.

A **spectroscope**[3] *is a device used to examine spectra.*

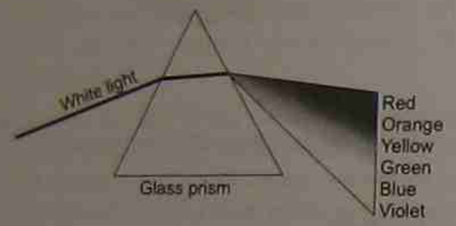


Figure 6.4 Continuous spectra

Essentially a spectroscope consists of a tube with a slit in one end and a prism or diffraction grating which splits the light into its constituent parts.

Spectra can be either:

1 emission or
2 absorption.

Emission Spectra[4]

It had long been known that most gases *emit* light when excited. This excitation could occur by:

1 heating the gas to a high temperature; or
2 passing an electric current through the gas at low pressure (see p.99).

As far back as 1752 the Scottish physicist Thomas Melville showed that the *emission spectra* of different gases were different. He showed that:

When an element is excited, the element emits light of definite wavelengths giving rise to a **line emission spectrum** *when viewed through a spectroscope (Figure 6.5).*

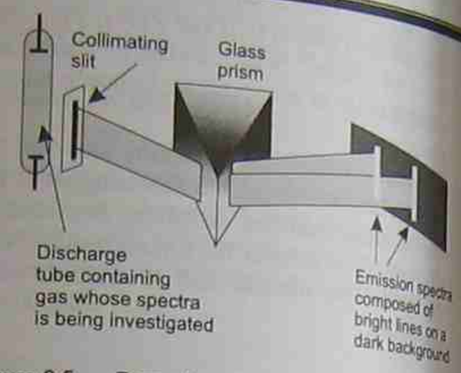


Figure 6.5 Formation of line emission spectra

Each element has a characteristic *line emission spectrum* (the lines being images of the spectroscope slit in specific wavelengths). In 1823 the British astronomer John Herschel made the suggestion that each gas could be identified from its unique line spectrum.

Spectra are an element's 'fingerprints' in that they are unique to each element, just as a person's fingerprints are unique to that person.

The spectrum of a gas to be extensively studied was that of the lightest gas, hydrogen.

EMISSION SPECTRUM OF HYDROGEN

In the visible and near-ultraviolet the emission spectrum of hydrogen consists of a series of lines corresponding to specific wavelengths (colours), as in Figure 6.6.

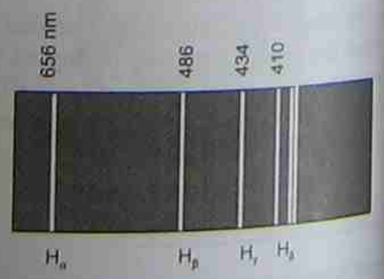


Figure 6.6 Hydrogen emission spectrum

[3] If the light to be analysed falls on a photographic plate it is called a *spectrometer*.

[4] http://jersey.uoregon.edu/elements/Elements.html displays the emission and absorption spectra of all the elements of the Periodic Table. Just click on an element and its spectrum is displayed. Another excellent site is http://phys.educ.ksu.edu/vqm/html/emission.html for a simulation of emission and absorption spectra. Requires *Shockwave*.

In 1885 a Swiss schoolteacher, Johan Balmer, found an *empirical formula*, (that is, a formula derived purely from experiments with no theoretical basis), which gave the wavelengths of the emission lines for hydrogen. The wavelength of each line could be found from:

$$\lambda = b\left(\frac{n^2}{n^2-2^2}\right)$$

where b is a constant and n is an integer (which is different for each line) as indicated in Table 6.1.

Table 6.1 The Balmer series for hydrogen

Name of line	n	λ	Colour
H_α	3	656.2	red
H_β	4	486.1	green
H_γ	5	434.0	blue
H_δ	6	410.13	violet

Written in its modern form, Balmer's formula is:

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

where R_H is a constant called the Rydberg constant, equal to $1.097 \times 10^7\ m^{-1}$.

Balmer speculated that other series lines might exist which prompted others to search for (and succeed in finding) them.

In general we can write:

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

where n_f can have the values 1, 2, 3, 4... and $n_i = n_f + 1, n_f + 2, n_f + 3 \ldots$ as shown in Table 6.2.

Table 6.2 The spectral lines of hydrogen

Series name	Discovered	Spectral region	Values in Balmer's equation	
			n_f	n_i
Lyman	1906-14	ultraviolet	1	2, 3, 4...
Balmer	1885	UV–visible	2	3, 4, 5...
Paschen	1908	infrared	3	4, 5, 6...
Brackett	1922	infrared	4	5, 6, 7...
Pfund	1924	infrared	5	6, 7, 8...

EXAMPLE 1

Calculate the wavelength of the first two lines of the Lyman series.

SOLUTION

From Table 6.2 we have $n_f = 1$ for the Lyman series and the first two lines will correspond to $n_i = 2$ and $n_i = 3$. Hence:

Similarly:

$$\frac{1}{\lambda} = R_H\left(\frac{1}{n_f^2}-\frac{1}{n_i^2}\right)$$
$$= R_H\left(\frac{1}{1^2}-\frac{1}{3^2}\right)$$
$$= 1.097\times10^7 \times \frac{8}{9}$$
$$\lambda = \frac{9}{8\times1.097\times10^7}\ \text{m}$$
$$= 1.02\times10^{-7}\ \text{m}$$
$$= 102\ \text{nm for the second line}$$

Extension

Absorption Spectra

Just as an element is capable of *emitting* certain frequencies of light, so too, it is capable of *absorbing* these *same* frequencies. In 1859 Kirchoff succeeded in showing that the absorption spectrum produced by passing white light through a cool gas matched exactly the emission lines produced by the same gas when excited (for example, by heating or

passing an electric current through the gas—see Figure 6.7).

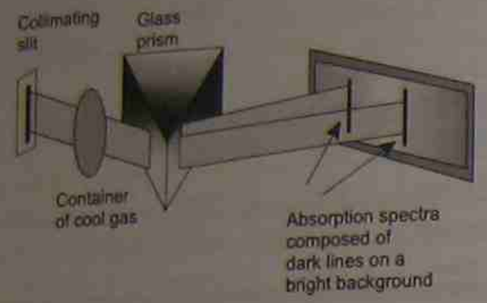


Figure 6.7 Formation of absorption spectrum of a gas

For example, when light passes through cooler layers of gas (for example, the photosphere of a star), certain *absorption lines* are observed when the light is viewed through a spectroscope. (In the solar spectrum these lines are referred to as *Fraunhofer lines*.)

By comparing the positions of these absorption lines with the positions of the emission lines from known elements, the composition of a substance can be deduced.

QUANTUM THEORY

Black Body Radiation

In the Preliminary Course Core Topic *The Cosmic Engine* we were introduced to the concept of a *black body* as a perfect emitter or absorber of energy.

It had long been known that there was a relationship between the dominant wavelength of electromagnetic radiation emitted by a hot object and its temperature. This is illustrated in Figure 6.8. We then saw in *From Ideas to Implementation* that, try as they might, physicists, using classical physics (the physics of Newton and Maxwell), could not get agreement between theory and experiment to explain the black body radiation curve[5]. A radical change in approach was needed. This was the *quantum theory* of physics.

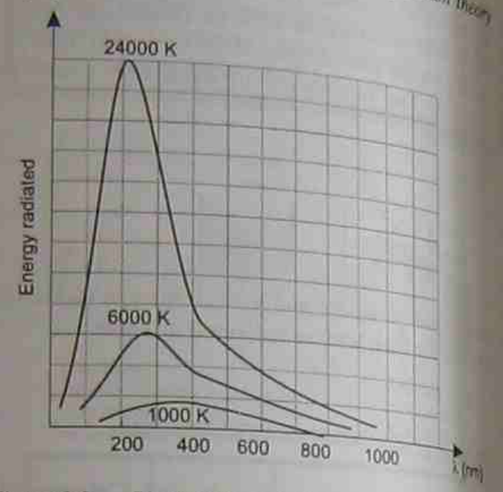


Figure 6.8 Black body radiation curve

Quantum physics began in 1900 with the German physicist Max Planck. Planck found that he could only get agreement between theory and experiment for black body radiation by making a fundamental change to the laws of physics! He proposed that:

> *Energy is not emitted by a hot object continuously as classical physics said it should, but rather it is emitted in little 'bursts' or 'packets of energy'—* **quanta** *(photons) of energy.*

Mathematically we write:

$$E = hf$$

where h is a constant called Planck's constant ($= 6.626 \times 10^{-34}$ J.s) and f is the frequency.

After it was used successfully to explain black body radiation, quantum theory's next big triumph was in explaining Bohr's model of the atom.

BOHR'S ATOM

In 1913 to account for the discrepancies between Rutherford's model of the atom and the available experimental evidence in particular, the emission spectrum of hydrogen, the Danish physicist Niels Bohr put forward some radical propositions. He postulated that:

1. Electrons can revolve in certain allowed orbits[6]—*stationary states* (*energy states*)—without radiating energy.
2. When an electron falls from a higher energy level to a lower energy level, it emits energy that is *quantised* by the Planck relationship $E_2 - E_1 = \Delta E = hf$
3. Angular momentum (mvr) is quantised and can only take values of $\frac{nh}{2\pi}$ where n is the *principal quantum number*.

The first postulate accounts for the *observed stability* of atoms. Why these stationary states existed was unknown. That they did exist was a fact.

The second postulate explains the line emission spectra. Emission (or absorption) of energy is discontinuous and corresponds to a transition between two stationary states. Since the energy is quantised, the frequency of the emitted (or absorbed) radiation is predetermined. A transition between different states will lead to different frequencies—colours (Figure 6.9). This postulate effectively sets limits on the allowed orbits (see below).

Using this mixture of classical and quantum physics, Bohr was able to derive the equation for the spectral lines of hydrogen (see p.229). He didn't know why the electrons obeyed his rules, only that they did! These were purely empirical results.

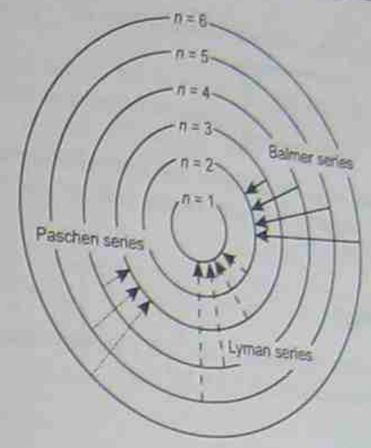


Figure 6.9 The cause of line emission spectra

Extension

Successes of the Bohr Model

Bohr was able to derive two expressions from his model. The first relates the radius of the electron orbit to the quantum number n and the second expression relates the energy of the orbit to the quantum number.

The Bohr Radii

By equating the electrostatic force of attraction between the nucleus and the electron in its orbit to the centripetal force required allowed Bohr to derive the following equation[7]:

$$r_n = \frac{h^2 n^2}{4\pi^2 kme^2}$$

where:

$n = 1, 2, 3\ldots$

$h = 6.626 \times 10^{-34}$ J.s (Planck's constant)

r_n = radius of the n^{th} stationary state ('orbit')

m = mass of the electron $= 9.109 \times 10^{-31}$ kg

$k = 9.0 \times 10^{9}$ N.m^2.C^{-2}

e = charge on the electron $= -1.602 \times 10^{-19}$ C

[5] Classical physics predicted that as the wavelength of the radiant energy decreased (say from the visible to the ultraviolet), the intensity of the radiation would increase without limit. This would violate the law of conservation of energy. This effect became known as the 'ultraviolet catastrophe'.

[6] These orbits were interpreted as the path the electrons followed as they revolved around the nucleus (somewhat like the orbits of the planets around the Sun).

[7] NB: The derivation of this formula is beyond the syllabus requirements.

This can be written in a simpler form as:

$$r_n = n^2 r_1$$

where r_1 is the radius of the first stationary state. This suggests that *only certain radii of orbits are allowed.*

EXAMPLE 2

Show that the radius of the first stationary state for the hydrogen atom is 5.3×10^{-11} m.

SOLUTION

We have the expression: $r_n = \dfrac{h^2 n^2}{4\pi^2 kme^2}$. The radius of the first stationary state has $n = 1$ and substituting the data we get:

$$r_n = \frac{(6.626\times10^{-34})^2 \times 1^2}{4\pi^2 \times 9.109\times10^{-31} \times 9\times10^9 \times (-1.602\times10^{-19})^2}$$
$$= 5.3\times10^{-11} \text{ m}$$

EXAMPLE 3

What is the radius of the second stationary state?

SOLUTION

$$r_n = n^2 r_1$$
$$r_2 = 2^2 r_1$$
$$= 4\times5.3\times10^{-11} = 2.1\times10^{-10} \text{ m}$$

Energy of the Orbits

Bohr was also able, by combining the expression for the potential energy of the electron-nucleus system to its kinetic energy, to derive an expression for the total electron energy in the stationary states. This expression is:

$$E_n = -\frac{2\pi^2 k^2 e^4 m}{h^2 n^2}$$

where: $n = 1, 2, 3\ldots$ and the other symbols are as discussed for the Bohr radius.

The negative sign indicates the electron is bound to the nucleus. It comes about because we define the zero of potential as being infinity. (Energy must be supplied to the electron to remove it from the nucleus, a process called *ionisation*.)

This expression can also be written as:

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

where E_1 is the energy of the electron in the first stationary state which is equal to -13.6 eV

EXAMPLE 4

What is the energy (in electron volts) of the electron in the second orbit?

SOLUTION:

$$E_n = \frac{1}{n^2} E_1$$
$$E_2 = \frac{1}{2^2} \times (-13.6) \text{ eV}$$
$$= -3.4 \text{ eV}$$

It is possible to determine the energy of each orbit in this manner and from this construct an energy level diagram for hydrogen (Figure 6.10).

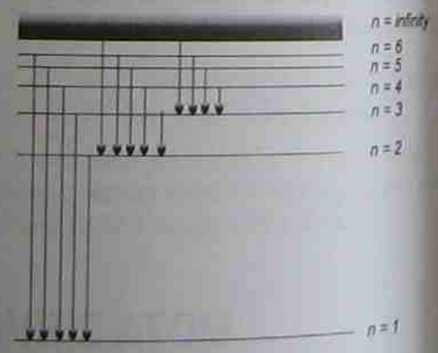


Figure 6.10 The energy levels for hydrogen

THE BOHR MODEL AND THE BALMER SERIES

One of the greatest successes of the Bohr model[8] was that it was able to provide a physical basis for the Balmer series formula (which up until that point was purely an empirical formula). Bohr's reasoning was as follows:

From Bohr's second postulate we have:

$hf = E_f - E_i$

From the expression for energy we have:

$E_i = \dfrac{1}{n_i^2} E_1$ and $E_f = \dfrac{1}{n_f^2} E_1$ hence:

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

and since: $c = f\lambda \Rightarrow f = \dfrac{c}{\lambda}$ the expression reduces to:

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

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

which is the Balmer formula!

EXAMPLE 5

The red line in the spectrum of hydrogen results from the transition of an electron from the 3rd energy level to the 2nd energy level. Calculate the wavelength of the red light.

SOLUTION

$$\frac{1}{\lambda} = R_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$
$$= 1.097\times10^7 \times \left(\frac{1}{2^2} - \frac{1}{3^2} \right)$$
$$= 1.097\times10^7 \times \left(\frac{1}{4} - \frac{1}{9} \right)$$
$$\lambda = 6.56\times10^{-7} \text{ m}$$
$$= 656 \text{ nm}$$

LIMITATIONS OF THE BOHR MODEL

For all of its success, the Bohr model of the atom had serious limitations:

1 It was an *ad hoc* mixture of classical and quantum physics. It assumed that some laws of classical physics held and others did not.

2 It did not work for multi-electron atoms (hydrogen has only one electron).

3 It could not explain the *relative intensities* of the spectral lines. Some lines were more intense than others. Why this should occur was unknown.

4 Certain spectral lines were found to consist of a number of very fine and close lines. The cause of these *hyperfine spectral lines* could not be explained.

5 The splitting of spectral lines when the sample was placed in a magnetic field—the *Zeeman effect*—could also not be explained.

It was clear that a new model was required to explain the way that matter was structured. This began with the work of de Broglie.

Extension

Franck-Hertz Experiment

In 1914 the Germans Franck and Gustav Hertz provided direct experimental evidence of energy levels. They bombarded mercury atoms with electrons and observed that the atoms would only absorb energy in *discrete amounts*.

[8] http://www.walter-fendt.de/ph11e/bohrh.htm
http://jersey.phys.nwu.edu/~anderson/java/vpl/atomic/hydrogen.ht
ns Both sites look at the Bohr model of the atom.

SECTION 2: QUANTUM PHYSICS

BIG IDEA:

The limitations of classical physics gave birth to quantum physics.

OUTCOMES:

Students learn to:

1 Describe the impact of de Broglie's proposal that any kind of particle has both wave and particle properties
2 Define diffraction and identify that interference occurs between waves that have been diffracted.
3 Describe the confirmation of de Broglie's proposal by Davisson and Germer.
4 Explain the stability of the electron orbits in the Bohr atom using de Broglie's hypothesis.

Students:

1 *Solve problems and analyse information using* $\lambda = h/mv$
2 *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.*

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WAVE-PARTICLE DUALITY OF LIGHT

In the Preliminary Course, *The World Communicates*, we saw that light exhibits properties that we normally say are *wave-like*, for example, interference[9] and polarisation. Then in the *HSC Course, From Ideas to Implementation*, we saw that in some situations light behaves as if it were a particle, for example, the photoelectric effect. The question is: *Is light a wave or is it a particle?*

This question has two answers—*light is both*. Which one of its identities it shows to the experimenter is dependent upon the particular situation being investigated. In some situations light acts as if it were a wave; in other situations it acts like a particle. This is the *wave-particle duality* of light.

[9] In *The World Communicates* we were introduced to the idea of the superposition of sound. This is an example of interference. All waves exhibit the phenomenon of interference.

Light, however, does not display both identities at the same time and at the same place. Light diffracts around an obstacle (wave property) and then falls onto a metal plate and cause photoemission (particle property) but it does not exhibit both properties at the same time.

To illustrate the duality of light, the diagram in Figure 6.11 is often used. This '*wave packet*' is particle-like in its finite size but wave-like in its varying amplitude. This amplitude is now viewed as a measure of the *probability* of finding a photon at a particular place.

1 Where the amplitude is large, so too is the probability of finding the photon.
2 Where the amplitude is small, so too is the probability of finding the photon.

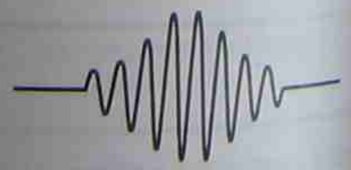


Figure 6.11 A *wave packet* or photon

Photon Momentum

Consider a photon of light. Using Einstein's mass-energy equivalence formula and Planck's equation, we have:

$$E = mc^2 = hf = h\frac{c}{\lambda}$$

The momentum of a particle is hence:

$$p = mc = \frac{h}{\lambda} \Rightarrow \lambda = \frac{h}{p}$$

That is, a photon of light has its momentum (p) related to its wavelength (λ) by the equation

$$\boxed{\lambda = \frac{h}{p}}$$

This equation relates the wave characteristic wavelength (λ) with the particle property of momentum (p).

Extension

Compton Scattering

In 1923 Arthur Compton investigated the effect of bombarding matter with X-rays. He found that some electrons were ejected and the bombarding X-rays were either transmitted or scattered. Some of the scattered X-rays had a frequency that was less than that of the initial rays.

Compton found that he could get a simple explanation of this effect by assigning to the X-rays a photon momentum of $p = \frac{h}{\lambda}$ and considered the interaction with the electrons as being a collision between two particles (Figure 6.12). He thus proved that X-rays interact with matter as if they had *a photon momentum of p and hence provide further confirmation of their particle nature.*

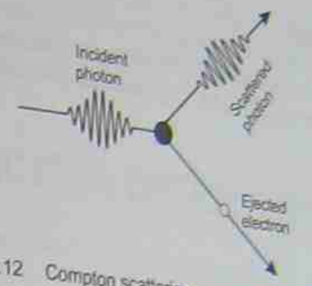


Figure 6.12 Compton scattering

MATTER WAVES

In 1924 the Frenchman Louis de Broglie generalised the equation already derived for a photon to include *anything* with momentum.

De Broglie proposed that if a physical phenomenon such as light, which was once considered to have a wave nature, was subsequently found to have a particle nature as well, then other phenomena, such as electrons, previously considered to have only a particle nature, could conversely, have a wave nature, as described by the expression:

$$\boxed{\lambda = \frac{h}{mv}}$$

De Broglie referred to these waves as *matter waves*.

EXAMPLE 6

What is the de Broglie wavelength of an object of mass $m = 1.0$ kg moving at a speed $v = 1.0\ \text{m.s}^{-1}$?

SOLUTION

$$\lambda = \frac{h}{mv}$$
$$= \frac{6.626\times10^{-34}}{1.0\times1.0}$$
$$= 6.626\times10^{-34}\ \text{m}$$

This is much less than atomic dimensions and is undetectable.

EXAMPLE 7

What is the de Broglie wavelength of an electron of mass $m = 9.109 \times 10^{-31}$ kg moving at 1.0×10^{6} m.s^{-1}?

SOLUTION

$$\lambda = \frac{h}{mv}$$

$$= \frac{6.626\times10^{-34}}{9.109\times10^{-31}\times1.0\times10^{6}} \text{ m}$$

$$= 7.3\times10^{-10} \text{ m}$$

This wavelength is comparable to atomic dimensions (in particular the atomic spacing in crystals). Hence it should be possible to prove the wave nature of matter (for example, electrons) by observing some characteristic wave property such as *interference* or *diffraction*.

DIFFRACTION

Diffraction *is the bending of waves around obstacles or through barriers.*

From Figure 6.13 we can see that the amount of diffraction depends on the ratio of the wavelength to the size of the gap or obstacle. It can also be seen that the waves bend into the geometrical shadow region.

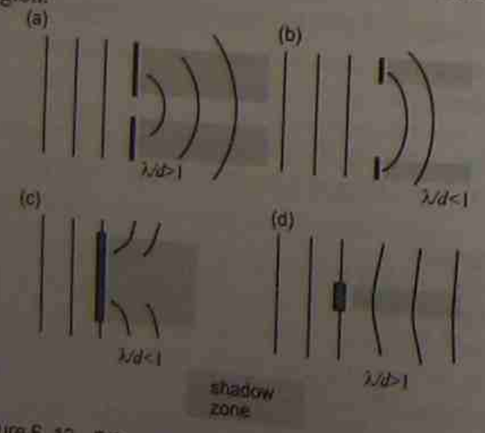


Figure 6. 13 Diffraction of waves

Interference

In the *Preliminary Course* we were introduced to the phenomenon of wave superposition.

The principle of superposition states: *If two or more waves of the same type pass through the same medium at the same time, the displacement at any point is the sum of the individual displacements.*

Another way of explaining superposition is that waves interact with each other when they meet.

The effect of one wave on another is called **interference** *and is only exhibited by waves.*

If two waves arrive at the same point in phase such that a crest meets a crest and a trough meets a trough, they reinforce each other. This interference is called *constructive interference* (Figure 6.14(a)).

If the two waves arrive at the same point π radians out of phase such that a crest meets a trough, they 'cancel each other out'. This is called *destructive interference* (Figure 6.14(b)).

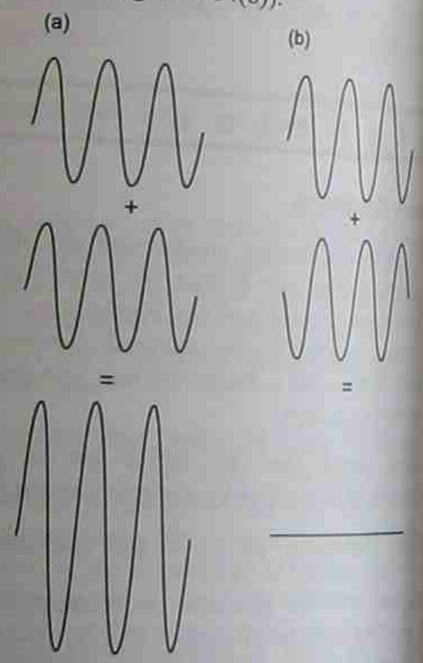


Figure 6. 14 Interference (a) constructive and (b) destructive

Two Source Interference

Consider Figure 6.15(a). Waves falling on a small opening emerge as circular waves. If there are two such sources as in Figure 6.15, the waves emerging from the two sources overlap and interfere. It follows that:

Interference *occurs between waves that have diffracted.*

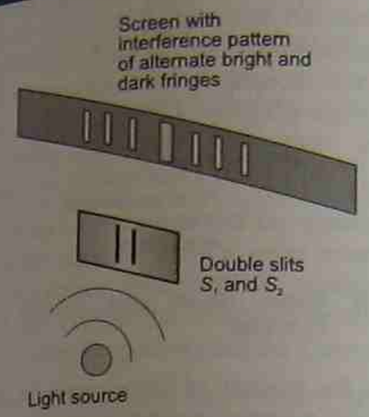


Figure 6. 15 Diffraction at a slit and subsequent interference of waves

The interference results in a series of bright and dark fringes. Bright fringes result when the two waves arrive at a point in phase and dark fringes when they arrive at a point with a π radian phase difference.

Consider Figure 6.16(a).

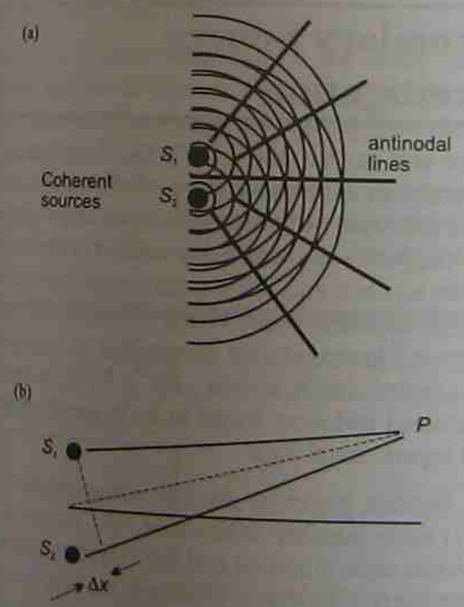


Figure 6. 16 Diffraction and interference between two sources

Waves from the two sources S_1 and S_2 overlap and interfere forming *anti-nodal* lines where crest meets crest and *nodal* lines where crests meet troughs.

Whether a point such as P is a point of constructive interference or destructive interference depends on the extra distance, Δx, travelled by the waves from S_2 compared to those from S_1.

ELECTRON DIFFRACTION

In a series of experiments commencing in 1923 the Americans Clinton J. Davisson and Lester H. Germer scattered electrons from the surface of a nickel crystal (Figure 6.17) and obtained an intensity pattern of the reflected electrons that showed *diffraction* effects like those for light discussed above. The electrons were exhibiting *wave characteristics*.

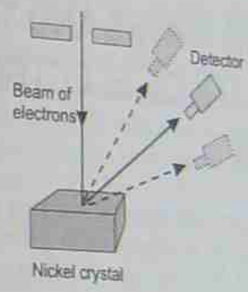


Figure 6.17 The Davisson and Germer experiment

In 1928 the British physicist G.P. Thomson[10] passed an electron beam through a thin sheet of gold foil and obtained diffraction patterns similar to that obtained by passing light through certain materials (Figure 6.18).

The wave nature of electrons is put to practical use in the *electron microscope* which uses electrons instead of light to view tiny objects. These devices are capable of magnifying many millions of times.

[10] Thomson succeeded in proving the wave nature of electrons some 28 years after his father J.J. Thomson first demonstrated their particle properties in his discovery of cathode rays.



Figure 6.18 Electron diffraction pattern formed when a beam of electrons is passed through a thin metal foil

MATTER WAVES AND THE STABILITY OF ELECTRON ORBITS

Bohr's first postulate said that electrons could rotate in their orbits or stationary states without radiating energy. Bohr, however, was unable to explain why this happened.

The concept of matter waves made it possible to show how the electrons could be stable in their orbits around the nucleus. If an integral number of electron wavelengths fitted into the circumference of the electron orbit, *standing waves*[11] would be possible and no energy would be lost (Figure 6.19). That is:

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

But $\lambda = \frac{h}{p} = \frac{h}{mv}$ which leads to:

$$\frac{nh}{mv} = 2\pi r$$

$$mvr = \frac{nh}{2\pi}$$

But this is Bohr's third postulate! Hence the relationship that Bohr had to *assume* is a direct consequence of the wave nature of matter and the quantisation of energy.

[11] In a standing wave, energy is continually transferred between kinetic energy and potential energy but is not lost.

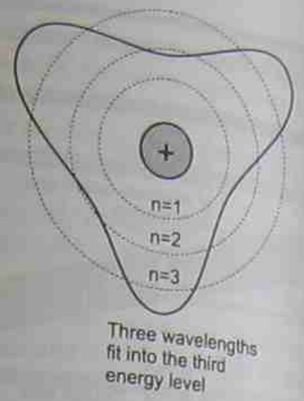


Figure 6.19 Matter waves and electron orbits of hydrogen

Note that the number of wavelengths in an orbit is equal to the quantum number n. In Figure 6.19, on the third energy level there are three wavelengths. (It should not be thought that the electron follows the wavy line. The wave represents the amplitude of the electron matter wave. Where the amplitude is greatest, so too is the probability of finding the electron. The wave is shown drawn on the Bohr orbit for convenience.)

Secondary Source Investigation

As we saw earlier (see p.227), the Bohr model was successful in explaining some of the characteristics of the spectrum of hydrogen but not other elements. Bohr originally neglected any motion of the nucleus, but the nucleus and the electron rotate around their common centre of mass. Using this modification, the spectra of *hydrogen-like* atoms that is, atoms with one electron (such as He^+, Be^{2+}, Li^{3+}...) could be determined and were found to be in good agreement with experimental data.

The German physicist Arnold Sommerfield (1868-1951) made another refinement. He suggested that the orbits were elliptical and not circular (by analogy with planetary motion). This enabled him to explain the fine structure of the hydrogen spectrum, that is, that each line was really made up of a number of closely spaced lines. Even better agreement was obtained when it was suggested that each electron was *spinning* on its own axis.

Heisenberg

The Bohr model, with these modifications, was the pre-eminent theory of the atom by 1920. In this year, the German born Werner Heisenberg (1901-1976) commenced his study at Munich University under Sommerfield. Following the completion of his doctorate he moved to the prestigious University of Gottingen and started work under the mathematician and physicist, Max Born. He then moved to Copenhagen in 1924 to study under Bohr.

By 1924 physicists accepted that the quantum theory needed to be replaced with a more encompassing *quantum mechanics* theory. (The modified theory could still not explain the relative intensities of the lines in the hydrogen spectrum and the Zeeman effect.)

In 1925 Heisenberg introduced a theory of quantum mechanics using complex mathematical constructs called *matrices*.

In 1926 the Austrian physicist Erwin Schrödinger proposed an alternative theory—wave mechanics. His theory was based on the matter wave idea introduced by de Broglie in 1924 (see p.231). At first the two theories appeared to be unrelated, but in May 1926, Schrödinger proved that Heisenberg's *matrix quantum mechanics* and his own *wave mechanics* were equivalent.

Heisenberg is also well known for what was to become known as the *uncertainty principle*. This effectively says that for an elementary particle such as an electron:

> *The more precisely the position is determined, the less precisely the momentum is known in the instant and vice versa.*

If Δp is the uncertainty in the momentum and Δx is the uncertainty in the position, then Heisenberg showed that:

$$\Delta p \Delta x \geq \frac{h}{2\pi}$$

where h is Planck's constant. This shows that as Δx decreases, Δp increases.

This relationship has profound implications for the way we view matter. Classical mechanics assumed that, given the position and momentum of an object such as a planet, it is possible to determine the position and momentum at any time in the future. (Classical physics is referred to as deterministic physics.) Quantum mechanics on the other hand, is non-deterministic as we can illustrate by Figure 6.20.

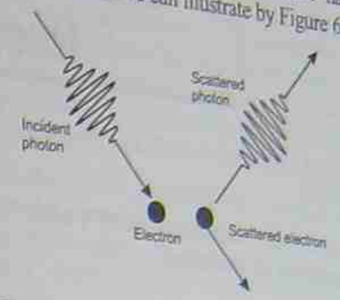


Figure 6.20 'Seeing' an electron

Suppose we wish to measure the position and velocity of an electron moving in an evacuated tube such as a cathode ray tube. To 'see' the electron we first have to interact with it by bouncing a photon off it. The small size of an electron means we have to use light of small wavelength (diffraction of waves means that large waves bend around small objects as if they were not there). Such waves, however, have high frequencies and hence energy ($E = hf$). The photon will hence give a large and random 'kick' to the electron, changing its momentum in a non-predetermined manner! (Conversely, if we lower the momentum of the photon to lessen its effect, the longer wavelength means we cannot know the position accurately.)

The uncertainty principle showed that we cannot speak with certainty about events on the atomic scale but must rather speak in terms of the *probability* of something occurring. (Max Born was the first to understand the probability interpretation of atomic behaviour.) This 'probability' interpretation underpins all of quantum mechanics.

Pauli

In 1925 the Austrian theoretical physicist, Wolfgang Pauli (1900-1958), a friend of Heisenberg, put forward the *exclusion principle* which states that no two electrons can occupy the same quantum state (energy state) of an atom. This principle led to an explanation of the regularity of elements in the periodic table.

The exclusion principle was subsequently found to be a consequence of the solution to Schrödinger's wave equation.

Pauli was also responsible for the prediction of the existence of the neutrino (see p.240).

SECTION 3: APPLICATIONS OF NUCLEAR PHYSICS

BIG IDEA:

The work of Chadwick and Fermi in producing artificial transmutations led to practical applications of radiation.

OUTCOMES:

Students learn to:

3 Define the components of the nucleus (protons and neutrons) as nucleons and contrast their properties.
1 Discuss the importance of conservation laws to Chadwick's discovery of the neutron.
2 Define the term 'transmutation'.
3 Describe nuclear transmutations due to natural radioactivity.
4 Describe Fermi's initial experimental observation of nuclear fission.
5 Discuss Pauli's suggestion of the existence of the neutrino and relate it to the need to account for the energy distribution of electrons emitted in β-decay.
6 Evaluate the relative contributions of electrostatic and gravitational forces between nucleons.
7 Account for the need for the strong nuclear force and describe its properties.
8 Explain the concept of a mass defect using Einstein's equivalence between mass and energy.
9 Describe Fermi's demonstration of a nuclear chain reaction in 1942.
10 Compare requirements for controlled and uncontrolled nuclear chain reactions.

Students:

1 Perform a first-hand investigation or gather secondary information to observe radiation emitted form a nucleus using a Wilson Cloud Chamber or similar detection device.
2 *Solve problems and analyse information to calculate the mass defect and energy released in natural transmutation and fission reactions.*
3 *Analyse information and use available evidence to assess how Chadwick's and Fermi's work changed understanding of the atom.*

Physics Stage 6 Syllabus Outcomes © Board of Studies NSW, 1999 (Amended 2000, 2001, 2002, 2003)

DISCOVERY OF THE NEUTRON

Protons and neutrons are collectively called **nucleons**.

Table 6.3 compares these two particles.

Table 6. 3 The proton and neutron

Property	Proton	Neutron
mass	1.673×10^{-27} kg	1.675×10^{-27} kg
charge	$+1.6\ 10^{-19}$ C	neutral

Symbolically the nucleus of an element (X say) is represented as ${}^{A}_{Z}X$ where:

The number of protons in the nucleus is referred to as the **atomic number** *Z. The sum of the protons and neutrons is the* **mass number** *A.*

The number of neutrons is found from $N = A - Z$

EXAMPLE 8

In the reaction ${}^{9}_{4}Be + {}^{4}_{2}He \rightarrow {}^{12}_{6}C + {}^{1}_{0}n$, give the composition of each element.

SOLUTION

Beryllium (Be) has 4 protons and 5 neutrons; helium (He) has 2 protons and 2 neutrons and carbon has 6 protons and 6 neutrons.

The Proton-Electron Hypothesis

Following Rutherford's discovery of the nucleus (see p.223) it was proposed that it contains A protons and A-Z electrons (where A is the mass number and Z is the atomic number). This would:

1 Result in a charge of Ze on the nucleus (which was in agreement with Rutherford's experimental results).
2 'Explain' the results of β^- emission—the emission of electrons from atoms. The electrons *had* to come from somewhere in the nucleus.

Progress in knowledge about the nucleus, however, showed this hypothesis to be incorrect. For example, application of the *uncertainty principle*[12] (see p.235) showed that the nucleus could not contain electrons. In addition, the mass of the nucleus was found to be about twice the atomic number, for example, hydrogen with $Z = 1$ had a mass of ~2 *atomic mass units* (u); oxygen with $Z = 8$ had a mass of ~16 u.

In 1920 Rutherford proposed that a neutral particle with similar mass to the proton—which he termed the *neutron*—might exist in the nucleus. The neutron's neutral charge would not affect the nucleus' charge and the extra mass would account for the measured mass of the nucleus.

Chadwick and the Neutron

In 1930, the Germans Walther Bothe and Becker discovered that bombarding beryllium with alpha particles resulted in the emission of a penetrating type of radiation. The radiation proved not to be gamma rays even though these were the *expected* penetrating radiation.

In 1932 the Englishman James Chadwick suggested that this radiation consisted of Rutherford's *neutrons*. These neutrons were ultimately found to have approximately the same mass as a proton.

A schematic diagram of the apparatus used by Chadwick to discover the neutron is shown in Figure 6.21.

1 Since ionisation is the principal method of detecting radiation, the uncharged neutrons would be hard to detect, as they would cause little or no ionisation.
2 The addition of proton-rich paraffin (containing lots of hydrogen atoms), enhances the detection. The neutrons eject protons as a result of elastic collisions and as these cause ionisation they are readily detected. (Joliot and Curie first did this experiment.)
3 By applying the laws of *conservation of momentum and energy*, Chadwick was able to prove the existence of the neutron. The equation for the reaction is

[12] This says that the more we know about the position of a particle such as an electron, the less we know about its energy. If an electron were confined in a space the size of a nucleus, its energy would be too great to stay there!

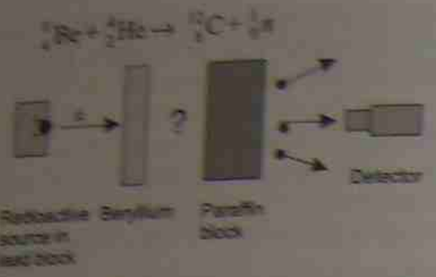


Figure 6.21 Chadwick's experiment

As a result of the work of Rutherford and Chadwick the nucleus was shown to consist of protons and neutrons.

RADIOACTIVITY

Radioactivity *is the spontaneous breakdown of an element into a new element by the emission of* α, β *and/or* γ *rays.*

Natural and Artificial Radioactivity

Natural radioactivity is exhibited by all of the naturally occurring isotopes above bismuth in the periodic table. In addition, radioactive isotopes (*radioisotopes*) exist for many other elements such as $^{3}_{1}H$ and $^{14}_{6}C$.

In 1933 Irene and Frederick Joliot-Curie (Marie Curie's daughter and her husband) produced the first artificial radioactive nuclei when they bombarded aluminium with alpha particles forming an isotope of phosphorus with a short half-life (a measure of how long it takes to decay).

Fermi (see p.239), also synthesised a large number of artificial radioisotopes by bombarding elements with neutrons.

Today, more than 400 artificial radioisotopes are known to exist, many are produced in particle accelerators (see p.251).

TRANSMUTATION AND NUCLEAR REACTIONS

Transmutation *occurs when one element changes into another element. Natural transmutations occur in radioactive decay such as alpha and beta decay.*

In all transmutations (as in all nuclear reactions), the mass number and atomic number are conserved, that is, the sum of the mass numbers on the left-hand side equals the sum of the mass numbers on the right-hand side and the sum of the atomic numbers on the left-hand side equals the sum of the atomic numbers on the right-hand side.

Alpha Decay

In alpha decay, a nucleus of element X (say) changes into the nucleus of another element Y according to the *nuclear equation*:

$$^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + ^{4}_{2}He$$

where $^{4}_{2}He$ is the *alpha particle*.

Beta Decay

There are two types of beta decay:

1 β^- decay and

2 β^+ decay.

β^- Decay

This is illustrated by the equation:

$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + ^{0}_{-1}e + \bar{\nu}$$

where $\bar{\nu}$ is a particle called an *antineutrino* (see later) and $^{0}_{-1}e$ is the beta minus particle (an electron).

Where does the electron come from? A neutron decays into a proton, an electron and a antineutrino—the electron and antineutrino are emitted but the proton stays behind, thus increasing the atomic number by 1. This is indicated as follows:

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

β^+ Decay

A positron (positive electron) is emitted after a proton decays into a neutron, a positron and a neutrino as follows:

$$^{A}_{Z}X \rightarrow ^{A}_{Z-1}Y + ^{0}_{+1}e + \nu$$

where ν is a neutrino. In this process a proton decays into a neutron and a positron as follows:

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

Gamma Decay

Gamma decay usually accompanies alpha and beta decay. A nucleus de-excites (loses energy) by emitting high-energy electromagnetic radiation without changing Z or A. As such this is *not* an example of transmutation.

$$^{A}_{Z}X^{*} \rightarrow ^{A}_{Z}X + \gamma$$

where * denotes an excited nucleus.

Artificial Transmutations

Rutherford achieved the first artificial transmutation in 1919 when he bombarded nitrogen gas with alpha particles and found that oxygen gas was produced!

The equation for this reaction is

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$$

ENRICO FERMI

As usual, Rutherford used an alpha particle to cause a transmutation. The neutron, however, because of its neutral nature, proved to be a better 'bullet' to cause a transmutation. (Alpha particles, because of their positive charge are repelled by the positive nucleus and find it more difficult to penetrate.)

The Italian Enrico Fermi was the first to realise the neutron's potential. With a group of co-workers in Rome between 1934 and 1938, Fermi bombarded as many of the known elements as possible with neutrons. In the majority of cases *new isotopes were formed*. Occasionally this new nucleus was radioactive and emitted a beta particle. For example, bombarding copper produced the following reactions:

$$^{63}_{29}Cu + ^{1}_{0}n \rightarrow ^{64}_{29}Cu$$

$$^{64}_{29}Cu \rightarrow ^{64}_{30}Zn + ^{0}_{-1}e$$

When Fermi and his group reached uranium, the heaviest known element, the results were confusing. They believed that they had created the isotope $^{239}_{93}U$ which they believed would undergo beta decay to form an isotope of the element with atomic number 93—the first transuranic element, that is,

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U$$

$$^{239}_{92}U \rightarrow ^{239}_{93}? + ^{0}_{-1}e$$

where '?' represents the unknown new element.

NUCLEAR FISSION

Fermi and his group just failed to discover nuclear fission in their experiments with uranium. In 1938 however, the German physicists Otto Hahn and Fritz Strassman repeated Fermi's experiments and bombarded $^{238}_{92}U$ with neutrons. In addition to the isotope $^{239}_{92}U$ found by Fermi, Hahn and Strassman detected the nucleus of the element barium $^{141}_{56}Ba$. This, they believed, must be a product of the *splitting of the nucleus* of another isotope of uranium, $^{235}_{92}U$ present in the original sample. They had discovered *nuclear fission* but were reluctant to state the conclusion that the uranium nucleus could be split.

On 16 January 1939 the Austrian physicists, Lise Meitner and Otto Frisch took the step, and stated that the neutron led to the breakdown of the uranium nucleus into *two nuclei of roughly equal size*—a process they called *nuclear fission* (because of its similarity to the fission of bacteria when they reproduce by 'splitting in half').

Chain Reaction

The reaction that Hahn and Strassman had produced was $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n + \text{energy}$

An alternative reaction is

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{139}_{57}La + ^{95}_{35}Br + 3^{1}_{0}n + \text{energy}$$

In both reactions, in addition to the two large fragments, three neutrons are produced. Since only one is required to initiate a nuclear reaction, the possibility of a chain reaction presented itself.

Critical Mass

The reason that Fermi had not detected fission is that neutron capture leads to fission in some cases and at other times to beta decay. Why is this?

For a chain reaction to continue there needs to be a balance between the production and loss of neutrons. Neutrons are lost from the reaction in three main ways:

1. capture by uranium without fission;
2. capture by other atoms in the sample or in the containing material; and
3. escape without capture.

There is a critical mass (critical size) where the production of neutrons just equals the loss of neutrons.

Moderators

U-235 is fissionable (undergoes fission) with thermal (slow) neutrons but not as readily with fast neutrons. The neutrons liberated by a chain reaction have high initial speeds and need to be slowed down to thermal energies. This slowing down can be achieved by collisions with atoms that won't readily absorb the neutrons in materials termed *moderators*.

Moderators include

1. ordinary water (H_2O)
2. 'heavy' water (deuterium oxide, D_2O)
3. graphite (as used in the first atomic 'pile', see below) and
4. beryllium.

THE NEUTRINO

In 1930 the Austrian physicist Wolfgang Pauli (see p.235) proposed the existence of a particle with properties unlike anything known at the time. It would be a particle with no electric charge, no mass, and no magnetic properties and would have almost no interaction with matter. It would, however, have energy, linear momentum and angular momentum (the momentum associated with a rotating body) as such, it was 'something' rather than 'nothing'.

Pauli called the particle a 'neutron' but (without with the particle discovered by Chadwick in 1932 also called the neutron, led to Fermi labelling the *neutrino*—'little neutral one' in Fermi's native Italian.

What led Pauli to predict the existence of such a particle? It came from experimental investigations of beta decay, for example

$$^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e$$

When the masses before and after were measured and the difference in mass was converted to energy according to Einstein's $E=mc^2$ equation, a discrepancy arose. The electron was found to have less energy than expected from the mass-defect—on average one-third of the energy that should be associated with the electron disappeared. Yet nothing could be found to make up the deficit. (Gamma rays were predicted to account for the difference but they could not be detected.) Pauli suggested that the energy that appeared to be 'lost' was carried away by the neutrino.

Without Pauli's postulated particle, the well established laws of conservation of energy, momentum, angular momentum would have to be abandoned—an idea that did not sit well with Pauli.

The experimental discovery of the neutrino did not occur until 1956, but by then physicists had already accepted its existence to preserve the conservation laws.

As it turns out, the neutrino associated with beta minus (β^-) decay is actually an anti-neutrino represented as $\bar{\nu}$ [1].

THE NUCLEAR FORCE

As we have seen, the nucleus contains positive protons and neutral neutrons. Since positive charges repel, it might be expected that the nucleus would 'blow itself apart' (see Example 9). The only known attractive force was that of gravity but it was too small (see Example 10) to account for the stability

[1] A horizontal 'bar' above a symbol denotes the antiparticle.

...ss attractive force is ...

Example

...lculate the electric force of repulsion between two ...rons found 1.0 x 10^{-15} m apart. NB: The force is ...

...ver $F = 9\times10^{9}\frac{q_1q_2}{d^2}$

Solution

$$F = 9\times10^{9}\frac{q_1q_2}{d^2}$$

$$= 9\times10^{9}\frac{(1.602\times10^{-19})^2}{(1.0\times10^{-15})^2}\ \text{N}$$

$$= 231.0\ \text{N}$$

Example 10

Calculate the gravitational force of attraction ...ween two protons separated by 1.0 x 10^{-15} m. ...(=6.67 x 10^{-11} kg^{-1}m^{3}s^{-2})

Solution

...e gravitational force of attraction between two ...ses m_1 and m_2 is given by:

$$F = 6.67\times10^{-11}\times\frac{m_1m_2}{d^2}$$

$$= 6.67\times10^{-11}\times\frac{(1.673\times10^{-27})^2}{(1.0\times10^{-15})^2}\ \text{N}$$

$$= 1.87\times10^{-34}\ \text{N}$$

...ously this force is too small to hold the protons ...ether.

...periments indicate that an extremely powerful but ...ort-range force acts equally between the following ...ticles: proton-neutron, proton-proton and ...utron-neutron. This *nuclear force* is brought about ...y an exchange of particles called *mesons* (just like ...e electromagnetic force is due to an exchange of ...otons).

...graph of the nuclear force versus the separation ...tween two nucleons is shown in Figure 6.22.

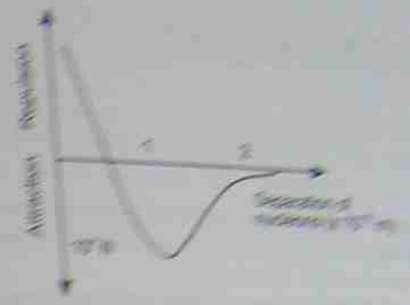


Figure 6.22 Nuclear force versus separation between nucleons

This graph shows that:

1. On average, two nucleons are separated by 1.3×10^{-15} m.
2. At distances greater than $\sim3\times10^{-15}$ m, the nuclear force is effectively zero.
3. If the nucleons come closer than $\sim0.5\times10^{-15}$ m, the nuclear force becomes a force of repulsion.
4. Should the nucleons move within a range of $\sim0.5\times10^{-15}$ m to $\sim3.2\times10^{-15}$ m, the nuclear force is attractive.
5. The force is much stronger than the Coulomb force between two protons (about 340 N at the mean separation compared to ~10,000 N for the nuclear force).

What gives rise to this force? To answer this we must consider the work of Einstein.

MASS DEFECT

Using a device called a *mass spectrograph* it is possible to measure the masses of atoms[*] and their components. When this is done it is found that:

> *The mass of the atom is less than the sum of the masses of its components (protons, neutrons and electrons). This difference is called the mass defect.*

[*] The masses of atoms are relative masses. They are compared to the mass of one carbon atom and are measured in atomic mass units (u). One atomic mass unit is defined as one twelfth of the mass of the carbon-12 atom (which, by definition, has a mass of 12.000000 exactly). 1 u is equal to 1.661×10^{-27} kg. 1 u is also equal to 931.5 MeV (mega electron volts).

In both reactions, in addition to the two large fragments, *three* neutrons are produced. Since only one is required to initiate a nuclear reaction, the possibility of a *chain reaction* presented itself.

Critical Mass

The reason that Fermi had not detected fission is that *neutron capture* leads to fission in some cases and at other times to beta decay. Why is this?

For a chain reaction to continue there needs to be a balance between the production and loss of neutrons. Neutrons are lost from the reaction in three main ways:

1 capture by uranium without fission;
2 capture by other atoms in the sample or in the containing material; and
3 escape without capture.

There is a critical mass (critical size) where the production of neutrons just equals the loss of neutrons.

Moderators

U-235 is fissionable (undergoes fission) with *thermal* (slow) neutrons but not as readily with *fast* neutrons. The neutrons liberated by a chain reaction have high initial speeds and need to be slowed down to thermal energies. This slowing down can be achieved by collisions with atoms that won't readily absorb the neutrons in materials termed *moderators*.

Moderators include

1 ordinary water (H_2O)
2 'heavy' water (deuterium oxide, D_2O)
3 graphite (as used in the first atomic 'pile', see below) and
4 beryllium.

THE NEUTRINO

In 1930 the Austrian physicist Wolfgang Pauli (see p.235), proposed the existence of a particle with properties unlike anything known at the time. It would be a particle with no electric charge, no mass, and no magnetic properties and would have almost no interaction with matter. It would, however, have energy, linear momentum and angular momentum (the momentum associated with a rotating body). As such, it was 'something' rather than 'nothing'!

Pauli called the particle a 'neutron' but confusion with the particle discovered by Chadwick in 1932, also called the neutron, led to Fermi labelling it the *neutrino*—'little neutral one' in Fermi's native Italian.

What led Pauli to predict the existence of such a particle? It came from experimental investigations of beta decay, for example

$$^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}e$$

When the masses before and after were measured and the difference in mass was converted to energy according to Einstein's $E=mc^2$ equation, a discrepancy arose. The electron was found to have less energy than expected from the mass-defect—on average one-third of the energy that should be associated with the electron disappeared—and nothing could be found to make up the deficit. (Gamma rays were predicted to account for the difference but they could not be detected.) Pauli suggested that the energy that appeared to be 'lost' was carried away by the neutrino.

Without Pauli's postulated particle, the well-established laws of conservation of energy, mass and angular momentum would have to be abandoned—an idea that did not sit well with Pauli.

The experimental discovery of the neutrino did not occur until 1956, but by then physicists had long accepted its existence to preserve the conservation laws.

As it turns out, the neutrino associated with beta-minus (β^-) decay is actually an *anti-neutrino* represented as $\bar{\nu}$ [13].

THE NUCLEAR FORCE

As we have seen, the nucleus contains positive protons and neutral neutrons. Since positive charges repel, it might be expected that the nucleus should 'blow itself apart' (see Example 9). The only known attractive force was that of gravity but it was too small (see Example 10) to account for the stability of

[13] A horizontal 'bar' above a symbol denotes the antiparticle.

the nucleus. Obviously another attractive force is required.

EXAMPLE 9

Calculate the electric force of repulsion between two protons placed 1.0×10^{-15} m apart. NB: The force is given by $F = 9\times10^9 \frac{q_1 q_2}{d^2}$

SOLUTION

$$F = 9\times10^9 \frac{q_1 q_2}{d^2}$$

$$= 9\times10^9 \frac{(1.602\times10^{-19})^2}{(1.0\times10^{-15})^2} \text{ N}$$

$$= 231.0 \text{ N}$$

EXAMPLE 10

Calculate the gravitational force of attraction between two protons separated by 1.0×10^{-15} m. ($G = 6.67 \times 10^{-11}$ kg.m^2.s^{-2})

SOLUTION

The gravitational force of attraction between two masses m_1 and m_2 is given by:

$$F = 6.67\times10^{-11} \times \frac{m_1 m_2}{d^2}$$

$$= 6.67\times10^{-11} \times \frac{(1.673\times10^{-27})^2}{(1.0\times10^{-15})^2} \text{ N}$$

$$= 1.87\times10^{-34} \text{ N}$$

Obviously this force is too small to hold the protons together!

Experiments indicate that an extremely powerful but short-range force acts equally between the following combinations: proton-neutron, proton-proton and neutron-neutron. This *nuclear force* is brought about by an exchange of particles called *mesons* (just like the electromagnetic force is due to an exchange of *photons*).

A graph of the nuclear force versus the separation between two nucleons is shown in Figure 6.22.

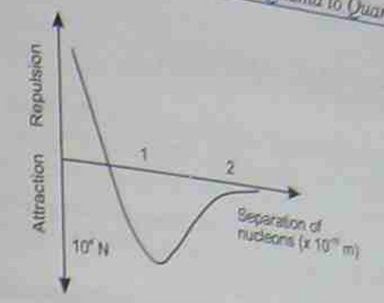


Figure 6.22 Nuclear force versus separation between nucleons

This graph shows that:

1 On average, two nucleons are separated by 1.3×10^{-15} m.
2 At distances greater than $\sim 2 \times 10^{-15}$ m, the nuclear force is effectively zero.
3 If the nucleons come closer than $\sim 0.5 \times 10^{-15}$ m, the nuclear force becomes a force of repulsion.
4 Should the nucleons move within a range of $\sim 0.5 \times 10^{-15}$ m to $\sim 2.2 \times 10^{-15}$ m, the nuclear force is attractive.
5 The force is much stronger than the Coulomb force between two protons (about 140 N at the mean separation compared to ~10,000 N for the nuclear force).

What gives rise to this force? To answer this we must consider the work of Einstein.

MASS DEFECT

Using a device called a *mass spectrograph* it is possible to measure the masses of atoms[14] and their components. When this is done it is found that:

The mass of the atom is less than the sum of the masses of its components (protons, neutrons and electrons)! This difference is called the **mass defect**.

[14] The masses of atoms are relative masses. They are compared to the mass of one carbon atom and are measured in atomic mass units (u). One atomic mass unit is defined as one twelfth of the mass of the carbon-12 atom (which, by definition, has a mass of 12.000000 exactly). 1 u is equal to 1.661×10^{-27} kg. 1 u is also equal to 931.5 MeV (mega electron volts).

BINDING ENERGY

Einstein's *Theory of Relativity* states that mass and energy are equivalent. The mass defect is 'converted' into the *binding energy* of the nucleus.

Binding energy *is the energy needed to separate the atom into its separate parts.*

It follows, therefore, that since work must be done to overcome the nuclear attractive force, the energy, and hence mass, of the components must increase. Conversely, when electrons and nucleons *form* an atom, energy is *released*.

EXAMPLE 11

Calculate the mass defect for a helium atom and its corresponding binding energy.

SOLUTION

A helium atom consists of two protons, two neutrons and two electrons:

Rest mass of two protons = 2 x 1.007276 u

Rest mass of two neutrons = 2 x 1.008665 u

Rest mass of two electrons = 2 x 0.000549 u

Total mass of constituent particles in free state = 4.032980 u

Rest mass of helium atom = 4.002602 u

Therefore mass defect = 0.030378 u

Because of the equivalence between binding energy and mass defect, the binding energy is given by:

$BE = 0.030378 \times 931.5$ MeV $= 28.3$ MeV

Binding Energy Per Nucleon

By taking the total binding energy of a nucleus and dividing it by the number of nucleons (protons and neutrons) we can calculate the *binding energy per nucleon* (*BE/A*). This is a more meaningful quantity that total binding energy since it tells us how tightly each nucleon is *bound* in the system.

For helium $\frac{BE}{A} = \frac{28.3}{4} = 7.1$ MeV per nucleon. This is a relatively high value and accounts for the emission of a helium nucleus in alpha particle radioactivity.

(The binding energy of the electrons is negligible compared to the nucleons which is why the binding energy of the atom is almost the same as the binding energy of the nucleus alone.)

A graph of binding energy per nucleon versus mass number is shown in Figure 6.23.

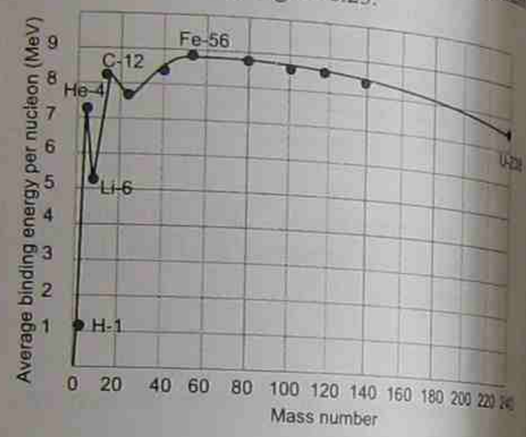


Figure 6.23 Graph of binding energy per nucleon versus mass number

This graph shows:

1. For $A > 60$, the binding energy per nucleon is roughly constant.
2. The most stable nucleus is Fe-56[15]. He-4 is also very stable (accounting for the emission of an alpha particle rather than the individual emission of 2 protons and 2 neutrons).
3. For high values of A, BE/A decreases. The effects of electrostatic repulsion between the positive protons become more obvious.
4. For low values of A, the BE/A is low; each nucleon is not uniformly surrounded by other nucleons.
5. The greater the BE/A the more stable the nucleus.

[15] This explains why iron is the highest nucleus synthesised by fusion in the interior of stars (see *The Cosmic Engine*)

FERMI AND NUCLEAR FISSION

On 2 December 1942 in the squash courts at the University of Chicago, a group of scientists lead by Enrico Fermi, using graphite blocks as a moderator, initiated the first *self-sustaining* nuclear fission reaction.

Prior to this event it was not known with certainty that a chain reaction would occur in uranium and that it could be controlled. The impetus for this work was the *Manhattan Project* (see p.250) set up to build the first atomic bomb.

Fermi and his co-workers used a mixture of 46 tonnes of natural uranium and uranium oxide interspersed in 40,000 graphite blocks. The graphite acted as a moderator which improved the chance of fission in the 0.7% of U-235 in the mixture by slowing down the neutrons. (Slow neutrons are more likely to interact with uranium nuclei than fast neutrons.)

Fermi controlled the reaction by inserting cadmium rods in the 'pile'. These 'control rods' absorb neutrons without reacting.

By slowly withdrawing the cadmium rods Fermi showed that the pile started to heat up—the nuclear fission reaction had begun. This heralded the beginning of the *nuclear age*.

CONTROLLED AND UNCONTROLLED CHAIN REACTIONS

An atom bomb is a good example of a uncontrolled chain reaction; a nuclear reactor on the other hand, is a controlled chain reaction.

In an uncontrolled chain reaction, each neutron released by the uranium atom as it splits is allowed to hit another uranium atom. There is a rapid build-up of atoms undergoing fission and a rapid release of energy (Figure 6.24(a)).

In a controlled chain reaction, however, only one neutron from each fission is available to split another uranium atom (all the others having been absorbed without causing fission, Figure 6.24(b)). These neutrons are absorbed by control rods made of materials such as cadmium (that absorb neutrons without undergoing fission).

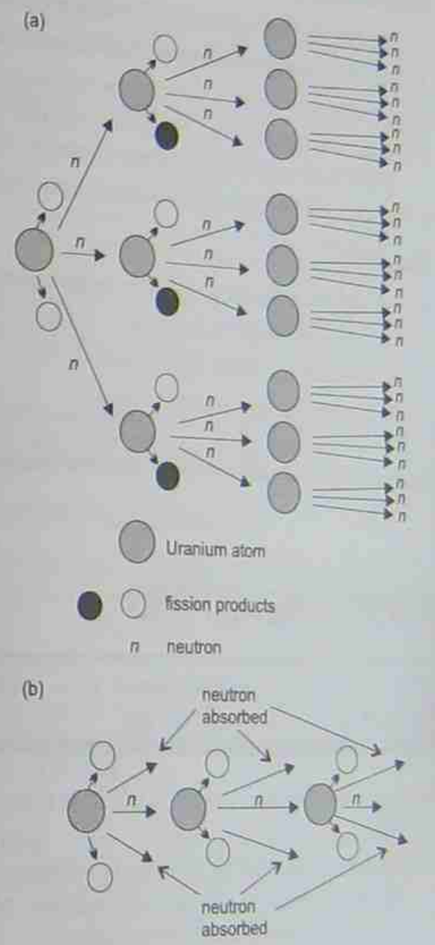


Figure 6.24 (a) Uncontrolled chain reaction (b) controlled chain reaction

SECTION 4: NUCLEAR APPLICATIONS

BIG IDEA:

An understanding of the nucleus has led to large science projects and many applications.

Students learn to:

1 Explain the basic principles of a fission reactor.
2 Describe some medical and industrial applications of radioisotopes.
3 Describe how neutron scattering is used as a probe by referring to the properties of neutrons.
4 Identify ways by which physicists continue to develop their understanding of matter using accelerators as a probe to investigate the structure of matter.
5 Discuss the key features and components of the standard model of matter, including quarks and leptons.

Students:

1 *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.*

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FISSION REACTORS

The purpose of a **nuclear reactor** *is to release nuclear energy at a controlled rate.*

Nuclear fission reactors can be classified as either:

1 *Thermal reactors*—where the neutrons producing the fissions have energy comparable to gas particles at normal temperatures. Most commercial reactors are of this type; or
2 *Fast reactors*—where the neutrons producing the fissions have large energies.

Thermal Reactors

The essential features of a thermal fission reactor are:

1 a core of fuel
2 a moderator
3 a means of regulating the number of free neutrons
4 a coolant
5 radiation shielding.

Fuel

The nuclear fuel must contain *fissionable* material. Natural uranium is composed of three isotopes: 99.283% U-238; 0.711% U-235; and 0.006% U-234. U-235 is fissionable with thermal neutrons; U-238 and U-234 are not. U-238 can be converted by *neutron capture* into fissionable plutonium-239 (Pu-239). U-238 is a *fertile* material. Most reactor fuel is a mixture of fissionable and fertile material.

In *enriched uranium* the proportion of U-235 is increased to improve the probability of fission occurring. Even then, not every lump of U-235 will sustain a chain reaction because:

1 the sample may not be pure and so impurity atoms may accept neutrons without undergoing fission
2 the size may be such that the neutrons can easily escape without hitting further U-235 atoms.

The smallest possible amount of fissionable material that will sustain a chain reaction is the **critical size** (or **critical mass**).

Moderators

As we saw earlier, U-235 is fissionable with thermal (*slow*) neutrons but not as readily with *fast* neutrons[16]. Since the neutrons liberated by a chain reaction have high initial speeds (energies) they need to be slowed down to thermal energies. This can be achieved by collisions with atoms that won't readily absorb neutrons in *moderators*.

Moderators include:

1 ordinary water
2 'heavy' water (deuterium oxide D_2O)
3 graphite (as used by Fermi in the first atomic *pile*)
4 beryllium.

Control Rods

The chain reaction can be controlled by inserting rods that absorb neutrons in the reactor core. Most reactors have two sets:

1 regulating rods for routine control
2 safety rods (held vertically) for emergency shutdown.

The rods are usually steel, containing *boron* or *cadmium* which readily capture neutrons (they are said to have a high *neutron capture cross-section*).

If the reaction is proceeding too fast, the control rods are pushed further into the reactor core and absorb additional neutrons so causing the reaction to slow down. Conversely, pulling the control rods further out of the reactor core allows more neutrons to initiate fission.

[16] Reactors using highly enriched uranium (for example, 75% U-235) need no moderator as they can operate with fast neutrons.

Coolant

Most of the energy in the fission reaction is carried off as kinetic energy by the fission products. These products collide with the surrounding material and produce heat. This heat is removed by a circulating coolant such as:

1 air
2 helium
3 'heavy' water
4 liquid sodium or
5 certain liquid organic compounds.

Radiation Shields

There are usually two shields:

1 A shield designed to protect the walls of the reactor from radiation damage and at the same time reflect neutrons back into the core.
2 A *biological shield* that is used to protect the reactor personnel. This consists of many centimetres of high-density concrete.

Extension

Nuclear Power Stations

Nuclear power stations use the heat produced by nuclear fission to boil water to produce steam to drive turbines that turn generators to make electricity.

The coolant collects the heat from the core. Figure 6.25 illustrates the essential components of a nuclear power station.

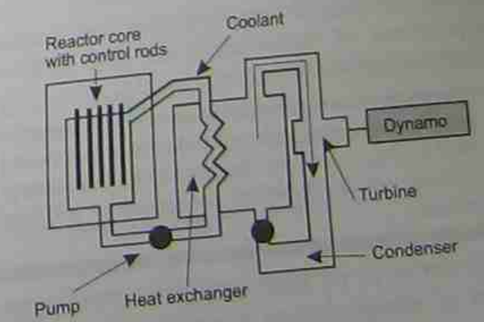


Figure 6.25 Nuclear power station

Fast Breeder Reactors

Fast breeder reactors use Pu-239 as a fuel and need no moderator. These reactors produce more fuel than they use. Surrounding the core is a blanket of U-238 which captures neutrons from the core and is converted into Pu-239 in the process as follows:

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U + \gamma$$

$$^{239}_{92}U \rightarrow ^{239}_{93}Np + ^{0}_{-1}e$$

$$^{239}_{93}Np \rightarrow ^{239}_{94}Pu + ^{0}_{-1}e$$

APPLICATIONS OF RADIOISOTOPES

As we saw earlier (p.239), Fermi showed that by bombarding stable elements with neutrons it was possible to produce new isotopes, many of which are radioactive.

> **Radioisotopes** *are radioactive isotopes.*

Radiation[17], despite its negative connotations with genetic mutations, nuclear fallout and nuclear reactor disasters has a number of positive uses for society including:

1 industrial applications
2 medical applications.

Radioactive Tracers

Before we look at some industrial and medical applications of radioisotopes we first need to understand radioactive tracers.

> *As the name suggests,* **radioactive tracers** *are used to trace (follow) the movement and storage of materials in chemical, biological or physical systems.*

This can be on the large scale, such as tracing the flow of sewage through a sewage system, to the molecular or atomic level. For example it is possible to trace the pathways of individual chemicals in complex biological reactions.

[17] We will use *radiation* here to refer to alpha, beta and gamma radiation from radioactive substances.

INDUSTRIAL APPLICATIONS

Measuring Wear in Machinery

Radioactive tracing can be used to investigate the amount of wear in machine parts by making part of the machine, say the pistons, radioactive (for example, by placing the pistons in a reactor and irradiating with neutrons). After operating the machine for some time, the amount of wear can be determined by measuring the amount of radioactivity in the lubricating oil. The greater the radioactivity, the more wear experienced by the pistons.

Thickness Control

The thickness of metal or plastic as it is manufactured can be monitored using radioisotopes. The amount of radiation passing through the metal or plastic is determined by the thickness. If it becomes too thick (or thin), the detector senses the change in radiation and can be used to adjust the machinery to ensure the correct thickness.

Power Supply

The heat produced by the radioisotope plutonium-238 (Pu-238) can be converted into electricity to power a cardiac pacemaker.

Extension

Radiometric Dating

Radioactivity provides scientists with a 'clock' by which they are able to determine the age of various geological, paleontological and archaeological materials. (This can be important in mineral exploration.) To do this they make use of the concept of the half-life of radioactive materials

Half-Life

The time taken for a particular radioactive element to decay is unique to that element and is best described in terms of the element's half-life.

> *The* **half-life** *of an element is defined as the time it takes for half a given mass of an element to decay into a new element.*

Half-lives may vary from microseconds to millions of years.

When a radioactive element decays it does so in a manner similar to that shown by the graph in Figure 6.26. It follows from the graph that if the half-life of a particular radioactive element is known and the fraction of parent element remaining in a sample can be measured, then the age of the sample can be determined.

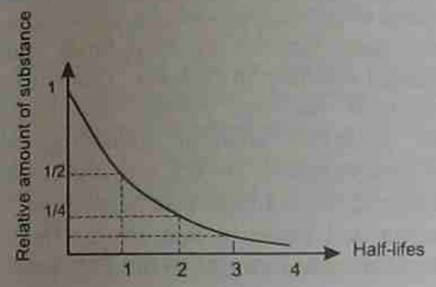


Figure 6.26 Half-life curve

If N_o is the number of atoms of a particular radioactive element at time zero, N is the number of atoms remaining after time t, and $T_{1/2}$ is the half-life, then the fraction remaining after time t is given by:

$$\frac{N}{N_o} = \left(\frac{1}{2}\right)^{t/T_{1/2}}$$

For example, if a radioactive element has a half-life of 2 days, what fraction remains after 8 days?

$$\frac{N}{N_o} = \left(\frac{1}{2}\right)^{t/T_{1/2}} = \left(\frac{1}{2}\right)^{8/2} = \left(\frac{1}{2}\right)^{4} = \frac{1}{16}$$

Radioactivity surrounds us; it is in the earth, in the oceans, in the air we breathe and in our tissues.

Geological Dating

The rocks of the earth's surface contain 5 parts per million (5 ppm) of uranium. Uranium decays over time to lead. The isotope U-238 decays to Pb-206 with a half-life of ~4.5 billion years and the isotope U-235 decays to Pb-207 with a half-life of ~700 million years!

By comparing the ratio of Pb-206 to U-238 and the ratio of Pb-207 to U-235 the age of the rocks can be determined.

Other radioactive substances can also be used. The most favoured methods for geological time keeping (with the *parent nuclide* written first and the *daughter nuclide* written second) are:

1 uranium/lead with a half life of 4500 million years
2 potassium-40/argon-40 with a half-life of 11,800 million years
3 rubidium-87/strontium-87 with a half-life of 50,000 million years
4 carbon-14/carbon-12 with a half-life of only 5,570 years.

Although the theory is well established, the technical difficulties inherent in radiometric determination of age lead to some uncertainties in the dating. Nevertheless, use of these techniques has enabled the Earth to be dated at approximately ~4,600 million years with the oldest rocks being dated at ~3,800 million years.

Radiocarbon Dating

Radiocarbon dating is a method for estimating the age of ancient artefacts. It relies upon the fact that there is a fixed proportion of radioactive C-14 in the atmosphere together with the stable C-12. These proportions are assumed to have remained constant for thousands of years. Plants absorb both the C-14 and C-12 and incorporate them into their structure for as long as they are alive but when they die the proportion of C-14 will decrease since no more is being absorbed. The proportion of C-14 in the sample under test can then be determined to give an estimate of the age of the sample.

Carbon dating is of use for only relatively 'recent' material up to about 70,000 years. In addition, as we have seen, it must be organic (once living) such as charcoal, cloth and plants.

There are many other uses in industry.

MEDICAL APPLICATIONS

The medical applications of radioisotopes include:

1 isotopic tracing/scanning
2 radiation therapy (radiotherapy).

These can all be classed as nuclear medicine.

Nuclear medicine *involves the use of radioisotopes in the diagnosis and treatment of disease.*

Isotopic Tracing/Scanning

By placing radioisotopes in a biological system, its progress through the system and/or its distribution can be investigated.

In this technique, a radioisotope of the same element as one being investigated (chemically they behave in an identical manner) is introduced into the body, usually by intravenous injection. Different organs take up the isotope in different amounts. By detecting the resulting emissions (by using detectors such as *Geiger* counters and *scintillation* counters), the distribution and concentration of the isotopes can be determined. This in turn can lead to the recognition of any abnormalities. The radioisotopes have short half-lives[18] and decay before causing damage to the body.

Iodine-131 is used to look for thyroid abnormalities as it concentrates in the thyroid gland. Similarly carbon-14 is used to scan for abnormalities associated with diabetes and anaemia.

Table 6.4 illustrates some radioisotopes used in scanning and the organs that they work with.

Table 6. 4 Radioisotopes used for scanning

Radioisotope	Organ to scan
iodine-131	thyroid, lung
chromium-51	spleen
selenium-75	pancreas
technetium-99m	bone, lung
gallium-67	lymphatics

[18] I-131 has a half-life of ~8 days, technetium has a half-life of ~6 hours.

Radiotherapy

In radiotherapy, radiation is used to destroy abnormal cells inside the body. Gamma-rays from cobalt-60 (as well as X-rays and electrons from particle accelerators) are used in the treatment of cancer. The radiation penetrates the abnormal cells, killing them or inhibiting their growth. Nearby healthy cells, affected by the radiation have a greater ability to recover. Nevertheless, the amount of radiation used has to be closely monitored and limited.

Beta Emitters

Sometimes a radiologist will use a *beta emitter*. The short range of penetration will be advantageous. For example, some tumours produce fluids within the body tissues resulting in *oedema*. This is extremely uncomfortable for the patient. By injecting a chromic phosphate solution containing the beta emitter phosphorus-32 (P-32), into the tumour, the short-range (2 mm - 8 mm) beta particles affect only the tumour and tissue in that range. The damage done to the tumour slows down the fluid production.

Cancer Treatment

Cancer radiotherapy relies on gamma emitters such as cobalt-60 (Co-60) with a half-life of 5.26 years. The radiation can be administered by:

1 implanting the actual radioactive material in the tumour; or
2 exposing the body to an external emitter that directs the rays to penetrate the body and the tumour.

The method to be employed depends on factors such as the size and location of the tumour.

Implants of radioactive materials in the form of wires, threads... using radioisotopes of gold, iridium, and caesium (in addition to cobalt) are most effective with small, rapidly growing tumours. They release the radiation over an extended period of time.

External irradiation causes more normal tissue damage but can treat larger tumours. A regime of 10 to 20 sessions over a period of months may be necessary.

Side effects of radiotherapy include nausea, hair loss, vomiting, blood loss, skin disorders and a drop in blood pressure.

Side effects of radiotherapy include nausea, hair loss, vomiting, blood loss, skin disorders and a drop in blood pressure.

NEUTRON SCATTERING

Neutron scattering *is a powerful method of analysing the internal structure and properties of matter using neutrons.*

A neutron is an uncharged particle with a mass slightly greater than that of the proton. Free neutrons (that is, free of the nucleus) interact with matter in a number of ways depending upon their velocity and the nature of the target. They include:

1 *Scattering*: This can be elastic (both kinetic energy and momentum conserved) or inelastic (kinetic energy conserved but momentum not conserved). In elastic collisions with low-mass nuclei, the neutron loses significant amounts of energy.
2 *Absorption*: These may lead to fission.
3 *Capture*: This may produce new elements, many of which are radioactive.

Neutrons, because of their neutral charge, penetrate matter more easily than do charged particles (for example, protons and electrons).

Neutrons with energies of < 1 eV[19] are termed *slow neutrons*. Those with energies > 1 keV are referred to as *fast neutrons*.

In neutron scattering, an energetic recoil nucleus is produced. The energy of the recoil nucleus varies depending on the type of collision —from zero for a grazing angle to a maximum for a head-on collision. If the neutron collides with a hydrogen nucleus it can transfer almost all its energy in a single collision; for heavier nuclei only a fraction is transferred in each interaction.

Neutron scattering techniques were first developed back in the 1940s and 1950s. Since then the technique has been used to look inside bulk matter to determine its structure and properties. It has been used in the development of magnetic materials for computer data storage, in the determination of the structure of superconductors and even in identifying the structure of viruses.

Neutrons, like all particles, exhibit wave-particle duality. When interacting with matter, the neutron collides with atomic nuclei and scatters in directions determined by the neutron's wavelength and the structure of the irradiated material. From these patterns, scientists can deduce the internal structure of the material. (Neutron scattering—*diffraction*—is analogous to electron diffraction discussed on p.232)

X-rays have been used for many years to probe the interior of materials. Unfortunately X-rays scatter off the electrons. This means they scatter well off high atomic mass atoms (lots of electrons) but they have great difficulty interacting with low mass atoms. They don't detect protons at all! Neutrons, on the other hand, scatter well from protons (the masses are almost the same) and this makes them ideal in determining the structure of solids containing hydrogen bonds (which includes all organic molecules in living things) and many inorganic substances.

[19] This is a common unit for particles on the atomic scale. One electron volt (1 eV) is the energy gained by an electron accelerated by a potential difference of 1 volt. It is equal to 1.6×10^{-19} J.

NEUTRON ACTIVATION ANALYSIS (NAA)

This is a technique where certain stable elements are made radioactive by bombarding them with a flux of neutrons. These radioactive elements then decay and the emitted particles have energies that allow them to be readily detected. For example, stable sodium atoms can be activated by neutron capture: ${}^{23}_{11}\mathrm{Na} + n \rightarrow {}^{24}_{11}\mathrm{Na} + \gamma$.

The ${}^{24}\mathrm{Na}$ nucleus then decays to give γ-rays, electrons and neutrinos: ${}^{24}_{11}\mathrm{Na} \rightarrow {}^{24}_{12}\mathrm{Mg} + \gamma + {}^{0}_{-1}e + \bar{\nu}$.

The electrons have a characteristic spread of energies and the γ-rays have energies of 2.75 MeV and 1.37 MeV. Sodium can thus be detected by the presence of lines at these energies in the gamma ray spectrum of the irradiated material. It is particularly useful in the analysis of the rare earth elements, uranium, barium, thorium and hafnium.

Secondary Source Investigation

The Manhattan Project

The Manhattan Project was the code name used for the United States effort to produce the atomic bomb during World War II. It was named after the Manhattan Engineering District of the US Army Corps of Engineers in New York, where much of the early work was done.

In 1938 German scientists discovered nuclear fission (see p.239). Physicists, many of whom were refugees from Nazi persecution, raised the possibility that Nazi Germany might develop an atomic bomb. They included the Hungarian physicists Leo Szilard, Edward Teller (who was to become the 'father' of the H-bomb) and Eugene Wigner. In 1939 Szilard, Teller and Wigner convinced Albert Einstein to write his famous letter to the American President Franklin D. Roosevelt advocating the immediate development of an atomic bomb. As a result, Roosevelt set up an *Advisory Committee on Uranium* in October of that year.

By March 1940 it was confirmed that the isotope uranium-235 (U-235) did in fact undergo fission with slow neutrons.

U-235, however, constitutes only a small percentage of uranium, the majority being U-238 which does not fission with slow neutrons. Two methods were ultimately used to separate U-235 from U-238:

1 *Gaseous diffusion*. By converting the uranium metal to the gas uranium hexafluoride and letting it pass through a series of membranes, it was predicted that the lighter U-235 would more readily diffuse and so its concentration could be increased after each membrane.
2 *Electromagnetic separation*: By bending a current of uranium ions in a magnetic field, the lighter U-235 ions would bend more easily than would the heavier U-238 ions, allowing them to be separated.

Although the two processes were theoretically possible, significant engineering problems had to be overcome before they became successful.

In 1940 the first *transuranic* element, neptunium, ($^{239}_{93}Np$) was discovered. It was suggested that this would decay into element 94. One of its isotopes with a mass number of 239 was predicted to undergo fission with slow neutrons. In mid 1941, plutonium ($^{239}_{94}Pu$), was identified and its ability to undergo fission was proven (and at a higher rate that U-235).

On 7 December 1941 the Japanese attacked Pearl Harbour which brought America into the war. This accelerated the race for the atomic bomb.

In May 1942, the army, under the command of Colonel Leslie Groves (soon to be promoted to Brigadier General) was brought into the construction activities necessary for the project to proceed. Groves purchased a site at Oak Ridge Tennessee for the gaseous diffusion plant and appointed the theoretical physicist Robert J. Oppenheimer to direct the actual weapon design and manufacture.

In December 1942 Enrico Fermi (see p.240) created the first chain reaction in a reactor.

By 1945 sufficient bomb-grade U-235 had been produced, (using gaseous diffusion followed by electromagnetic separation), to be fashioned into a bomb. A gun-type bomb was made, consisting of a piece of U-235 in a barrel that could be fired into another piece of U-235, to form a supercritical mass.

Meanwhile the production of Pu-239, produced by bombarding U-238 in a reactor in Hanford Washington, was proceeding in tandem with the U-235 production. Unlike the U-235 bomb, however, the Pu-239 bomb was made by having a sphere of Pu-239, surrounded by explosives. The resulting *implosion* would result in a supercritical mass faster than was possible in a barrel.

The first atom bomb (using Pu-239) was successfully exploded on 16 July 1945 near Alamogordo, New Mexico, with an explosive energy equivalent to 20,000 tonnes of TNT! At this time, the U-235 bomb was on its way to the Pacific.

On 6 August 1945 the U-235 bomb (nicknamed *Little Boy*) was dropped on Hiroshima. Three days later a Pu-239 bomb (*Fat Boy*) was dropped on Nagasaki. The next day, Japan surrendered.

The Manhattan Project was the largest and most costly (~$US2 billion in '1945' dollars) project of the war. It was an engineering feat un-paralleled to that day. The gaseous diffusion plant alone used more electricity than the entire city of Boston!

The 'success' of the project also ensured that humankind had developed the power to destroy itself. The Cold War and the resulting arms race cost us the chance to eradicate disease and hunger.

NUCLEAR STABILITY AND PARTICLE ACCELERATORS[20]

As mentioned earlier (see p.242), the stability of a nucleus is determined by the value of the binding energy per nucleon. The larger this value the more stable the nucleus.

To investigate the nuclear force and the nature of the fundamental particles, the nucleus needs to be disrupted. To do this energy must be put into the nucleus.

This energy input requires *particle accelerators* to accelerate the particles (for example protons) to the required energy. In 1930 John D. Cockroft and Ernest T.S. Walton created the first 'atom smasher' producing the reaction: ${}^1_1p+{}^7_3\text{Li}\rightarrow{}^4_2\text{He}+{}^4_2\text{He}$

Particle accelerators include:

1 Van de Graaff generators
2 cyclotrons
3 betatrons
4 synchrotrons
5 linear accelerators.

Extension

Van de Graaff generators

In the early 1930s Van de Graaff devised a continuous high voltage supply that could be used to accelerate protons and other ions to energies of 0.5 MeV. The operation is as shown in Figure 6.27.

1 Charge (either positive or negative) is 'sprayed' on to an endless belt and is carried to the top of the generator.
2 The charge is transferred to the dome and moves to the outside of the sphere.

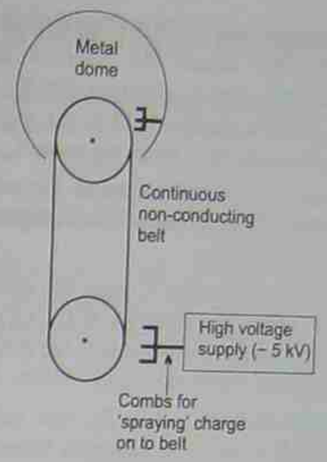


Figure 6. 27 Van der Graaff generator

3 Charge is continually added to the dome to build up a high potential difference which can be used to accelerate particles to high energies. (On small classroom generators, the initial charge is produced by friction with the bottom roller rather than by a high voltage source.)

Cyclotrons

Laurence and Livingston in California invented the cyclotron in 1931. The basic structure of the cyclotron is shown schematically in Figure 6.28. It is used to accelerate ions.

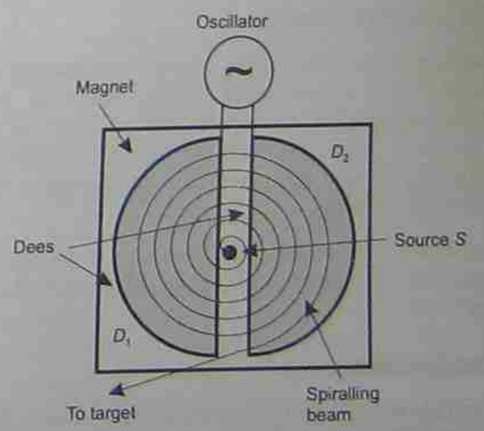


Figure 6. 28 Cyclotron

It works as follows:

1 An ion source is located near the midpoint of the gap between the D-shaped magnets (called dees).

[20] http://wwwpdg.cern.ch/pdg/cpep/variation.html Website of the world's major particle accelerators.

2 The dees are connected to a high frequency AC source. This causes the potential difference between the dees to alternate rapidly with the result that the electric field in the gap reverses direction millions of times per second.

3 The dees are placed between the poles of a powerful electromagnet. The magnetic field bends the particles.

4 Ions from the source S enter the electric field and are accelerated across it to D_2 (say), where it moves in a circular path due to the *B* field (there is no *E* field within the dees).

5 If when the ion leaves D_2, the polarity has switched, it will be accelerated towards D_1 and will increase in speed. Thus, it will move in a circle of increased radius.

6 By repeated polarity changes, the ion can be continually accelerated until it reaches the required speed and energy when it is then allowed to strike a target.

The Betatron

This device is an *electron* accelerator (hence *betatron*). It differs from a cyclotron in that:

1 the electrons are accelerated by a rapidly changing magnetic field; and

2 the circular orbit has a constant radius.

The Synchro-Cyclotron

Because of relativistic mass increase with increasing speed, the cyclotron is limited in increasing the energy of particles. This results from the fact that as *v* increases, *m* increases and so the angular velocity falls. The particle then arrives too late to receive the accelerating 'kick'.

To overcome this, the accelerating frequency is varied to keep in phase with the orbit times of the particles.

The Synchrotron

Particles at high energies (for example, from a Van de Graaff generator) are injected into a single circular evacuated tube. They pass round the tube under the influence of a large magnet and are 'kicked' along at the right time by a high-frequency supply.

To keep the particles on the same path as their mass increases, the strength of the electromagnet is steadily increased.

A synchrotron has been built in the USA with the ability to accelerate particles to energies of 500 GeV! (1 GeV = $\sim 10^9$ eV)

Linear Accelerator

A linear accelerator consists of a series of *drift tubes* connected to an oscillator (Figure 6.29). The oscillator is connected in such a way that each tube has the opposite polarity to the preceding tube.

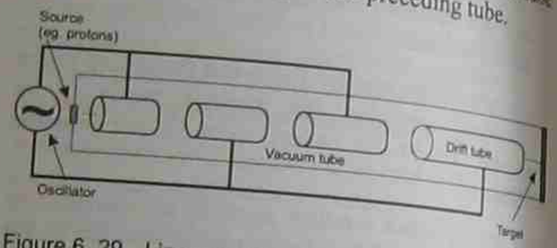


Figure 6. 29 Linear accelerator

1 Charged particles for example protons, emitted from a source are attracted to the first tube which is momentarily negative.

2 The charge accelerates in the electric field that exists in the gap between the tubes and hence gains energy.

3 The electric field inside the drift tube is zero and so the charge drifts along and does not accelerate when inside the tube.

4 The oscillator's frequency is arranged so that by the time the charge gets to the end of one tube, the next tube has changed its polarity. The tube it is leaving now repels the proton and it is attracted to the next tube which, provides additional energy.

5 To compensate for the increased velocity of the particles as they move down the line of tubes, each tube is made progressively longer than the preceding one; this ensures that the charge gets to the end just as the polarity reverses in the tubes.

Linear accelerators are used individually and in conjunction with other accelerators. The most famous linear accelerator is the *Stanford Linear Accelerator Centre (SLAC)* with a three-kilometre-long tube[21].

CERN

CERN is the acronym for *Conseil Européen pour la Recherche Nucléaire*, now known as the European organization for Nuclear Research, and represents one of the most famous atomic research establishments in the world today. Its establishment was an effort to bring back the European physicists who had emigrated to the United States as a result of World War II. CERN has the most powerful and versatile facilities of its kind in the world. The site covers more than 100 hectares in Switzerland and, since 1965, more than 450 hectares in France. The *Large Electron-Positron Collider* (1989), with a circumference of almost 27 km, has facilitated detailed studies of the *Z* particle and the standard model of particle physics (see p.253).

Accelerators assist in the investigation of matter in two ways:

1 High energy means high speed and from the de Broglie relationship $\lambda = \frac{h}{mv}$ this means short wavelength. Smaller wavelengths mean greater resolution adding fine detail to the observations.

2 High energy means high mass particles can be produced (from $E = mc^2$). The vast majority of elementary particles[22] can only be 'observed' after their creation in high-energy accelerators; they are not normally 'visible' at typical energies.

As the energy of accelerators was increased, more and more particles were discovered. The quest was on to make sense of this myriad of particles, both old and new.

[21] www2.slac.stanford.edu/vvc/home.html is an excellent virtual visitor site about SLAC. You can find out about accelerators, particle detectors, a history of SLAC, the theory behind particle physics…

[22] http://wwwpdg.cern.ch/pdg/cpep/map_proj.html *The Particle Adventure Roadmap*. This is an excellent site that looks at elementary particles including the standard model of matter.

THE STANDARD MODEL[23]

The **standard model** *is a theory that attempts to describe all interactions of subatomic particles (except those due to gravity).*

Its success lies in its ability to use a small number of particles and interactions to explain the existence of hundreds of particles and their interactions.

We saw earlier that there are four fundamental forces:

1 gravity

2 electromagnetic

3 strong nuclear force and

4 weak nuclear force.

Their relative strengths and range are shown in Table 6.5.

Table 6. 5 The four fundamental forces

Force	Relative strength	Range (m)
strong nuclear	1	10^{-15}
weak nuclear	10^{-5}	10^{-17}
electromagnetic	$\frac{1}{137}$	infinite
gravity	6×10^{-39}	infinite

The standard model has two main components to explain these forces:

1 *The electroweak theory*—first proposed in 1968 by Steven Werinberg, Sheldon Glashow and Abdus Salam. This describes interactions through the electromagnetic and weak forces. It proposes that the weak nuclear force is mediated by three *bosons* (Figure 6.30) called W^+, W^- and Z just as the electromagnetic force is mediated by the *photon*.

2 *Quantum chromodynamics*—the theory of the strong force. Formulated in 1977 it describes a

[23] http://wwwpdg.cern.ch/pdg/cpep/standard_model.html Standard Model of Matter from CERN. Another excellent site is found at http://www2.slac.stanford.edu/vvc/theory/model.html

quantum property called *colour* (see later)—hence the name.

Note that gravity is not part of the standard model.

Families of Matter

Physicists currently view matter as being grouped into three families—*quarks*, *leptons* and *bosons* (Figure 6.30).

The standard model explains interactions in terms of these families, which it further classifies as:

1 *Matter particles*. These are fundamental particles (that is, they have no *known* smaller parts). They are the *quarks* and *leptons*.

2 *Force-carrier particles*. Each type of fundamental force is caused by the exchange of *force-carrier* particles (also called *messenger or exchange* particles). These are the *fundamental* (or *gauge*) bosons. They include photons and gluons.

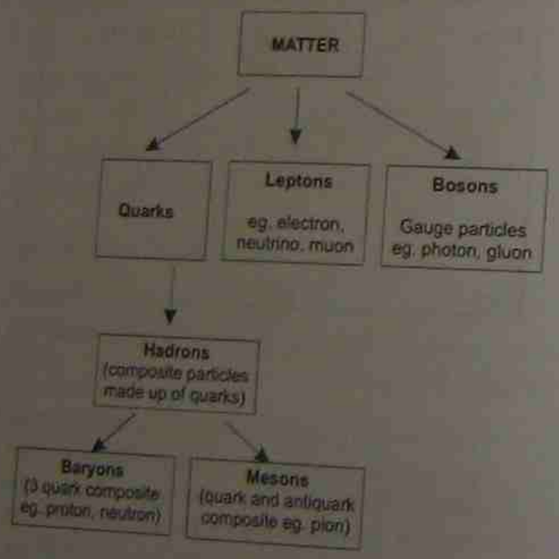


Figure 6.30 Families of matter

MATTER PARTICLES

Twelve fundamental particles make up all known matter. There are six quarks and six leptons. (In addition, for each matter particle there is a corresponding antimatter particle.)

Quarks

In 1964, theoretical considerations led the physicists Murray Gell-Mann and George Zweig to independently propose the existence of particles with charges that were sub-multiples of the electronic charge.

> **Quarks** *are fundamental particles with charges* $-\frac{1}{3}e$ *and* $+\frac{2}{3}e$

Quarks[24] are considered 'point-like' in that they have no measurable size and are fundamental since they have no known components.

There are six varieties (flavours) of quarks (Table 6.6).

Table 6.6 Quarks

Quark (q)	Symbol	Mass (GeV/c^2)[25]	Electric charge
up	u	0.004	+2/3
down	d	0.008	-1/3
strange	s	0.15	-1/3
charm	c	1.5	+2/3
bottom	b	4.7	-1/3
top	t	176	+2/3

The theory of *Quantum Chromodynamics* suggests that each quark (and antiquark) has a quantum property called *colour*[26]. (Because it is analogous to electric charge in the *electroweak* theory, physicists often talk about *colour*-charge.) Quarks can be *red*, *blue* or *green* (and antiquarks can be antired, antiblue and antigreen). Quarks of different colour-charge are attracted to each other: red attracts green; red attracts blue... Quarks with similar colour-charge repel each other.

When quarks (and antiquarks) combine to form hadrons (see below), they do so in certain colour combinations. The net colour-charge is zero[27].

The six quarks are generally grouped in three pairs: up/down, charm/strange and top/bottom.

Hadrons

Quarks do not exist in isolation. (Quarks are so strongly bound to each other—physicists say they are confined—that it would take more energy than is currently available in the biggest particle accelerators to separate them.) They are always combined with one or two other quarks forming composite particles called *hadrons*.

> **Hadrons** *are composite particles made of quarks. Hadrons are divided into* **baryons** *(three quark combinations) and* **mesons** *(two quark combinations). Hadrons interact through the strong nuclear force.*

Hadrons always have an integral charge and although individual quarks have *colour-charge*, hadrons are colour-neutral.

As mentioned above, hadrons are classified as either:

1 baryons or

2 mesons.

BARYONS

In the quark model, nucleons—protons and neutrons—are made up of three quarks (denoted qqq). A proton is made of two *up* quarks (each with a charge of $+\frac{2}{3}e$ and one *down* quark (with a charge of $-\frac{1}{3}e$). A proton is represented as *uud*. The charge is found from: $\frac{2}{3}e+\frac{2}{3}e-\frac{1}{3}e=+e$. The neutron is made from one up and two down quarks (*udd*). Charge is found from: $\frac{2}{3}e-\frac{1}{3}e-\frac{1}{3}e=0$

MESONS

Mesons are combinations of a quark and an antiquark (denoted as $\bar{q}q$ where $\bar{q}$ is the antiquark).

An example of a meson is a negative *pion* (π^-). It is made from an anti-up-quark and a down quark ($\bar{u}d$).

Mesons are unstable and decay in millionths of seconds.

Leptons

> **Leptons** *are particles with little or no mass. They do not experience the strong force. Rather they interact through the weak force and gravity (and charged leptons also interact through the electromagnetic force).*

As with quarks, there are six varieties (flavours) of leptons (Table 6.7). The electron, muon and the tau are alike in that they are negatively charged but the muon and tau have more mass.

Table 6.7 Leptons

Lepton (l)	Symbol	Mass (GeV/c^2)	Electric charge
electron	e^-	0.000511	–1
electron-neutrino	ν_e	$<7 \times 10^{-9}$	0
muon	μ^-	0.106	–1
muon-neutrino	ν_μ	<0.0003	0
tau	τ^-	1.7771	–1
tau-neutrino	ν_τ	<0.03	0

The other three leptons are neutrinos. They have no charge and little, if any, mass. Each electrically charged lepton has a corresponding neutrino.

As with quarks, for each lepton there is a corresponding *antilepton*. Unlike quarks, however, that are only found in combination with other quarks, leptons do exist independently.

[24] Gell-Mann took the term *quark* from the book *Finnegan's Wake* by the Irish author James Joyce.

[25] High energy physicists use these units for mass when the mass of the particle is dependent on the velocity according to $m=\frac{E}{c^2}$

[26] This has no relationship with colour as we know it. It is just a means used by physicists to identify a quantum mechanical property of matter.

[27] The colours of quarks were chosen as red, blue and green because light of these colours combine to form white light.

Generations

Each of the six quarks and leptons can be paired providing three *generations* of particles (Table 6.8).

Table 6.8 Generations of particles

Generation	Quark	Charge	Lepton	Charge
First	up	$+\frac{2}{3}$	electron	–1
	down	$-\frac{1}{3}$	electron-neutrino	0
Second	charm	$+\frac{2}{3}$	muon	–1
	strange	$-\frac{1}{3}$	muon-neutrino	0
Third	top	$+\frac{2}{3}$	tau	–1
	bottom	$-\frac{1}{3}$	tau-neutrino	0

Each generation consists of a set comprising each charge type of quark and lepton.

The first generation particles (up and down quarks, the electron and electron-neutrino) constitute everyday matter.

Second and third generation particles are unstable and decay into first generation particles.

As a result, the heavy quarks, *s*, *c*, *b* and *t* do not exist in normal matter. They must be 'created' in particle accelerators.

Each generation is more massive than the previous one.

FORCE-CARRIER PARTICLES

The four forces mentioned earlier are carried by force-carrier particles—bosons (also called *gauge particles*). They are:

1 gravity by the *graviton* (this is still to be discovered);
2 electromagnetic by the *photon*;
3 strong nuclear by the *gluon* (this keeps quarks together); and
4 weak nuclear by the *weakon* (weak boson).

PROBLEMS OF THE STANDARD MODEL

As with all models of matter, the standard model explains some phenomena but not all. It cannot, for example, explain:

1 why quarks have the masses they do
2 why the top quark (discovered in 1995) is so massive (~190 times the proton mass)
3 how to incorporate gravity.

The search continues for the ultimate truth—the so-called *theory of everything*!

SUMMARY

- The Rutherford model of the atom pictured a dense positive nucleus surrounded by electrons. Most of the atom is empty space.
- The line emission spectrum of hydrogen was central to the development of Bohr's model. Each line could be represented by the equation $\frac{1}{\lambda} = R_H\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$
- Planck postulated that energy came in 'lumps' or quanta given by $E = hf$
- Bohr made a number of postulates in his model of the atom, including Planck's postulate.
- Bohr was successful in explaining the existence of line emission spectra.
- Bohr was unsuccessful in explaining a number of observations of spectra.

- Just as light exhibits wave properties (for example, interference) and particle properties (for example, the photoelectric effect), so too de Broglie postulated that all matter has this same wave-particle duality.
- Matter waves have a wavelength given by $\lambda = \frac{h}{p} = \frac{h}{mv}$
- Davisson and Germer successfully demonstrated electron diffraction.
- Matter waves explain the stability of electron stationary states.
- Electron microscopes utilise the wave nature of electrons to provide enormous magnifications.
- Electron microscopes use magnetic lenses to focus electrons.
- Chadwick discovered the neutron in 1932.
- Transmutation, the conversion of one element into another, occurs in natural radioactivity and can be induced.
- Fermi first demonstrated a nuclear chain reaction from nuclear fission in 1942.
- Pauli hypothesised the existence of the neutrino to account for energy discrepancies in beta emission.
- Nucleons (protons and neutrons) are held together by the strong nuclear force.
- The mass defect is the difference between the mass of an atom and the sum of the masses of its parts.
- Mass defect is converted into binding energy according to $E = mc^2$
- Chain reactions can be controlled or uncontrolled depending on how many neutrons are available for the next fission.
- Fission reactors use the heat from nuclear fission to drive generators to produce electricity.
- Radioisotopes find extensive uses in industry and medicine.
- Neutron scattering is an effective way to probe inside bulk matter.
- Physicists use particle accelerators to probe inside atoms.
- Matter is composed of quarks, leptons and bosons.
- Cosmology seeks to explain the universe's structure and existence; it requires quantum mechanics to do this.

Key Terms

accelerator
antiparticle
Balmer series
binding energy
black body radiation
Bohr
Chadwick
chain reaction
control rods
Davisson and Germer
de Broglie
electron diffraction
electron microscope
electroweak theory
emission spectrum
Fermi
fission reactor
gluon
hadron
Heisenberg
hydrogen spectrum
lepton
magnetic lens
mass defect
matter waves
meson
moderator
neutrino
neutron scattering
nucleons
nucleus
orbit
Pauli
photon
quantum
quark
radioactivity
radioisotope
Rutherford
spectra
standard model
tracers
transmutation
wave-particle duality

QUESTIONS AND PROBLEMS ON QUANTA TO QUARKS

SECTION 1: MODELS OF THE ATOM

1 Describe the Rutherford scattering experiment.

2 Define the following terms:

(a) spectra

(b) line emission spectra

(c) spectroscope.

3 The Balmer equation for the hydrogen spectrum is $\frac{1}{\lambda} = R_H\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$. Explain the meaning of each term.

4 The green line in the spectrum of hydrogen results from the transition of an electron from the 4th energy level to the 2nd energy level. Calculate the wavelength and photon energy of the green light.

5 What was Planck's hypothesis that Bohr used to help explain spectra?

6 State Bohr's three main postulates.

7 What was the major success of Bohr's model of the atom?

8 List five limitations of Bohr's model.

SECTION 2: QUANTUM PHYSICS

1 What is meant by wave-particle duality?

2 Calculate the wavelength of an electron of mass 9.109×10^{-31} kg moving at 1.5×10^{6} m.s^{-1}.

3 Describe the Davisson and Germer experiment.

4 How are matter waves used to explain the stability of electron orbits?

SECTION 3: APPLICATIONS OF RADIOACTIVITY

1 Describe Chadwick's experiment that led to the discovery of the neutron.

2 Define the following terms:

(a) radioactivity

(b) transmutation

(c) radioisotope

(d) nucleon.

3 How can radioisotopes be produced?

4 What were Fermi's contributions to physics?

5 What led Pauli to hypothesise the existence of the neutrino?

6 Define the following terms:

(a) mass defect

(b) binding energy.

7 Calculate the total binding energy of the carbon-12 atom. You will require the following data:

mass of carbon-12 = 12.000000 u

mass of proton = 1.007276 u

mass of neutron = 1.00866 u

mass of electron = 0.000546 u

SECTION 4: NUCLEAR APPLICATIONS

1 Explain the basic principles of a fission reactor.

2 Describe *one* medical or industrial use of radioisotopes.

3 What is neutron scattering and what is it used for?

SECTION 5: THE STRUCTURE OF MATTER

1 Briefly describe the operation of *one* type of particle accelerator.

2 Briefly describe the current model of matter.

3 What are quarks?

4 What are the different characteristics attributed to quarks?

TEST QUESTIONS ON QUANTA TO QUARKS

Each QUESTION is composed of a number of parts. Suggested marks for each part are indicated. In keeping with the format of the HSC Examination, each question totals 25 marks.

The following data may be required:

Table 6. 9

Electron volt	1 eV = 1.602×10^{-19} J
Charge on electron	$e = -1.602 \times 10^{-19}$ C
Mass of electron	$m_e = 9.109 \times 10^{-31}$ kg
Planck constant	$h = 6.626 \times 10^{-34}$ J.s
Rydberg constant	$R_H = 1.097 \times 10^{7}$ m^{-1}
Speed of light	$c = 3.00 \times 10^{8}$ m.s^{-1}

QUESTION 1

(a) After the results of a famous experiment were analysed, Lord Rutherford commented *'...it was almost as incredible as if you fired a 15 inch shell at a piece of tissue paper and it came back and hit you...'*

(i) Recall what Rutherford is referring to in this comment. (1 mark)

(ii) Recall who conducted the experiment about which this comment was made. (1 mark)

(iii) Recall what Rutherford deduced from this observation. (1 mark)

(b) The equation $\frac{1}{\lambda} = R_H\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$ is an equation relating to the spectrum of hydrogen.

(i) Recall the meanings of each of the terms in this equation. (2 marks)

(ii) For the Balmer series of hydrogen, $n_f = 2$. Predict the value of n_i corresponding to the longest wavelength. (1 mark)

(iii) Calculate this wavelength in nm. (1 mark)

(c) In 1924 Louis de Broglie proposed the relationship $\lambda = \frac{h}{p}$

(i) Define the meaning of each symbol. (1 mark)

(ii) Describe how this equation shows the wave-particle duality of matter. (2 marks)

(d) Briefly describe the experiment conducted by Davisson and Germer in 1923 and discuss its implications. (4 marks)

(e) Pauli postulated the existence of a particle called the neutrino many years before its discovery.

(i) Recall what led Pauli to postulate the neutrino. (2 marks)

(ii) Explain why it was so hard to discover. (1 mark)

(f) Radioisotopes have extensive uses in medicine, agriculture and in engineering. Take any one of these areas and recall an example of the use of radioisotopes. (3 marks)

(g) A source of α, β and γ radiation is placed in a strong magnetic field as shown in Figure 6.31. From what you know of the properties of these radiations, draw the likely path of each ray through the field. (2 marks)

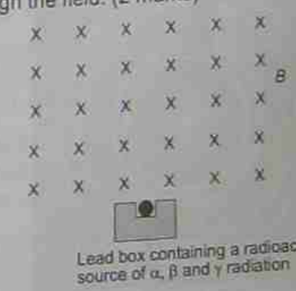


Figure 6. 31

(h) Physicists currently view matter as being divided into three families: *quarks*, *leptons* and *bosons*.

(i) Define the term quarks. (1 mark)

(ii) Recall one example of a lepton. (1 mark)

(iii) Recall one example of a boson. (1 mark)

QUESTION 2

(a) In 1911, at the instigation of Rutherford, Geiger and Marsden investigated the effects of firing alpha particles at a thin sheet of gold foil.

(i) Recall what results were expected on Thomson's 'plum pudding' model of the atom. (1 mark)

EXAM PREPARATION

To be fully prepared for the examination you must ensure that you follow an effective program of study and revision.

1 The *'secret of success'* in the HSC is consistency in study and revision. Study regularly—15 minutes of study each weeknight is far better than 2 hours once a week. Constant review also ensures that you keep up to date with the work in class. In physics, as in many other subjects, you cannot understand a concept unless you have mastered the earlier concepts and ideas. Each night, read through the work from that day's lesson and make brief notes of important concepts, terms, equations... Some students prefer to do this using mind maps, others use different coloured pens. Use what works best for you! Check that you understand the work. If not, refer to the relevant section in this book. Remember to also use your teacher to help you clarify your understanding.

2 Regularly check the module *outcomes* to ensure you have covered the required material. Remember the practical skills outcomes.

3 Success is also dependent on you being familiar with the HSC-style questions. While this may prove more difficult in the first few years of the *New HSC*, nevertheless many of the questions will be similar to those of previous years. Copies of past papers can be downloaded from the *NSW Board of Studies* web site www.boardofstudies.nsw.edu.au. Practise answering these questions. See also *Excel HSC Physics Sample Examinations* by this author for a number of sample papers based on the 2001 Specimen Paper.

4 Using the Board of Studies web site you can obtain copies of *Physics Examination Reports*. From these you can find the common mistakes and misunderstandings of students. Learn from these!

5 It needs to be stressed that in addition to the *Knowledge and Understanding* outcomes the examination will test *Skills*. You must actively participate in practical lessons and learn the required skills. Ensure that you complete the practical work and hand it in for assessment when required to do so.

Chapter One

Space

SECTION 1: GRAVITY

BIG IDEA:

The Earth has a gravitational field that exerts a force on objects both on it and around it.

OUTCOMES:

Students learn to:

1 Define weight as the force on an object due to a gravitational field.
2 Explain that a change in gravitational potential energy is related to work done.
3 Define gravitational potential energy as the work done to move an object from a very large distance away to a point in a gravitational field $E_p = -G\frac{m_1 m_2}{r}$

Students:

1 *Perform an investigation, and gather information to determine a value for acceleration due to gravity using pendulum motion, or computer assisted technology and identify reasons for possible variations from the value 9.8 $m.s^{-2}$*
2 *Gather secondary information to predict the value of acceleration due to gravity on other planets.*
3 *Analyse information using the expression $\vec{F} = m\vec{g}$ to determine the weight force for a body on Earth and for the same body on other planets.*

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CONTEXTUAL OUTLINE

On 4 October 1957 the world stood in awe as the first artificial satellite, *Sputnik 1*, was launched by the Soviet Union. Four months later on 31 January 1958 the United States launched its first satellite.

Manned space flight began on 12 April 1961, when the Russian cosmonaut Yuri Gagarin blasted into orbit. Although his flight lasted only 108 minutes it represented an important milestone in humankind's progress.

Concerns about the ability of the Earth to maintain its human population in the face of pollution, global warming and the ever-increasing number of inhabitants have some people speculating about the prospect of humans living in space in giant *space stations*.

This topic looks at the physics behind human exploration of space and the technology required, including putting an object into orbit, maintaining the orbit and allowing for safe return to Earth. It concludes with a look at Einstein's *theory of special relativity* and its implications for deep space travel in terms of our understanding of space and time.

We begin this topic with a look at gravity—a force integral to the study of space.

NEWTON'S LAW OF UNIVERSAL GRAVITATION

As we saw in the Preliminary Course *The Cosmic Engine*, gravity is a force that acts between any two (or more) objects in the universe. Isaac Newton showed that:

> *The* **gravitational force of attraction** *between any two objects of mass m_1 and m_2 whose centres are separated by a distance r is proportional to the product of their masses and inversely proportional to the square of their separation.*

Mathematically this is written as:

$$F = G\frac{m_1 m_2}{r^2}$$

where G is the *universal gravitational constant*. Its value is $6.67 \times 10^{-11}\ N.m^2.kg^{-2}$.

THE GRAVITATIONAL FIELD

Surrounding any object with mass is a *gravitational field*. This is a 'region of influence' in which another mass would experience a force due to the presence of the first mass.

We saw in *The Cosmic Engine* that the gravitational field, g, of a mass m at a distance r from the mass is given by:

$$g = \frac{Gm}{r^2}$$

This shows that the gravitational field strength is determined by the mass of the object producing the field and the distance from it. The gravitational field of the Earth decreases as the square of the distance from the centre of mass.

The direction of the Earth's field is towards the centre of the Earth (locally we say that the field acts 'down').

EXAMPLE 1

Determine the gravitational field strength (g) on the surface of the Earth given that the average radius of the Earth (R) is 6380 km and the mass of the Earth (M_E) is 5.983×10^{24} kg.

SOLUTION

$$g = \frac{GM_E}{R^2}$$

$$= \frac{6.67\times10^{-11}\times5.983\times10^{24}}{(6380\times10^3)^2}\ N.kg^{-1}$$

$$= 9.804\ N.kg^{-1}\ (\text{or } m.s^{-2})$$

This value varies slightly at different points on the Earth due to the variation in radius (the Earth is not a perfect sphere).

EXAMPLE 2

Determine the acceleration due to gravity (g) at an altitude of 150 km above the surface of the Earth.

SOLUTION

$$g = \frac{GM_E}{R^2}$$

$$= \frac{6.67\times10^{-11}\times5.983\times10^{24}}{(6380\times10^3+150\times10^3)^2}\ N.kg^{-1}$$

$$= 9.36\ N.kg^{-1}\ (\text{or } m.s^{-2})$$

It is obvious that gravity decreases with distance from the Earth.

EXAMPLE 3

Determine the acceleration due to gravity on the surface of the moon given that the mass of the moon $M_m = 7.36 \times 10^{22}$ kg and its radius R is 1740 km.

SOLUTION

$$g = \frac{GM_m}{R^2}$$

$$= \frac{6.67\times10^{-11}\times7.36\times10^{22}}{(1740\times10^3)^2}\ m.s^{-2}$$

$$= 1.62\ m.s^{-2}$$

Secondary Source Investigation

Acceleration Due to Gravity on Other Planets

Table 1.1 shows the masses and radii of the planets expressed as a multiple of the mass and radius of the Earth respectively. The approximate acceleration due to gravity on these planets is shown and has been calculated as follows:

We have $g = \frac{GM}{r^2}$ and so:

$$\frac{g_{planet}}{g_{earth}} = \frac{\frac{GM_{planet}}{r_{planet}^2}}{\frac{GM_{earth}}{r_{earth}^2}}$$

$$= \left(\frac{M_{planet}}{M_{earth}}\right) \times \left(\frac{r_{earth}}{r_{planet}}\right)^2$$

Hence:

$$g_{planet} = \left(\frac{M_{planet}}{M_{earth}}\right) \times \left(\frac{r_{earth}}{r_{planet}}\right)^2 \times g_{earth}$$

Table 1.1 Approximate acceleration due to gravity of the planets

Planet	Mass (M_E)	Radius (r_E)	$g(m.s^{-2})$
Mercury	0.06	0.38	3.7
Venus	0.82	0.95	8.9
Earth	1.00	1.00	9.8
Mars	0.11	0.53	3.8
Jupiter	318	11.2	25..5
Saturn	95	9.4	10.8
Uranus	14.5	3.98	8.8
Neptune	17.2	3.88	11.8
Pluto	0.002	0.18	0.6

WEIGHT

Weight is a force. In particular:

> *The* **weight** *of an object is the force of gravity acting on it.*

Mathematically:

$$\vec{W} = m\vec{g}$$

where $\vec{W}$ is the weight in newtons (N), m is the mass in kilograms (kg) and $\vec{g}$ can be either:

1. the *acceleration due to gravity* (= 9.8 $m.s^{-2}$ at the Earth's surface), or
2. the *gravitational field strength* (= 9.8 $N.kg^{-1}$ at the Earth's surface).

Extension

Weighing the Earth

Once G was known, it was possible to calculate the mass of the Earth. It follows that the force of attraction of a body on the Earth's surface given by the law of universal gravitation must also equal the weight of the object. Hence:

$$mg = G\frac{mM}{r^2}$$

$$M = \frac{r^2 g}{G}$$

where M is the Earth's mass, r is its radius and g is the acceleration due to gravity.

All quantities on the right-hand side of the equation are known so M can be calculated. It is equal to 5.983×10^{24} kg.

EXAMPLE 4

What is the weight of an object on the moon if its weight on the Earth is 1500 N?

SOLUTION

The mass of the object is constant and is independent of its location. Weight, on the other hand varies with location.

The mass of the object is found from:

$$W = mg$$
$$m = \frac{W}{g}$$
$$= \frac{1500}{9.8}\text{kg}$$
$$= 153.1\text{ kg}$$

Hence the weight on the moon (where g = 1.62 m.s^{-2} as calculated in the previous example) is found from:

$$W = mg$$
$$= 153.1 \times 1.62\text{ N}$$
$$= 248\text{ N}$$

1st Investigation: Finding *g* from a Pendulum[1]

A student performed the following experiment to determine g.

Theory: The period of oscillation (T) of a simple pendulum of length l is given by the formula $T = 2\pi\sqrt{\frac{l}{g}}$ where g is the acceleration due to gravity. (NB: This is true for angles of up to ~10° from the vertical.)

Aim: To find the value of g by measuring the period of a pendulum of known length.

Method: A mass was tied to the end of a piece of string and attached to a horizontal support as shown in Figure 1.1.

The length of the pendulum was measured from the point of support to the centre of the mass. The mass was pulled to the side so that the string made an angle of <10° to the vertical and was released. The time for 10 oscillations (complete to and fro motion) was recorded. The length was varied and the process was repeated. The results are recorded in Table 1.2 with the calculated values of g also shown.



Figure 1. 1 Simple pendulum

Results:

Table 1. 2 Pendulum data

Length (l) (± 0.005 m)	Time for 10 oscillations (s)	Period T (s)	g (m.s^{-2})
1.00	20.08	2.008	9.79
0.80	17.90	1.790	9.86
0.60	15.64	1.564	9.68
0.40	12.58	1.258	9.98

The average value of g is found to be 9.83 m.s^{-2}

Conclusion: The acceleration due to gravity was found using a simple pendulum to be $g = 9.8 \pm 0.$ m.s^{-2}. (This includes all values between 9.6 and 10.0 m.s^{-2})

[1] http://www.phy.ntnu.edu.tw/java/pendulum30/pendulum Simple pendulum simulation that allows the above experiment to be done as a virtual experiment. To stop the swing, place the cursor on the circle where the pendulum is attached, depress the left mouse button and hold it down.

WORK

When a force is applied to an object and the object moves, we say *work* has been done on the object.

Work *(W) is the product of the force (F) and the displacement (s) in the direction of the force.*

$$W = Fs$$

Work is only done in the scientific sense when the point of application of the force moves.

When work is done on an object there is a corresponding change in the *kinetic* and/or *potential* energy of the object.

GRAVITATIONAL POTENTIAL ENERGY

As we lift an object from the ground to a height above the ground we do work on it. This work is stored in the object as *gravitational potential energy*. For an object of mass m at a height h above the Earth's surface the gravitational potential energy E_p is given by:

$$E_p = mgh$$

This equation is valid only when the object is near the Earth's surface. For objects such as satellites, which are high above the Earth's surface, an alternative expression is used to calculate the gravitational potential energy.

The **gravitational potential energy** *is a measure of the work done in moving an object from infinity to a point in the field.*

The general expression for the gravitational potential energy of an object of mass m at a distance r *from the centre of the Earth* (or other planet) is given by:

$$E_p = -G\frac{mM_E}{r}$$

where M_E is the mass of the Earth (or other planet). Although we can define the zero of potential to be wherever we like, it is mathematically convenient to *define* the zero of potential energy at an infinite distance from the centre of the Earth!

It follows that to move an object away from the Earth we must do work on it. If, after this work is done the potential energy is zero (by definition) then it must be negative when near the Earth. Such a system is called a *bound* system.

The *change* in the potential energy of a body as it moves from one point to another is the same, regardless of the choice of reference level and it is only the *difference* in potential energy that is significant.

Change in Gravitational Potential Energy Near the Earth

The change in gravitational potential energy of a mass m_1 when its distance from the Earth's centre increases from r_A to r_B is given by:

$$\Delta E_p = -G\frac{mM_E}{r_B} - \left(-G\frac{mM_E}{r_A}\right)$$
$$= GmM_E\left(\frac{1}{r_A} - \frac{1}{r_B}\right)$$

EXAMPLE 5

What is the change in gravitational potential energy for a satellite of mass 100 kg raised to a height of 300 km above the Earth's surface?

SOLUTION

$$\Delta E_p = GmM_E\left(\frac{1}{6380\times10^3} - \frac{1}{(6380+300)\times10^3}\right)$$
$$= 6.67\times10^{-11}\times100\times5.983\times10^{24}\times7\times10^{-9}\text{ J}$$
$$= 2.81\times10^8\text{ J}$$

(This compares with 2.90×10^8 J found from the more familiar potential energy equation $E_p = mgh$.)

The gravitational attraction of the Earth is the major obstacle to space flight. In the next section we will look at how gravity can be overcome so that craft can leave the Earth and go into orbit.

SECTION 2: SPACE LAUNCH AND RETURN

BIG IDEA:

Many factors have to be taken into account to achieve a successful rocket launch, maintain a stable orbit and return to Earth.

OUTCOMES:

Students learn to:

1 Describe the trajectory of an object undergoing projectile motion within the Earth's gravitational field in terms of horizontal and vertical components.
2 Describe Galileo's analysis of projectile motion.
3 Explain the concept of escape velocity in terms of the:
- gravitational constant
- mass and radius of the planet.

4 Outline Newton's concept of escape velocity.
5 Analyse the forces involved in uniform circular motion for a range of objects, including satellites orbiting the Earth.
6 Identify why the term 'g-forces' is used to explain the forces acting on an astronaut during launch.
7 Discuss the effect of the Earth's orbital motion and its rotational motion on the launch of a rocket.
8 Analyse the changing acceleration of a rocket during launch in terms of the:
- Law of Conservation of Momentum
- forces experienced by astronauts.

9 Compare qualitatively low Earth and geostationary orbits.
10 Define the term orbital velocity and the quantitative and qualitative relationship between orbital velocity, the gravitational constant, the mass of the satellite and the radius of the orbit using Kepler's Law of Periods.
11 Account for the orbital decay of satellites in low Earth orbit.
12 Discuss issues associated with safe re-entry into the Earth's atmosphere and landing on the Earth's surface.
13 Identify that there is an optimum angle for safe re-entry for a manned spacecraft into the Earth's atmosphere and the consequences of failing to achieve this angle.

Students:

1 Solve problems and analyse information to calculate the actual velocity of a projectile from its horizontal and vertical components using:

$v = u + at$

$v_x = u_x$

$v_y^2 = u_y^2 + 2a_y\Delta y$

$\Delta y = u_y t + \frac{1}{2}a_y t^2$

2 *Perform a first-hand investigation, gather information and analyse data to calculate initial and final velocity, maximum height reached, range, time of flight of a projectile, for a range of situations by using simulations, data loggers and computer analysis.*

3 *Identify data sources, gather, analyse and present information on the contribution of one of the following to the development of space exploration: Tsiolkovsky, Oberth, Goddard, Esnault-Pelterie, O'Neill or von Braun.*
4 *Solve problems and analyse information to calculate centripetal force acting on a satellite undergoing uniform circular motion about the Earth using* $F = \frac{mv^2}{r}$
5 *Solve problems and analyse information using* $\frac{r^3}{T^2} = \frac{GM}{4\pi^2}$

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PROJECTILE MOTION

Any object thrown through the air is a projectile. Examples include a golf ball after it has been hit with the club, artillery shells fired from guns, arrows fired from bows, cricket balls hit or thrown, footballs kicked or passed…

Any moving object that moves only under the force of gravity is a **projectile**.

Although at first glance projectile motion appears quite complicated, it turns out that it can be analysed in terms of two simple motions studied already—*constant velocity* motion and *constant acceleration*.

Experimentally it is found that if two objects of the same or different mass are released from the same height and allowed to fall straight down, they reach the ground at the same time. (Galileo discovered this over two hundred years ago.) This neglects the effects of air resistance.

Similarly two objects, one falling straight down and the other projected horizontally from the same height, also reach the ground at the same time as indicated in Figure 1.2. This shows that *the horizontal motion has no effect on the vertical motion*—they are independent of each other.

The reason for this 'unexpected' result is that gravity is the only force acting on the objects and this always acts towards the centre of the Earth.

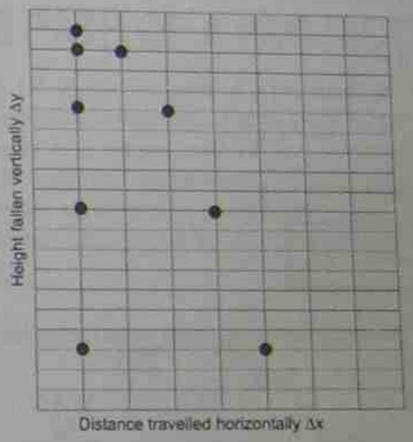


Figure 1.2 Projectile motion. An object moving horizontally falls at the same rate as an object falling straight down.

Projectile motion *can be analysed by realising that:*

1 the horizontal motion is **constant velocity** *motion; and*

2 the vertical motion is **constant acceleration** *(with acceleration of g).*

EQUATIONS OF UNIFORMLY ACCELERATED MOTION

Before we can investigate projectile motion further, we need to investigate the equations of uniformly accelerated motion.

Conventions

As we first saw in the Preliminary Topic *Moving About*, the following symbols are commonly used to represent the quantities given:

$\vec{v}$ – final velocity

$\vec{u}$ – initial velocity

$\vec{a}$ – acceleration

t – time

$\vec{s}$ – displacement

From our definition of acceleration and using the above conventions we have:

$$\vec{a} = \frac{\Delta\vec{v}}{\Delta t} = \frac{\vec{v} - \vec{u}}{t}$$

Rearranging we find:

$$\boxed{\vec{v} = \vec{u} + \vec{a}t}$$

From the definition of average velocity we have:

$$\vec{v}_{av} = \frac{\vec{s}}{t}$$

So it follows that:

$$\vec{s} = \vec{v}_{av} \times t = \left(\frac{\vec{v} + \vec{u}}{2}\right) \times t = \left(\frac{\vec{u} + \vec{a}t + \vec{u}}{2}\right) \times t$$

Therefore:

$$\boxed{\vec{s} = \vec{u}t + \tfrac{1}{2}\vec{a}t^2}$$

Note that the statement $\vec{v}_{av} = \left(\frac{\vec{v} + \vec{u}}{2}\right)$ is true only for constant acceleration.

From the first equation, squaring both sides we find:

$$v^2 = u^2 + 2aut + a^2t^2 = u^2 + 2a(ut + \tfrac{1}{2}at^2) = u^2 + 2as$$

Therefore:

$$\boxed{v^2 = u^2 + 2as}$$

Note that this last equation does not have vec signs. Although velocity is a vector, velocity squa is a scalar (since it is always positive). Also, t product of acceleration and displacement is a scala

Problem Solving

In solving problems using the equations of moti the following steps should be employed:

1 Write down what data are known and wh needs to be found. (This is very helpful choosing which of the three equations to use.)

2 Take the initial direction of movement as bei positive.

3 All quantities whose direction is opposite to th of the initial velocity are negative.

4 Substitute the given data into the equation a solve. Add the correct unit to the answer.

EXAMPLE 6

An object starts from rest with an acceleration 5 m.s^{-2}. Find:

(a) the velocity and displacement after 10 s;

(b) the deceleration needed to bring the body to re in the next 5 s.

SOLUTION

(a) Data: $u = 0$ m.s^{-1}

$v = ?$ m.s^{-1}

$a = 5$ m.s^{-2}

$t = 10$ s

$s = ?$ m

$v = u + at$

$= 0 + (5 \times 10)$

$= 50$ m.s^{-1}

$s = ut + \frac{1}{2}at^2$

$= (0 \times 10) + (\frac{1}{2} \times 5 \times 10^2)$ m

$= 250$ m

(b) Data: $v = 0$ when brought to rest

$u = 50$ m.s^{-1}

$a = ?$ m.s^{-2}

$t = 5$ s

$v = u + at$

$0 = 50 + (a \times 5)$

$a = -10$ m.s^{-2}

The negative sign shows that the acceleration is in the opposite direction to the initial motion.

EXAMPLE 7

A body is projected vertically upwards with an initial velocity of 50 m.s^{-1}. Find:

(a) velocity after 2 s;

(b) maximum height it reaches;

(c) velocity with which it returns to Earth.

Note: The acceleration due to gravity always acts down and is of magnitude 9.8 m.s^{-2}.

SOLUTION

(a) Data: $u = 50$ m.s^{-1}

$v = ?$ m.s^{-1}

$t = 2$ s

$a = -9.8$ m.s^{-2}

$v = u + at$

$= 50 + (-9.8 \times 2)$ m.s^{-1}

$= 50 - 19.6$ m.s^{-1}

$= 30.4$ m.s^{-1}

(b) Data: $v = 0$ at maximum height

$a = -9.8$ m.s^{-2}

$u = 50$ m.s^{-1}

$s = ?$ m

$v^2 = u^2 + 2as$

$0 = 50^2 + (2 \times -9.8 \times s)$

$19.6s = 2500$

$s = 127.6$ m

(c) Data: $s = 0$ when returns to Earth

$u = 50$ m.s^{-1}

$v = ?$

$a = -9.8$ m.s^{-2}

$v^2 = u^2 + 2as$

$= 50^2 + (2 \times -9.8 \times 0)$ m.s^{-1}

$v = \pm 50$ m.s^{-1}

The only solution consistent with the data is $v = -50$ m.s^{-1}, since the direction of motion has to be opposite to the initial direction.

THE PATH OF A PROJECTILE

Figure 1.3 shows the path of a projectile thrown at an angle to the horizontal. The velocity at any point is simply the *vector sum* of the horizontal and vertical velocity components at that point. The horizontal component is constant; the vertical component changes at g, the acceleration due to gravity.

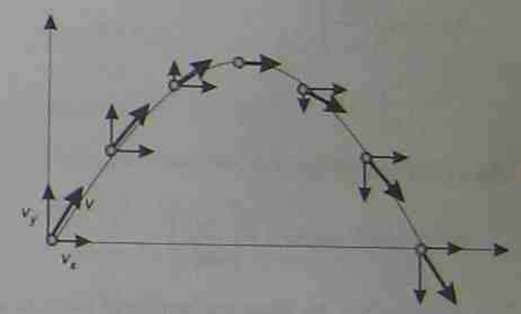


Figure 1. 3 The path of a projectile is simply the vector sum of its components

Trajectories

We are now in a position to be able to analyse projectile motion mathematically. Figure 1.4 represents a projectile thrown horizontally with speed v_x. Because of the independence of the vertical and horizontal components of the motion, *the vector sum of these motions describes the motion of the projectile*. Consequently:

1 *Horizontally*—constant velocity

that is, $\Delta x = u_x t$ (1)

2 *Vertically*—constant acceleration

that is, $\Delta y = \frac{1}{2} a_g t^2$ (2)

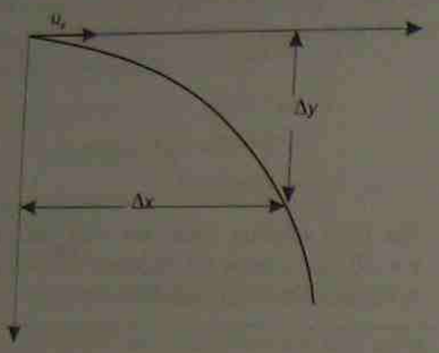


Figure 1.4 The trajectory of a projectile fired horizontally

From equation (1) we get:

$$t = \frac{\Delta x}{u_x} \quad (3)$$

Combining equation (2) and (3) we get:

$$\Delta y = \frac{1}{2} a_y \left(\frac{\Delta x}{u_x} \right)^2$$

$$= \frac{1}{2} \frac{a_g}{u_x^2} (\Delta x)^2$$

This can be written as:

$$\Delta y = k(\Delta x)^2 \text{ where } k = \left(\frac{a_g}{2u_x^2} \right)$$

This equation has the same mathematical form as a *parabola*. It follows therefore that:

> *The path followed by a projectile—its* **trajectory**—*is a parabola.*

Air resistance means that in real life this is not fully correct. We will continue, however, for simplicity, to neglect air resistance in our analysis[2].

[2] http://www.phy.ntnu.edu.tw/~hwang/projectile/projectile.html Projectile motion simulation

http://www.explorescience.com/activities/Activity_page.cfm?ActivityID=32 The classic 'shoot the monkey' simulation.

EXAMPLE 8

A search party travelling horizontally in a plane at 50 m.s^{-1} approaches a group of lost hikers. The purpose of the flight is to drop a supply of food in a specially designed package to the hikers with a parachute. If the plane cannot descend below a height of 100 m for safety reasons, what horizontal distance in front of the hikers must the pilot release the package to come as close as possible to the party?

SOLUTION:

The falling package is in effect a projectile. The distance that the package must be released in front of the hikers is determined by the horizontal speed of the package (and hence the plane), and the time it takes to drop the 100 m.

The latter is determined by considering the vertical motion of the package, that is:

$$\Delta y = u_y t + \frac{1}{2} a_g t^2$$

$$100 = 0 + \frac{1}{2} 9.8 t^2$$

ie. $t = 4.5$ s

Hence the distance in front of the hikers at which the package must be released is given by:

$$\Delta x = u_x t$$

$$= 50 \times 4.5 \text{ m}$$

$$= 225 \text{ m}$$

EXAMPLE 9

An object is projected at an angle of 30° to the horizontal at a velocity of 50 m.s^{-1}. Taking the acceleration due to gravity as 10 m.s^{-2}, calculate:

(a) the maximum height reached

(b) the range of the projectile.

SOLUTION:

(a) Rather than substitute into the maximum height and range formulae we will start from first principles, that is, because the horizontal and vertical motions are independent, we can consider the motion as two components at right angles to each other:

The vertical component of the velocity is given by:

$$u_y = u \sin\theta$$

$$= 50 \sin 30$$

$$= 25 \text{ m.s}^{-1}$$

At the top of its motion $v_y = 0$ and we also have:

$$u_y = 25 \text{ m.s}^{-1}$$

$$a_g = -10 \text{ m.s}^{-1}$$

$$\Delta y = ?$$

$$v_y^2 = u_y^2 + 2 a_g \Delta y$$

$$0 = 25^2 + (2 \text{ x } -10 \text{ x} \Delta y)$$

$$20 \Delta y = 625$$

$$\Delta y = 31.25 \text{ m}$$

(b) The time to reach the top is found from:

$$v_y = u_y + at$$

$$0 = 25 + -10t$$

$$t = 2.5 \text{ s}$$

The time of flight therefore = 5.0 s

The horizontal component of velocity (which with the time of flight determines the range) is given by:

$$u_x = u \cos\theta$$

$$= 50 \cos 30$$

$$= 43.3 \text{ m.s}^{-1}$$

The range is given by:

$$\Delta x = u_x t$$

$$= 43.3 \text{ x } 5 \text{ m}$$

$$= 216.5 \text{ m}$$

EXAMPLE 10

A rock is thrown horizontally out to sea from the top of a vertical cliff face with an initial velocity of 20 m.s^{-1} as shown in Figure 1.5. It is seen to reach the water after 3.0 s. Find:

(a) the height of the cliff

(b) the horizontal distance out from the cliff base that the stone hits

(c) the velocity just before it hits the water.

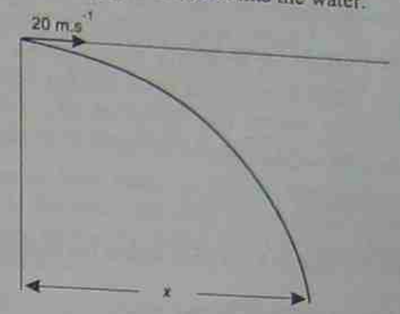


Figure 1.5

SOLUTION:

(a) Since the initial velocity is horizontal, the vertical component of velocity is zero. Our data is therefore:

$$u_y = 0$$

$$a_g = 9.8 \text{ m.s}^{-1}$$

$$t = 3 \text{ s}$$

$$\Delta y = ?$$

Using the equations of kinematics we have:

$$\Delta y = u_y t + \frac{1}{2} a_g t^2$$

$$= 0 + \frac{1}{2} \text{ x } 9.8 \text{ x } 3^2 \text{ m}$$

$$= 44.1 \text{ m}$$

(b) The distance out from the cliff face the rock hits is found from:

$$\Delta x = u_x t$$

$$= 20 \times 3 \text{ m}$$

$$= 60 \text{ m}$$

(c) The velocity just before the rock hits is *the vector sum of the horizontal and vertical velocities* at this time.

Horizontally:

$v_x = u_x = 20 \text{ m.s}^{-1}$ (since the horizontal velocity is constant).

Vertically:

$v_y = u_y + at$

$= 0 + 9.8 \times 3\ \text{m.s}^{-1}$

$= 29.4\ \text{m.s}^{-1}$

From Figure 1.6 we have:

$v = \sqrt{v_x^2 + v_y^2}$

$= \sqrt{20^2 + 29.4^2}\ \text{m.s}^{-1}$

$= 35.6\ \text{m.s}^{-1}$

Thus $\vec{v} = 35.6\ \text{m.s}^{-1}$ at 55.8° below the horizontal.

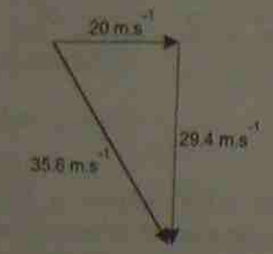


Figure 1. 6

EXAMPLE 11

A stone is projected out from the top of a high cliff. It leaves at 15 m.s^{-1} at 30° to the horizontal as shown in Figure 1.7. Find:

(a) the velocity of the stone after 2.0 s.

(b) the displacement of the stone at this time.

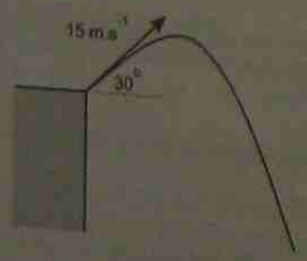


Figure 1. 7

SOLUTION:

Remember, *the motion of a projectile is simply the sum of its two components.*

(a) Horizontally—constant velocity

$u_x = u\cos\theta = 15\cos 30 = 13.0\ \text{m.s}^{-1}$

Vertically—constant acceleration (with up the positive direction)

$v_y = u_y + at$

$= v\sin\theta + at$

$= 15\sin 30 + (-9.8) \times 2$

$= -12.1\ \text{m.s}^{-1}$

This indicates the stone is travelling down after 2 From Figure 1.8 we have:

$v = \sqrt{v_x^2 + v_y^2}$

$= \sqrt{13.0^2 + (-12.1)^2}$

$= 17.8\ \text{m.s}^{-1}$

Also from Figure 1.8 we can see that:

$\tan\theta = \dfrac{12.1}{13.0}$

ie. $\theta = 43°$

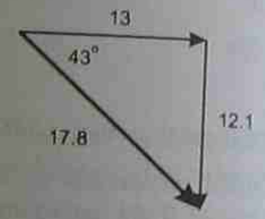


Figure 1. 8

That is, after 2.0 s the stone is travelling at 1 m.s^{-1} at 43° below the horizontal.

(b) Horizontally:

$\Delta x = u_x t = 15\cos 30 \times 2 = 26.0\ \text{m}$

Vertically:

$\Delta y = u_y t + \frac{1}{2} a_g t^2$

$= (15\sin 30 \times 2) + \frac{1}{2}(-9.8) \times 2^2$

$= -4.6\ \text{m}$

(This indicates that the stone is 4.6 m vertica below the point of projection after 2.0 s)

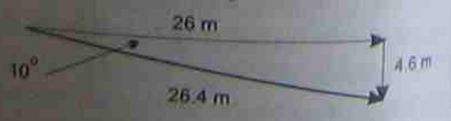


Figure 1. 9

From Figure 1.9 we have:

$s = \sqrt{x^2 + y^2}$

$= \sqrt{26^2 + (-4.6)^2}$

$= 26.4\ \text{m}$

Also, we have from Figure 1.9:

$\tan\theta = \dfrac{4.6}{26} \Rightarrow \theta = 10.0°$

The displacement after 2.0 s is 26.4 m at 10° below the horizontal.

GALILEO'S ANALYSIS OF PROJECTILE MOTION

Contrary to his predecessors, Galileo (1564–1642) emphasised the importance of mathematics in understanding natural phenomena and the need for experimentation.

In 1638 Galileo published the *Dialogues Concerning Two New Sciences*. In it he deduced the parabolic shape of the trajectory of a projectile, using a similar method to that we used on p.9. This made the analysis much easier since the properties of the parabola were known since the times of the ancient Greeks.

Prior to Galileo the general view of the day was that a projectile would follow a path like that represented in Figure 1.10.

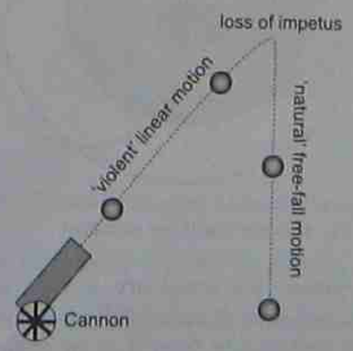


Figure 1. 10 Projectile motion as viewed in Galileo's day based on the ideas of Aristotle

This followed the views of Aristotle (~330 BC) whose teachings had been accepted without question for hundreds of years. Aristotle and his followers taught that a thrown object such as a spear would fall straight down when it left the thrower's hand except that its initial motion would create a vacuum and air rushing to fill this vacuum would provide an 'impetus' to push the spear forward. The spear's path would follow a straight line until it lost its impetus and fell to the ground in so-called 'natural' motion. The horizontal and vertical motions were thought to be sequential.

It seems hard today to believe that this is what people thought—one only has to throw a stone to another person to realize that the stone follows a curved path.

Contrary to Aristotle's view, Galileo reasoned that the motion of a projectile had two distinct motions: a vertical accelerated motion (where the displacement is proportional to the square of the travel time) and a constant velocity horizontal motion. *These motions occurred simultaneously.*

Using an inclined plane[3] Galileo was able to show the independence of these two motions and that they combined to produce a parabolic path for a projectile.

ESCAPE VELOCITY

If an object is projected upward with a large enough velocity it can escape the gravitational pull of the Earth (or other planet) and go into space. The necessary velocity to leave the Earth (or other planet) is called the **escape velocity**.

What factors determine this velocity?

Extension

Suppose an object of mass m is projected vertically upward from the Earth's surface (mass of M_E and radius R_E) with an initial velocity u. The initial

[3] In Galileo's day there were not the accurate timing devices that are available to us. By rolling balls down inclined planes Galileo was able to 'dilute' the motion enabling reasonably accurate time measurements to be taken. In this way he was able to show that for a uniformly accelerated object the distance was proportional to the travel time squared.

mechanical energy, that is, kinetic and potential energy (see p.5) is given by:

$$E_{k_1} + E_{p_1} = \tfrac{1}{2}mu^2 - G\frac{M_E m}{R_E}$$

Let us assume that the initial speed is just enough so that the object reaches infinity with zero velocity. The value of the initial velocity for which this occurs is the escape velocity v_e.

When the object is at infinity the mechanical energy is zero (the kinetic energy is zero since the velocity is zero and the potential energy is zero because this is where we selected the zero of potential energy).

Hence $\tfrac{1}{2}mv_e^2 - G\frac{M_E m}{R_E} = 0$ which leads to:

$$v_e = \sqrt{\frac{2GM_E}{R_E}}$$

It can be seen from the equation above that the escape velocity depends on the gravitational constant, the mass and the radius of the planet.

By substituting into the equation it is found that the escape velocity from the Earth is ~11.2 km.s^{-1}. Since the mass of the object is not in the equation it follows that the escape velocity is the same for all objects (be they gas molecules or spacecraft)!

Table 1.3 shows the escape velocities for the planets and the Moon.

Table 1. 3 Escape velocities for the planets and the Moon

Planet	v_e (km.s^{-1})
Mercury	4.3
Venus	10.3
Earth	11.2
(Moon)	2.3
Mars	5.0
Jupiter	60
Saturn	36
Uranus	22
Neptune	24
Pluto	1.1

The lower the escape velocity the less likely it is that the planet has an atmosphere. Mercury for example would have lost its atmosphere over time as its escape velocity is relatively low and gas molecules would have speeds exceeding this value.

NEWTON AND ESCAPE VELOCITY

Isaac Newton in his *Principia Mathematica* first proposed the idea of artificial satellites of the Earth. Figure 1.11 is an adaptation of a diagram from his book[4]. He considered how a projectile could be launched horizontally from the top of a high mountain so that it would not fall to Earth.

As the launch velocity was increased, the distance that the object would travel before hitting the Earth would increase (*A* and *B*) until such a time that the velocity would be sufficient to put the object into orbit around the Earth (*C*). At this speed the curvature of the Earth exactly matches the curvature of the projectile.

A higher velocity would lead to the object escaping from the Earth.

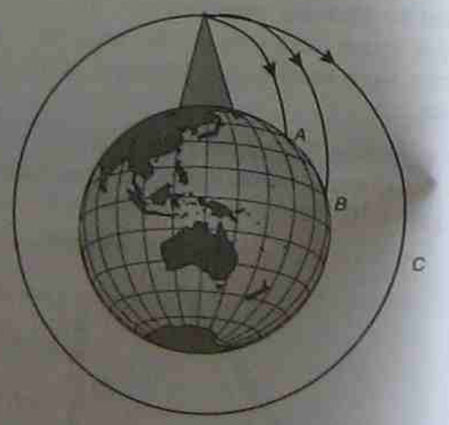


Figure 1. 11 Newton's artificial satellites

Newton placed his imaginary cannon on a high mountain and fired it horizontally because he knew that if he had simply fired it at an angle from the Earth's surface it would *always* crash back to Earth.

[4] http://www.phys.virginia.edu/classes/109N/more_stuff/Applets/newt/newtmtn.html Applet simulating Newton's cannon for projectile motion.

It would attempt to follow an ellipse, but the focus of that ellipse would lie within the Earth and so the cannonball would return and crash!

To understand how objects such as satellites can go into circular orbits, we must first look at the forces involved in circular motion.

CIRCULAR MOTION

Circular motion is a very a common two-dimensional motion. It is exhibited by various diverse systems including the moon revolving around the Earth (to a good approximation), wheels on moving cars and bicycles, particles in centrifuges, charged particles in cyclotrons (particle accelerators), cars travelling around corners...

To simplify this study we will concentrate on *uniform circular motion*.

The motion of an object in a circular path with constant speed is called **uniform circular motion.**

Although the speed remains the same in uniform circular motion, it follows that an object travelling in a circular path must be *accelerating*, since the velocity (that is, the speed in a given *direction*) is continually changing. This is indicated by Figure 1.12 where $\vec{v}_1 \neq \vec{v}_2$ even though $v_1 = v_2$.

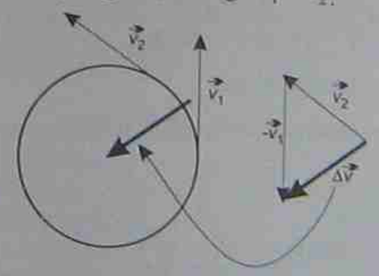


Figure 1. 12 Circular motion and centripetal acceleration

The change in velocity is given by $\Delta\vec{v} = \vec{v}_2 - \vec{v}_1$ and since $\vec{a} = \frac{\Delta\vec{v}}{\Delta t}$ it follows that the object is accelerating.

Centripetal Acceleration

As can be seen from Figure 1.12, when the change in velocity $\Delta\vec{v}$ is placed in the average position between $\vec{v}_1$ and $\vec{v}_2$, it is directed towards the *centre* of the circle. Thus, this is the direction of the *centripetal* (centre-seeking) acceleration.

When an object is moving with uniform circular motion, the acceleration (the **centripetal acceleration***) is directed towards the centre of the circle.*

For an object moving in a circle of radius r with an *orbital velocity* of v, the centripetal acceleration a_c is given by:

$$a_c = \frac{v^2}{r}$$

Centripetal Force

From Newton's Second Law, $F = ma$, it follows that an object travelling in a circular path experiences a force. This force—the *centripetal force*—acts towards the centre of the circle.

For an object of mass m moving in a circle of radius r with an *orbital velocity* of v, the centripetal force F_c is given by:

$$F_c = \frac{mv^2}{r}$$

Table 1.4 illustrates some examples of circular motion and the source of the centripetal force.

Table 1. 4 Centripetal forces

Example of Centripetal force	Source of Centripetal force
Mass attached to a string and whirled in a horizontal circle	Tension in the string
Car travelling around a corner	Friction between the tyres and the road
Rider at bottom of curve on roller coaster	Reaction force of seat upwards on rider
Earth orbiting the Sun	Gravitational force between Earth and Sun
Satellite orbiting the Earth	Gravitational force between Earth and satellite

It is important to note that a centripetal force does not arise as a result of circular motion—circular motion is only possible if a centripetal force is present.

EXAMPLE 12

A car is travelling at constant speed around a circular track. The centre of mass of the car moves in a radius of 50 m. If the car's mass is 1500 kg and its speed is 30 $m.s^{-1}$ calculate the resultant force acting on the car.

SOLUTION

$$F=\frac{mv^2}{r}=\frac{1500\times30^2}{50}=2.7\times10^4\ \text{N}$$

EXAMPLE 13

A car of mass 1500 kg goes over the crest of a hill, the surface of which is the arc of a vertical circle of radius 30 m. What is the maximum speed at which the car may travel and still be in contact with the road?

SOLUTION

If the car just maintains contact with the road then only the weight of the car provides the necessary centripetal force, that is:

$mg=\frac{mv^2}{r}$, therefore

$$v=\sqrt{gr}=\sqrt{9.8\times30}=17.1\ \text{m.s}^{-1}$$

EARTH ORBITS

A satellite can be put into Earth orbit by lifting it to a sufficient height (with rockets) and then giving it the required horizontal velocity so that it does not fall back to Earth (as predicted by Newton, p.14).

For the satellite to circle the Earth, the centripetal force required is provided by the gravitational attraction between the satellite and the Earth, that is:

$$F_c=\frac{mv^2}{r}=G\frac{mM_E}{r^2}$$

Hence the orbital speed is given by:

$$v=\sqrt{\frac{GM_E}{r}}$$

This equation shows that the orbital speed of satellite depends on the radius of the orbit and mass of the planet it is revolving about, but independent of the mass of the satellite.

The speed is inversely proportional to the square root of the radius. The smaller the radius, the fast the satellite must travel to stay in orbit at that radius.

EXAMPLE 14

The Russian space station *Mir* was destroyed March 2001 when it burnt up in the Earth atmosphere following a controlled de-orbit. Prior that it moved in a circular orbit of altitude 390 k for almost 15 years.

(a) Determine the orbital velocity required to ha kept *Mir* in a circular orbit at that altitude.

(b) Calculate the centripetal force required if M had a mass of 133 tonnes.

SOLUTION

(a) $$v=\sqrt{\frac{GM_E}{r}}$$

$$=\sqrt{\frac{6.67\times10^{-11}\times5.983\times10^{24}}{(6380+390)\times10^3}}\ \text{m.s}^{-1}$$

$$=7.678\times10^3\ \text{m.s}^{-1}$$

(b) The centripetal force is found from:

$$F_c=\frac{mv^2}{r}$$

$$=\frac{133000\times(7.678\times10^3)^2}{(6380+390)\times10^3}$$

$$=1.16\times10^6\ \text{N}$$

Orbital Speed and Period

The period (T) of an object in circular motion is t time for one complete revolution. In one revolut the object moves a distance equal to t circumference of a circle of radius r hence $v=\frac{2\pi r}{T}$

EXAMPLE 15

What was the period of the *Mir* space station in Example 14?

SOLUTION

$$v=\frac{2\pi r}{T}\Rightarrow T=\frac{2\pi r}{v}$$

$$T=\frac{2\pi\times(6380+390)\times10^3}{7.678\times10^3}\ \text{s}$$

$$=92.3\ \text{min}$$

It can be shown that a 'craft' in a low circular orbit of 150 km altitude requires a speed of 7.82×10^3 $m.s^{-1}$ to maintain an orbit (Figure 1.13(a)). For speeds less than this the craft will fall back to Earth (following an elliptical orbit).

For speeds greater than this, the craft will move away from the Earth (Figure 1.13(b)) slowing down as it does until it eventually returns in an elliptical orbit. The greater the speed, the larger is the ellipse (Figure 1.13(c)).

If the speed is greater than or equal to the escape velocity, the craft will not return—the ellipse is infinite in size (Figure 1.13(d)).

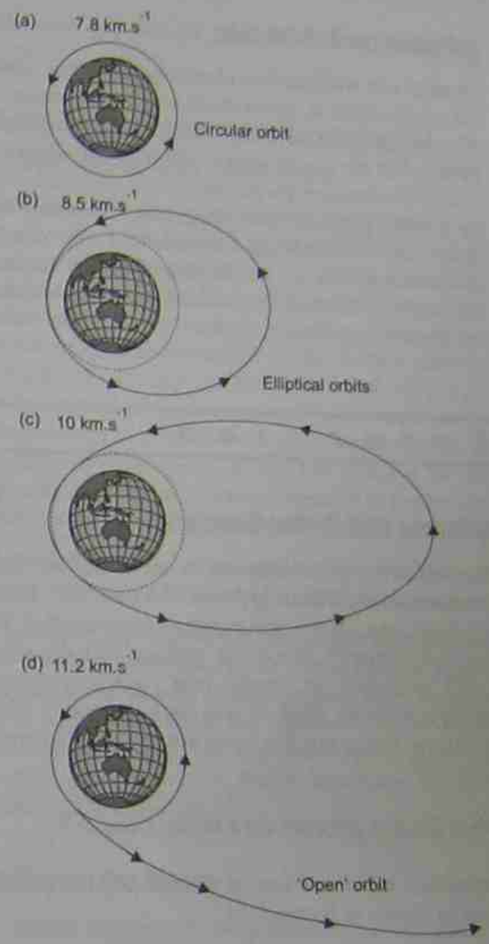


Figure 1. 13 Earth orbits

ACCELERATION AND THE HUMAN BODY

The human body is relatively unaffected by high speeds. For example, we experience no sensation of speed when travelling at a few hundred kilometres per hour in a jet airliner. Changes in speed, however, that is, accelerations, can and do affect the human body creating *'acceleration stress'*.

g-forces

Acceleration forces—*g*-forces—*are measured in units of gravitational acceleration g. For example, a force of 5g is equivalent to acceleration five times the acceleration due to gravity.*

If the accelerations are along the body's long axis (for example, the person is standing up and is accelerating vertically) then two distinct effects are possible.

1 If the acceleration is in the direction of the person's head they may experience a 'black out' as the blood rushes to their feet; or

2 If the acceleration is towards their feet, they make experience a 'red out' where the blood rushes to their head and retina (creating the red sensation in their eyes).

g-forces on Astronauts

Humans can withstand accelerations up to four times the normal (that is, 4g) without any undue concern[5]. Accelerations up to ~10g are tolerable for short times *when the acceleration is directed parallel to a line drawn between the person's front and back*, that is, at right angles to their long axis. These are the types of accelerations experienced by early astronauts at take-off and landing. For this reason, they reclined in specially moulded seats which direct the accelerations to their back.

Extension

g-forces and Roller Coasters[6]

Anyone who has ridden on a roller coaster has experienced significant *g-forces*. As you 'fall' from a height, you experience *negative g-forces* (that is, you feel 'lighter'). When you 'pull out' of a dip after a hill or follow an 'inside loop', you experience *positive g-forces* (that is, you feel 'heavier'). The positive *g-forces* are like those astronauts experience at lift-off.

What Causes g-forces on a Roller Coaster?

Consider a rider in a 'car' at the bottom of an inside loop as shown in Figure 1.14.

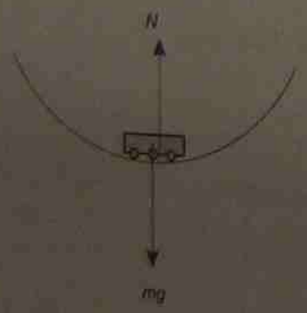


Figure 1.14 Forces on a rider on an 'inside loop'

The rider has two forces acting on them:

1 their normal weight (mg) acting down; and
2 the 'normal reaction force' (N) acting up. This is the push of the seat upwards on their bottom (which, by Newton's Third Law, is equal to the push of the rider on the seat).

Assume that the loop is part of a circle of radius R. As discussed earlier, a *centripetal force* is required for the rider to travel in a circle. This is the difference between the normal force and the weight force, that is:

$$N - mg = \frac{mv^2}{R}$$

$$N = mg + \frac{mv^2}{R}$$

The *g-forces* are found from the 'normal force' divided by the weight. That is:

$$g \text{ felt by rider} = \frac{N}{mg}$$

$$= \frac{mg + \frac{mv^2}{R}}{mg}$$

$$= 1 + \frac{v^2}{gR}$$

It follows that the higher the speed v and the 'tighter' the loop (that is, the smaller the radius), the greater will be the *g-forces*.

Most roller coasters keep the g-forces at less than 5g.

The *Space Shuttle*[7]

The *Space Shuttle* has engines whose thrust can be varied. They are 'throttled back' during the later stages of ascent so that forces do not exceed 3g (that is, accelerations of 3g). This is only about a third of the accelerations of earlier rockets and allows non-flight specialists to venture into space.

Accelerations >10g are generally fatal (especially for any length of time). This determines the maximum

[5] http://www.hq.nasa.gov/office/pao/History/afspbio/pan5-4.htm History of study into g-forces by NASA.

[6] http://www.kent.wednet.edu/staff/trobinso/physicspages/PhysOfg/Roller-Taylor/rollercoasters.htm and the physics of roller coasters

[7] http://www.seds.org/ssa/docs/Space.Shuttle/index.shtml On the 'map' of the Space Shuttle and it tells you about that component.

http://spaceflight.nasa.gov/shuttle/reference/ More good information on the Shuttle.

decelerations that astronauts can safely withstand on re-entry (see p.23).

LAUNCHING A ROCKET

Imagine the *Space Shuttle* sitting on the launch pad and facing skywards. The shuttle consists of three main components:

1 The winged *orbiter* that carries the crew and cargo;
2 An *external tank* containing fuel (liquid hydrogen) and an oxidiser (liquid oxygen) to power the orbiter's three main engines; and
3 Two large solid propellant *booster rockets* (fuelled with a mixture of aluminium powder, ammonium perchlorate powder and iron oxide catalyst bonded together with a polymer binder).

At lift off, the entire system has a mass of approximately 2.0×10^6 kg and the engines provide 31×10^6 N (31 MN) of thrust.

Momentum Conservation

The rocket engines generate thrust by burning fuel and expelling the resulting gases. Conservation of momentum means that as the gases move one way, the rocket moves the other. (Momentum before the burning is zero; hence momentum after is also zero. The gases carry momentum in one direction—'down'—and so the rocket carries an equal momentum in the opposite direction—'up'.)

As the fuel is consumed and the gases expelled, the mass of the system decreases. Since the acceleration is proportional to the thrust and inversely proportional to the mass (Newton's Second Law), as the mass decreases, the acceleration increases. Hence the forces on the astronauts increase.

After ~2 minutes the boosters are jettisoned (and are parachuted back to Earth for retrieval and reuse). When the propellants in the external tank are fully used, the tank is released and burns up in the Earth's atmosphere. By this time, the orbiter has reached approximately 99% of the speed required to place it in Earth orbit. Small rockets on the orbiter provide the additional thrust necessary to push the orbiter to the speed required to place it in orbit around the Earth.

Using the Earth's Rotation to Place the Space Shuttle into Earth Orbit

Launching the shuttle vertically and then tilting the trajectory so that the path is parallel to the Earth's surface when the correct orbital speed is reached, allows the shuttle to achieve Earth orbit. The tilting takes place in the easterly direction. This allows scientists to take advantage of the Earth's easterly velocity of ~464 $m.s^{-1}$ at the equator and ~410 $m.s^{-1}$ at the latitude of Cape Canaveral.[8] (This is similar to the situation in cricket where a fast bowler bowls to a batsman—the speed of the ball relative to the ground is the speed of the ball relative to the bowler *plus* the speed of the bowler relative to the ground.)

A westerly trajectory could be used but an additional ~600 $m.s^{-1}$ would be required from the spacecraft.

The higher the latitude the less contribution is made by the Earth's rotation. Hence launch sites are placed as near to the equator as practicable. Cape Canaveral is at latitude 28° north; the Russian sites are above latitude 50° north; the European Space Agencies launch site at Kourou in South America is the most ideally sited at latitude 5°.

A Trip to the Moon

Consider Figure 1.15. To send a craft to the moon it is first put into a low circular Earth orbit (as just discussed, Figure 1.15(a)). Then, from a point on the opposite side to where it is planned to rendezvous with the moon, rockets are fired to put it into an elliptical orbit (Figure 1.15(b)). This *'injects'* the craft into the moon's orbit (Figure 1.15(c)).

The trajectory is designed so that the craft and the moon reach the same point in space at the same time. Rockets are then fired to put the craft into orbit around the moon or to land on it.

[8] The horizontal component of the Earth's rotation is found from $v_{horizontal} = 464 \cos(\text{latitude})$

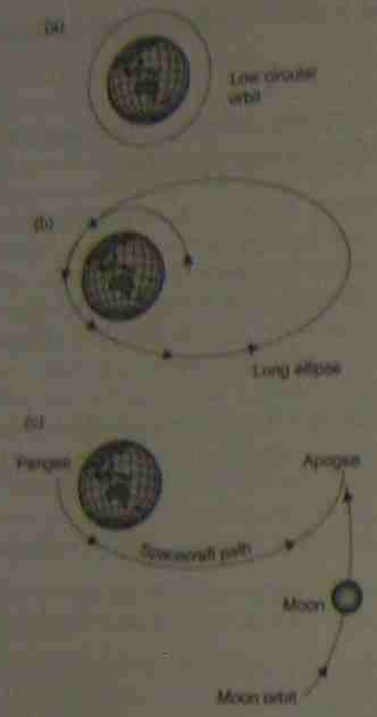


Figure 1.15 A trip to the moon

Extension

A Trip To The Planets (Interplanetary Spacecraft)

A similar process to that for the moon is used to send spacecraft to other planets (for example, Mars and Jupiter) except now we consider motion around the Sun.

Consider Figure 1.16. The Earth revolves around the Sun at a speed of ~30 km.s^{-1} as shown in Figure 1.16(a). If the speed of the craft is greater than the Earth's escape velocity, the craft will escape the Earth's pull. This can be relatively easily achieved by launching the craft in the direction of the Earth's motion (Figure 1.16(b)).

The craft will go into orbit *around the Sun* (just like any planet) so that Kepler's Law of Periods holds[9], that is, $\frac{r^3}{T^2}=\frac{GM}{4\pi^2}$ where T is in years and r is in astronomical units. By choosing the correct speed it is possible to arrange for the craft to intercept the planet as in Figure 1.16(c).

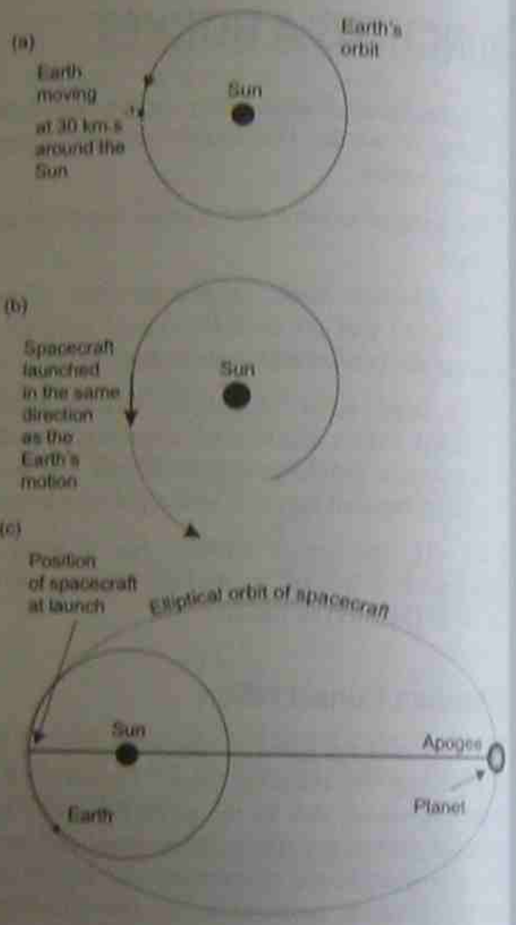


Figure 1.16 Interplanetary travel

It should be obvious that a space probe cannot be sent up at just any old time. To minimise the required velocity and travel time it is imperative that the Earth, Sun and planet (for example, Mars) be in the correct positions[10]. For Mars, this only happens every 780 days (~2 years). Hence Mar's probes can only be, at best, every two years and then there is only a small period of time in which launch will be successful. This is the *launch window*.

[9] http://jersey.uoregon.edu/kepler/kepler.html Java applet to simulate Kepler's Third Law

[10] Orbits requiring minimum energy expenditure were first calculated in 1925 and are known as *Hohmann Transfer Orbits*. While energy requirements are minimised, the time requirements are not. In most cases a compromise trajectory is used.

To probe the inner planets (Mercury and Venus), the craft is fired in the opposite direction to the Earth's orbit around the Sun. This ensures that the craft will have an orbital velocity around the Sun of <30 km.s^{-1} and consequently cannot maintain the Earth orbit. As a result, the craft falls closer to the Sun, traversing an elliptical path.

LOW EARTH ORBITS

As we discussed previously (p.15), a satellite can be put into Earth orbit. The required orbital velocity depends on the radius of the orbit (and hence on the altitude above the Earth) as indicated in Table 1.5.

Table 1.5 Altitude versus orbital velocity

Altitude (km)	Orbital velocity (km.h^{-1})
200	29,000
1730	25,400
35,800	11,300

Satellites in low altitude orbits (altitudes ranging from ~300 km to ~800 km) are 'hidden' for part of their orbit round the Earth.

It is possible, however, to put a satellite in an orbit so that it is visible at all times from a point on the Earth. These are *geostationary* orbits.

GEOSTATIONARY (GEOSYNCHRONOUS) ORBIT

A **geosynchronous orbit** *is one in which the satellite has a period of 24 hours. If the orbit is in the equatorial plane, the satellite appears to stay above the same point on the Earth—such an orbit is said to be* **geostationary**.

Such geostationary orbits are essential to modern communications. By placing a satellite in a geostationary orbit, signals can be bounced off it to receiving stations in different parts of the world (see Figure 1.17).

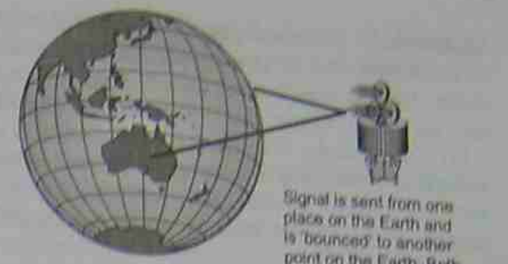


Figure 1.17 Communication with a geostationary satellite

EXAMPLE 16

At what altitude must a satellite be placed to be in a geostationary orbit?

SOLUTION

From the mathematical form of Kepler's Third Law we have:

$$\frac{r^3}{T^2}=\frac{GM}{4\pi^2}$$

$$r^3=\frac{GMT^2}{4\pi^2}$$

$$=\frac{6.67\times10^{-11}\times5.983\times10^{24}\times(24\times60\times60)}{4\pi^2}$$

$$=7.546\times10^{22}\text{ m}$$

$$r=4.23\times10^7\text{ m}=42\,300\text{ km}$$

Hence the altitude (that is, the distance above the Earth's surface) = 42,300 – 6,380 = 35,800 km

Comparing Low-Earth Orbits with Geostationary Orbits

As we have seen, geostationary orbits are essential to modern communication systems. There are, however, other uses of satellites that require that they be placed in low-earth orbit. Among these are the uses of satellites in spying missions by the military, surveying weather conditions, mapping ecological threats…

Geostationary satellites are placed in orbit ~35,800 km above the equator and have a period of 24 hours. Satellites placed in low-Earth orbit have a period less than 24 hours. If the orbit is *polar*, that is, the

satellite orbits in a plane perpendicular to the plane of the equator and so passes over the poles of the Earth, then the orbit's orientation is fixed in space and the Earth rotates under the satellite (Figure 1.18). For example, if the period of a satellite is 6 hours then in one polar revolution its orbit will rotate 90° to the west, as the Earth rotates under the satellite. In a couple of days the whole Earth could be mapped.



Figure 1.18 Polar orbits

ORBITAL DECAY

Low altitude orbiting objects such as satellites and discarded 'space junk' re-enter the Earth's atmosphere and generally burn up. The reason they re-enter is that although the atmosphere is very thin, nevertheless friction results in a loss of energy as heat, which causes it to move closer to the Earth where the atmosphere is thicker which causes more energy loss which … In 1979 the American space station *Skylab* crashed to Earth (with debris landing in the Indian Ocean and in Western Australia). It did so as a result of atmospheric drag that was exacerbated by sunspot activity.

Compared to low-Earth orbit satellites, geostationary satellites (see p.21) are so far above the Earth's atmosphere that frictional forces are negligible.

SAFE RE-ENTRY

Re-entry *is the return of a spacecraft into the Earth's atmosphere and subsequent descent to Earth.*

There are significant technical difficulties involved in safe re-entry, the most important being:

1 the heat generated as the spacecraft contacts the Earth's atmosphere; and

2 keeping the retarding-forces (*g*-forces) within safe limits for humans.

Heating Effects

The Earth's atmosphere provides *aerodynamic drag* on the spacecraft and as a result high temperatures are generated by friction with air molecules.

In early space exploration, including the *Mercury*, *Gemini* and *Apollo* missions, the blunt end of the nose cone was oriented to enter the atmosphere first (see Figure 1.19). This followed the realisation that when a blunt end hits the atmosphere it sets up a shock wave that carries away much of the heat. In addition, this end was covered with a *heat shield* made of *ablative* material that would burn up (and in this way prevent the spacecraft overheating).

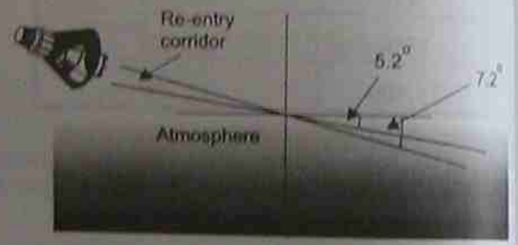


Figure 1.19 Spacecraft re-entry into the Earth's atmosphere

The *Space Shuttle*, on the other hand, uses four types of material to limit the orbiter's temperature to about 200° C.

1 Reinforced carbon-carbon composite to protect the nose cone and leading edges of the wings where the temperature exceeds 1300°C.

2 20 000 reusable low-density silica tiles, mainly on the lower shuttle surfaces where the temperature approaches 750°C.

3 7000 reusable low temperature tiles on the upper wing and sides of the fuselage where temperatures range from 400°C to 700°C.

4 A flexible reusable surface insulation applied directly to the payload bay doors, the fuselage sides and upper wing areas where the temperature does not exceed 400°C.

The shuttle also enters the atmosphere with its 'nose up' ensuring that the flat underbelly is presented to the air setting up a shock wave as for the nose cones of earlier missions.

g-forces

The angle of re-entry is critical: too shallow and the spacecraft will bounce off the atmosphere back into space; too steep and the *g*-forces will be too great for the crew to survive (and the temperatures generated with the atmosphere will be too high even for the refracting materials used).

The 'allowed' angle of re-entry for the *Mercury*, *Gemini* and *Apollo* missions was $-6.2° \pm 1°$ relative to the Earth's horizon. It can be shown that for angles of re-entry $<5.2°$ the craft will 'skip' back into space and for angles $>7.2°$ the *g*-forces will be too large.

It's a credit to space explorers and the teams on the ground that they can guide the craft into such a small *'re-entry window'*.

Deorbiting the Shuttle

The *Space Shuttle* is safely brought back to Earth with its occupants experiencing forces no greater that 3*W* as follows. First the shuttle is reoriented; the engines are fired in the direction of the orbiter's motion to slow it down. A second 'burn' points the nose forward and sets the nose with an attitude (angle) of $-40°$ to the atmosphere (see earlier). Approximately 30 minutes after the initial burn the shuttle reaches an altitude where the heating effects are significant, reaching a maximum –20 minutes before landing. Four S-turn manoeuvres during the last 16 minutes before landing slow the shuttle down further (just like a skier). By now the atmosphere is dense enough to provide lift to the wings.

Seventeen seconds prior to landing the shuttle's glide path angle is changed from its current 22° to 1.5°. The landing gear is lowered 14 seconds before touchdown and the shuttle is brought in to land. A small parachute assists in bringing it to rest.

Ionisation Blackout

The high temperatures generated by re-entry result in ionisation of the atoms of the air. This prevents communication between the spacecraft and the ground. In the early *Apollo* flights this lasted for ~3 minutes; for the shuttle it lasts ~16 minutes.

Columbia Disaster

On 1 February 2003 the Space Shuttle *Columbia*, with seven astronauts aboard, disintegrated over Texas as it returned from a mission. At the time of writing (April 2003) the cause of the disaster was believed to be a long narrow slit on Columbia's left wing that may have let in scorching heat from the re-entry.

This gap may have been caused by a missing or broken seal on the leading edge of the wing believed to be where a piece of foam insulation hit during lift off some days earlier.

This tragedy illustrates both the technological advances made in sending people into orbit and the dangers inherent in such a mission.

Secondary Source Investigation

Rocketry[11]

Space exploration and travel relies on rockets to put the spacecraft into space.

Rocketry had its beginnings as far back as the thirteenth century when Chinese armies were reported to have used rockets in warfare. From China they spread to Europe and most of Asia. The use of rockets for fireworks remained however their prime use, although by the early 1800s rockets were being used to carry explosives in war. British troops used rockets against the United States in the War of 1812.

The modern study of rocketry had a number of important contributors, among these being Tsiolkovsky, Esnault-Pelterie, Goddard, Oberth and O'Neill. The German Wernher von Braun (later to take American citizenship) also made significant contributions to the development of sophisticated rockets.

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[11] http://spaceline.org/rockethistory.html History of rocketry site. http://www.ssi.org/body_obit.html for the life of Gerard O'Neill.

Konstantin Tsiolkovsky (1857—1935)

Modern rocketry theory began in 1903 when a Russian schoolteacher, Konstantin Tsiolkovsky published a scientific paper—*Investigations of Space by Means of Rockets*—which set out for the first time the correct theory of rocket power. Tsiolkovsky also was the first person to suggest the concepts of multi-stage rockets and liquid fuels and he developed wind tunnels to study aerodynamics. From the latter he developed advance designs for aeroplanes and for an all-metal *dirigible*.

Back in 1896 he commenced his work titled *Exploration of Cosmic Space by Means of Reactive Devices* which dealt with the problems of using rockets in space, the heating effects of air friction and fuel supply maintenance.

Tsiolkovsky also made important theoretical contributions to the explanation of the stratosphere and interplanetary flight.

Robert Esnault-Pelterie (1881—1957)

Frenchman, best known as an aviator pioneer (in 1907 he built the first all-metal monoplane), and for his interest in space exploration. The latter occupied his time from 1912—1930.

In 1912 he presented a paper (*Considerations of the Results of an Unlimited Lightening of Motors)* to the French Physics Society in which he gave one of the first scientific discussions of the inherent problems of space travel. He even speculated that nuclear energy would be needed for space travel.

In 1927 he gave a lecture to the French Astronomical Society subsequently published as *Rocket Explosion of the Very High Atmosphere and the Possibility of Interplanetary Travel.*

In 1930 he published his book *Astronautics* introducing that word to our vocabulary. In it he discussed the possibility of space travel and his work on high-altitude rocket flight including calculations of trajectories to the planets. A further edition in 1934 gave considerably more attention to space travel. By this time he had been convinced by the work of others that nuclear energy was not necessary; that chemical energy would suffice for trips to the moon. (In October 1931 Esnault-Pelterie lost 4 fingers in an accident using a rocket fuel mixture of liquid oxygen and tetranitromethane!)

Robert H. Goddard (1882—1945)

The American pioneer rocket scientist Robe Goddard (acknowledged as the 'father' of m rocketry), was the first person to prove that r would work in a vacuum and did not require a push against' to provide propulsion.

In 1919 he published a treatise on *A Meth Reaching Extreme Altitudes* in which he propo rocket that could reach the moon. Goddard anal the energy yield and thrust per unit mass of va fuels (including liquid fuels) and developed a r motor that could use the liquid fuels petrol liquid oxygen.

Then in 1926, Goddard successfully launched first liquid-propellant rocket (all previous roc had used solid fuels). This reached an altitud 57 m and a speed of 97 km.h^{-1}. In 1929 he sen the first instrument-carrying rocket. Godd accumulated over 200 patents relating to rocket his career.

Largely unrecognised in his own lifetime, Godda work was utilised by German scientists in development of their wartime rockets.

Hermann Oberth (1894—1989)

The Austrian Hermann Oberth in 1923 publishe book titled *The Rocket into Interplanetary Space* which he set out for the first time a mathemat description of the conditions required for a rocke reach escape velocity. (This book was supplemented 1925 by one titled *The Possibility of Reach Celestial Bodies* in which Walter Hohmann provi the first detailed calculations of interplanetary orbits

Oberth also simulated weightlessness and in 1929 book *Ways to Spaceflight* predicted the development electric propulsion and the ion motor.

Gerard O'Neill (1927—1992)

The American physicist Gerard O'Neill ma significant contributions to physics including hig energy particle physics and space exploration. In t former he invented the *colliding beam storage ri* allowing investigations of subatomic particles (s Option Topic *Quanta to Quarks)*. In the latter he responsible for advocating the colonisation of space

An enthusiastic university lecturer, in the late 6 (around the time of the *Apollo* missions) he ask his class to write a paper on human habitation

space. He was so taken by the enthusiasm of their responses that he wrote his own paper in 1974 on *The Colonisation of Space.*

In 1978 he published *The High Frontier* in which he suggested that space colonies might be the answer to many of the Earth's problems: overpopulation, pollution, the need for environmentally 'clean' energy … He designed a space colony placed in a kilometre-long cylinder positioned between the Earth and the moon.

In 1978 a working model of a *mass driver* was built. This device, invented by O'Neill, was to be used for cheap and efficient transfer of materials such as mineral ores from the low-gravity moon or an asteroid into orbit. This was done using electro-magnetic drive coils to provide the necessary force.

Wernher von Braun (1912—1977)

The Second World War provided the impetus to rapidly advance rocket science. The Germans under the leadership of Wernher von Braun developed the V-2 guided missile that rained death and destruction on London in the last months of the war. Victorious American forces captured many of these rockets and sent them back to America. In addition, almost the entire German rocket development team went to America at the war's end to continue their work. (Some German rocket scientists even 'found their way' to the Soviet Union.)

Within months of their arrival in America, von Braun's team were assembling, testing and supervising V-2 rocket launches for high altitude research. von Braun became an American citizen in 1955 and in 1958 headed the team that put America's first satellite, *Explorer I*, into space, some three months after the Soviets had put *Sputnik I* into space. von Braun continued to lead rocket development in America culminating in the *Saturn* series of rockets. The *Saturn V* rocket carried the first men to the Moon in 1969.

von Braun is also responsible for the idea of the space station and the space shuttle.

SECTION 3: THE SOLAR SYSTEM

BIG IDEA:

The Solar System is held together by gravity.

OUTCOMES:

Students learn to:

1 Define Newton's Law of Universal Gravitation $F = G\frac{m_1 m_2}{d^2}$

2 Describe a gravitational field in the region surrounding a massive object in terms of its effects on other masses in it.

3 Discuss the importance of Newton's Law of Universal Gravitation in understanding and calculating the motion of satellites.

4 Identify that a 'slingshot' effect is provided by planets for space probes.

Students:

1 *Present information and use available evidence to discuss the factors affecting the strength of the gravitational force.*

2 *Solve problems and analyse information using* $F = G\frac{m_1 m_2}{d^2}$

Physics Stage 6 Syllabus Outcomes © Board of Studies NSW, 1999 (Amended 2000, 2001, 2002, 2003)

NEWTON'S LAW OF UNIVERSAL GRAVITATION

As mentioned earlier (see p 1), Newton proposed that any two objects in the universe attract each other with a force given by $F = G\frac{m_1 m_2}{d^2}$. Here F is the force, G is a constant called the '*universal gravitational constant*', m_1 and m_2 are the masses of the two objects and d is the separation of between the centres of the two objects.

Cavendish's Experiment

In 1798 Henry Cavendish first succeeded in determining the value of G. Its current accepted value is 6.67×10^{-11} N.m^2.kg^{-2}.

EXAMPLE 3

Two objects of mass 1 kg and 2 kg respectively are separated by 0.5 m in air. What force acts between the two masses?

SOLUTION

$$F = G\frac{m_1 m_2}{d^2}$$

$$= \frac{6.67 \times 10^{-11} \times 1 \times 2}{0.5^2}\ \text{N}$$

$$= 5.34 \times 10^{-10}\ \text{N}$$

EXAMPLE 4

Two objects of mass m_1 and m_2 respectively are separated by a distance d. They exert a force F on each other. If the masses are halved and the distance tripled, what is the size of the new force?

SOLUTION

$$F = G\frac{m_1 m_2}{d^2}$$

$$F' = G\frac{\frac{1}{2}m_1 \frac{1}{2}m_2}{(3d)^2} = \frac{F}{36}$$

that is, the new force is $\frac{1}{36}$ of the original force.

Gravitational Field

In Chapter Two, *Electricity in the Home*, we were introduced to the concept of a *field* as a way of explaining so called '*action at a distance*', where two (or more) separated objects exert forces on each other without direct contact between them. Just as we use the *electric* field and the *magnetic* field to explain forces between charges and magnetic poles respectively, so too we can use the *gravitational field* to explain the forces between two (or more) objects with mass.

An object of mass m_1 for example produces a gravitational field in the space surrounding it. A second object of mass m_2 placed in the field will experience a force *due to the field*. Similarly m_2 produces a field that acts on m_1.

Gravitational fields, like electric and magnetic fields are *force fields*. Masses experience a force when placed in the gravitational field of another mass.

Just as we define an electric field as the force per unit charge, so too we *define the gravitational field as the force per unit mass.*

Field Mathematics

From the equation $F = G\frac{m_1 m_2}{d^2}$, we define the gravitational field (g_1) due to mass m_1, as the ratio of the force acting on mass m_2 to the mass m_2. That is,

$$g_1 = \frac{F}{m_2} = \frac{G\frac{m_1 m_2}{d^2}}{m_2} = G\frac{m_1}{d^2}.$$

By symmetry the gravitational field g_2 due to mass m_1 is given by $G\frac{m_2}{d^2}$.

It follows that the gravitational field of a mass m at a distance d from the mass is given by:

$$g = G\frac{m}{d^2}$$

EXAMPLE 5

Calculate the value of 'g' – the acceleration due to gravity – on Jupiter, given that its radius is 7.18×10^7 m and its mass is 1.88×10^{27} kg.

SOLUTION

We have:

$$g = \frac{Gm_J}{d^2}$$

$$= \frac{6.67 \times 10^{-11} \times 1.88 \times 10^{27}}{(7.18 \times 10^7)^2}$$

$$= 24.3\ \text{m.s}^{-2}$$

At the Earth's surface, g is equal to 9.8 N.kg^{-1}, which is the same as 9.8 m.s^{-2} – the value of the *acceleration due to gravity*. (This explains why we can calculate the weight of a *stationary* object from $W=mg$.) The g refers to the strength of the field rather than to any acceleration of the mass.

Kepler's Law of Periods and Newton's Law of Universal Gravitation

Orbital velocity

Consider the motion of an object in a circular path (Figure 4.17) of radius r. In one revolution it moves a distance equal to the circumference of the circle, that is, $2\pi r$.

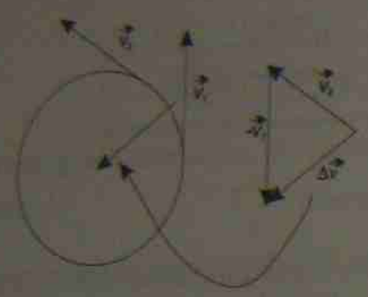


Figure 4. 1 Orbital velocity

The speed v with which it moves in a circle is called the *orbital speed* (or 'orbital velocity', although strictly speaking this continually changes as the direction of the object changes, as it moves around the circle). If the time to make one complete revolution is given by the *'period' T*, then the orbital speed v is given by:

$$v = \frac{2\pi r}{T}$$

Since the object's *velocity* is changing due to its continual change in direction, it follows that the object must be *accelerating*. (The object does not get faster, only its direction changes.) This requires a force, the *centripetal* (centre seeking) force. This force acts towards the centre of the circle and has magnitude given by $F = \frac{mv^2}{r}$.

For a planet revolving around the Sun in a circular orbit or radius r, the centripetal force is provided by the gravitational attraction between the planet and the Sun. If the mass of the planet is m and the mass of the Sun is M, then:

$$F = G\frac{Mm}{r^2} = \frac{mv^2}{r}$$

$$G\frac{Mm}{r^2} = \frac{m\left(\frac{2\pi r}{T}\right)^2}{r}$$

$$\frac{GM}{r^2} = \frac{4\pi^2 r}{T^2}$$

That is:

$$\frac{r^3}{T^2} = \frac{GM}{4\pi^2}$$

This last equation is Kepler's Law of Periods (also called Kepler's Third Law) which he derived from empirical data! We can see how it is a necessary consequence of Newton's Law of Universal Gravitation!!!

EXAMPLE 6

Calculate the mass of Jupiter given that Io, one of its satellite moons, has a period of 1.53×10^5 s moving in an approximately circular orbit of 4.20×10^8 m.

SOLUTION

Letting M_J and r be the mass of Jupiter and the distance between their centres respectively, we have:

$$\frac{r^3}{T^2} = \frac{GM_J}{4\pi^2}$$

Hence:

$$M_J = \frac{4\pi^2 r^3}{GT^2}$$

$$= \frac{4\pi^2 \times (4.20 \times 10^8)^3}{6.67 \times 10^{-11} \times (1.53 \times 10^5)^2} \text{ kg}$$

$$= 1.87 \times 10^{27} \text{ kg}$$

NEWTON'S LAWS AND THE MOTION OF SATELLITES

As we saw in the Preliminary Course *The Co... Engine*, the motion of the planets around the Su... be described by the equation $\frac{r^3}{T^2} = \frac{GM}{4\pi^2}$. ... equation is found by comparing the force fro... Law of Universal Gravitation with the force req... to keep an object in circular motion. That is:

$$F_c = \frac{mv^2}{r} = \frac{GmM}{r^2}$$

$$v^2 = \frac{GM}{r} = \left(\frac{2\pi r}{T}\right)^2$$

$$\frac{r^3}{T^2} = \frac{GM}{4\pi^2}$$

This equation represents the mathematical form of Kepler's Law of Periods

Kepler's Laws not only apply to planets and comets orbiting the Sun, but they also apply to satellites (both natural and artificial) and spacecraft orbiting planets. Kepler's Third Law can, for example be used to calculate the mass of a planet by determining the period and radius of a satellite of that planet.

EXAMPLE 17

Calculate the mass of Jupiter given that Io, one of its satellite moons, has a period of 1.53×10^5 s when moving in an approximately circular orbit of 4.20×10^8 m.

SOLUTION

Letting M_J and r be the mass of Jupiter and the distance between their centres respectively, we have:

$$\frac{r^3}{T^2} = \frac{GM_J}{4\pi^2}$$

Hence:

$$M_J = \frac{4\pi^2 r^3}{GT^2}$$

$$= \frac{4\pi^2 \times (4.20 \times 10^8)^3}{6.67 \times 10^{-11} \times (1.53 \times 10^5)^2} \text{ kg}$$

$$= 1.87 \times 10^{27} \text{ kg}$$

Newton's Law of Universal Gravitation determines the motion of satellites, enabling scientists to calculate their position and velocity at any instant. It also controls the motion of spacecraft travelling through the solar system to other planets.

THE 'SLINGSHOT' EFFECT[12]

Many of today's space probes to distant planets such as Jupiter use a *gravitational 'slingshot' effect* (also known as a *gravity-assist trajectory*) that brings the probe close to other planets to increase the probe's velocity. In 1974, *Mariner* 10 was directed past Venus on its way to Mercury. The *Pioneer* and *Voyager* probes that went to the outer planets and became the first manmade objects to leave the Solar System also used this method.

How does this work? Why isn't the increase in speed of a probe as it approaches a planet cancelled out by the decrease as it recedes?

Consider a trip to Jupiter such as the *Galileo* probe launched in 1989 that involved a single fly-by of Venus and two of the Earth. As the probe approaches Venus (Figure 1.20(a)), it is accelerated by Venus' gravitational attraction, causing it to speed up relative to Venus. (By Newton's Third Law, Venus will also experience a force slowing it down. Its mass, however, is so much greater than that of the probe that the velocity decrease is imperceptible.)

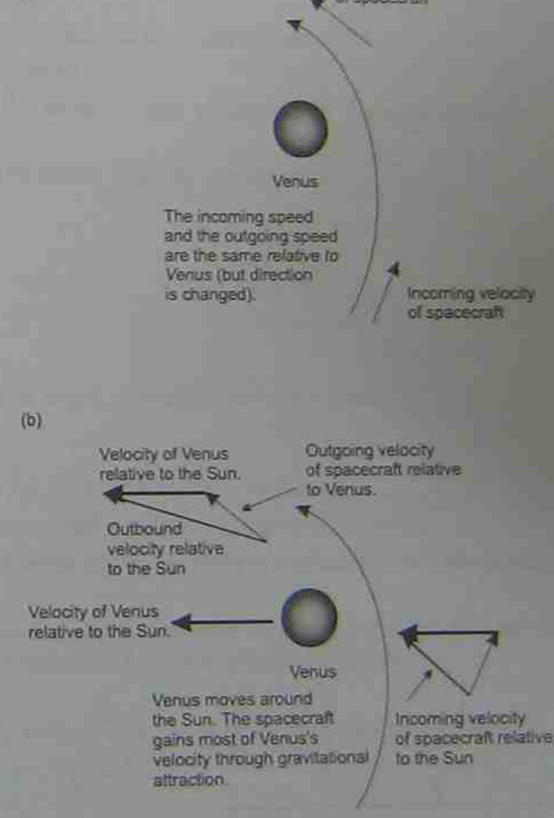


Figure 1. 20 The slingshot effect

[12] http://www.sciam.com/askexpert/astronomy/astronomy10.html Experts from Scientific American answer questions about the slingshot effect.

As the probe passes Venus, its speed is reduced (relative to Venus)[13]. Relative to the Sun, however, its speed has increased (Figure 1.20(b)). The probe picks up *angular momentum*[14] from the planet (which loses an equal amount of angular momentum). Gravity allows the 'coupling' between the probe and planet to facilitate the transfer. For this reason, gravity-assist trajectories should more correctly be called *angular momentum-assist trajectories*.

[13] In fact, the speed of receding is the same as the speed of approach relative to Venus.

[14] Angular momentum is the momentum of a rotating object ($= mvr$) where m is the mass, v is the orbital velocity and r is the radius of the orbit.

SECTION 4: SPECIAL RELATIVITY

BIG IDEA:

Current and emerging understanding about time and space has been dependent upon earlier models of the transmission of light.

OUTCOMES:

Students learn to:

1 Outline the features of the aether model for the transmission of light.
2 Describe and evaluate the Michelson-Morley attempt to measure the relative velocity of the Earth through the aether.
3 Discuss the role of the Michelson-Morley experiment in making determinations about competing theories.
4 Outline the nature of inertial frames of reference.
5 Discuss the principle of relativity.
6 Describe the significance of Einstein's assumption of the constancy of the speed of light.
7 Identify that if c is constant then space and time become relative.
8 Discuss the concept that length standards are defined in terms of time in contrast to the original metre standard.
9 Explain qualitatively and quantitatively the consequence of special relativity in relation to:
- the relativity of simultaneity
- the equivalence between mass and energy
- length contraction
- time dilation
- mass dilation.

10 Discuss the implications of mass increase, time dilation and length contraction for space travel.

Students:

1 *Gather and process information to interpret the results of the Michelson-Morley experiment.*
2 *Perform an investigation to help distinguish between non-inertial and inertial frames of reference.*
3 *Analyse and interpret some of Einstein's thought experiments involving mirrors and trains and discuss the relationship between thought and reality.*
4 *Analyse information to discuss the relationship between theory and the evidence supporting it, using Einstein's predictions based on relativity that were made many years before evidence was available to support it.*
5 *Solve problems and analyse information using:* $E = mc^2$, $m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$, $l = l_0\sqrt{\left(1-\frac{v^2}{c^2}\right)}$ and $t = \frac{t_0}{\sqrt{1-\frac{v^2}{c^2}}}$

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Table 3.2

Material	*Density* (kg/m^3)	*Compressive strength* (N/mm^2)
Structural concrete	2400	25–40
Staffordshire blue brick or similar	2000	48.4
Lightweight concrete	2000	15–30
Common brickwork	1760	20.0
Aerated concrete	700	2.8–5.5

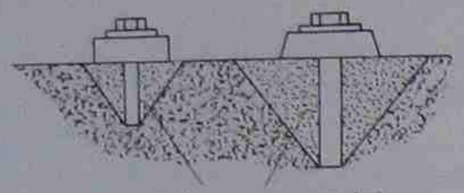


Fig. 3.1 Effect of the depth of a fixing

effectiveness falls off when the hole diameter exceeds 16 mm. It is recommended for most mass walling bases, except those which are extremely hard.

5. Electric hammer drill — This is a quick method of forming holes up to 24 mm diameter with reasonable accuracy in dense concrete, hard brickwork and hard stone.

6. Pneumatic hammer drill — This is the fastest method, but hole accuracy and shape are not always as good as they might be. This method is recommended for large-diameter holes for heavy-duty civil engineering fixings.

Drilling speed Masonry drills produce their best performance when used at medium or slow drilling speeds (400 to 600 rpm, fully loaded). High speeds result in overheating and consequent premature drill wear. Lower speeds, on the other hand,

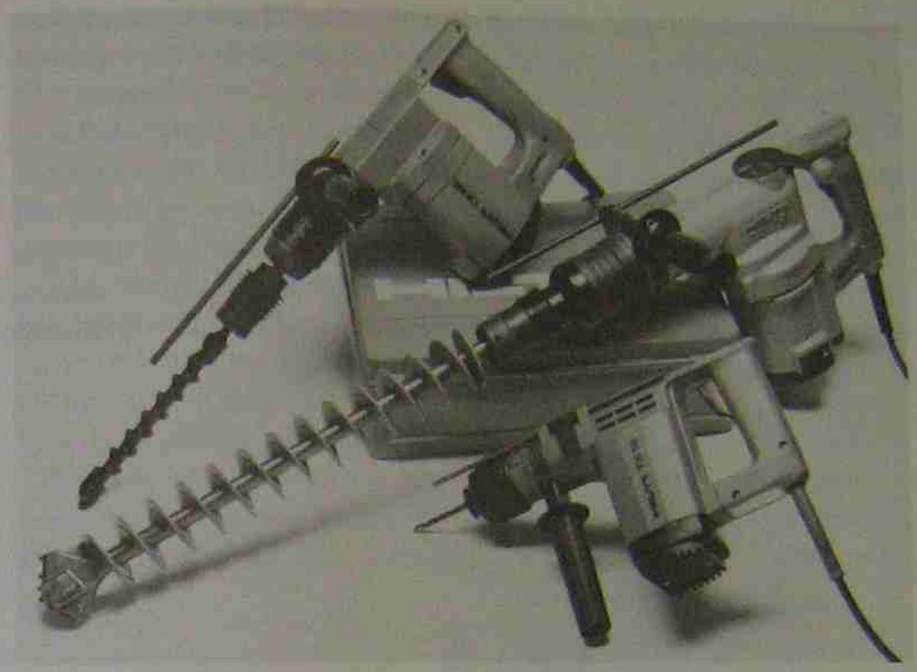


Fig. 3.2 The Hilti range of electro-pneumatic drilling machines

generate less heat which can be dissipated up the drill shank (Fig. 3.2).

De-speed adaptors are available to enable high-speed drills to operate at lower speeds. They also permit high-speed drills to make much larger holes.

Where a walling base is faced with a delicate material, such as glass or glazed tile, it is wise to use a Durium-tip drill at slow speeds.

Impact adaptor There are adaptors available which convert rotary drills into impact tools. These usually only permit the use of the smaller sizes of drill bit.

Points to remember

Whatever method of drilling is used, certain points should be observed:

1. The correct combination of rotary drill or hammer, drill bit or tool should always be used. The size of drill bit must always be that recommended for the particular size of fixing. This is essential if the fixing is to achieve its full performance.
2. Every rotary drill or hammer is limited in its performance

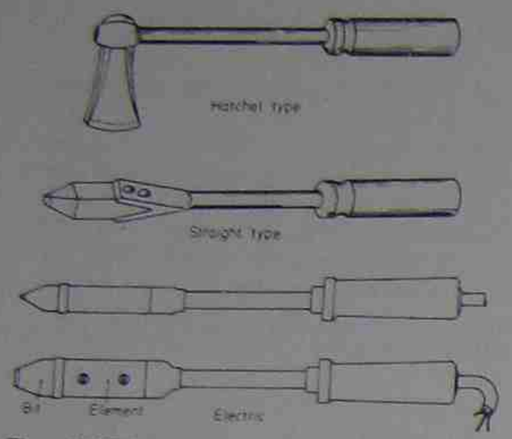
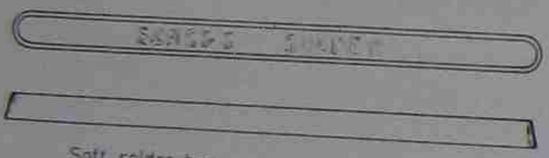


Figure 3.127 *Soldering irons*

SOFT SOLDER

Soft solder is a mixture of tin and lead which melts at the relatively low temperature of 183°C. The proportion is approximately two parts of tin to one part of lead. It is available in bar form for general engineering work and also in the form of wire with a resin flux core.



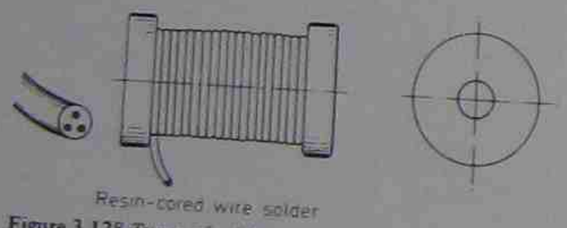


Figure 3.128 *Types of solder*

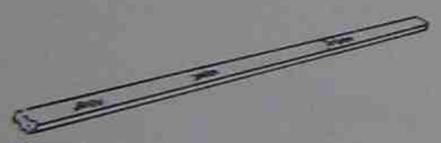


Figure 3.129 *Silver solder*

SILVER SOLDERING

Silver solder is an alloy of silver, copper and zinc with a melting point of about 700°C, that is, lower than that required for brazing. It may be used for joining brass and copper. The solder is supplied in a strip form.

FLUX

Flux is a substance which, when heated, provides a liquid or gaseous shield which excludes oxygen and prevents oxidisation of the surface of the metal being soldered. It may be an active flux such as zinc-chloride (killed spirit) or a passive flux such as resin.



Figure 3.130 *Soft solder fluxes*

BRAZING (HARD SOLDERING)

In brazing, the joining metal is brass consisting of varying proportions of copper and zinc known as 'spelter'. The brazing temperature of about 900°C is much higher than that for soft soldering. Spelter is supplied in the form of round rod of small diameter or in granular form mixed with flux.

Borax is generally used as brazing flux in the form of a powder which is mixed to a paste with water. The heat of brazing melts the borax to form a protective slag.

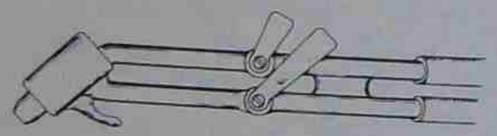


Figure 3.131 *Gas-air brazing torch*

BRAZING TORCH

A special torch is required for brazing. The usual type is supplied with mains gas and air from a blower, and it is fitted with adjustable gas and air taps for controlling the flow and mixture of gases.

BRAZING HEARTH

Brazing is best carried out in a hearth designed for the purpose. The hearth is made from steel lined with fire brick and has an electrically-driven air blower mounted on it.

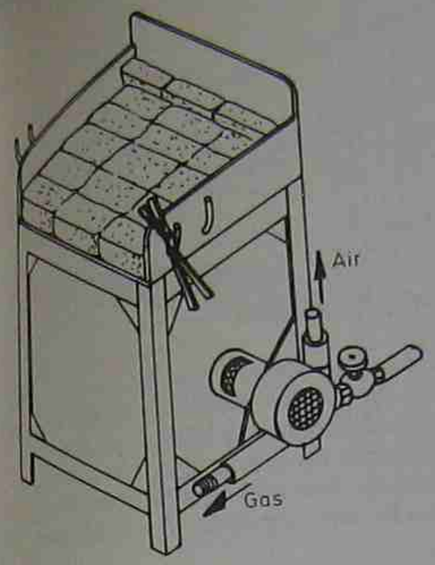


Figure 3.132 *Brazing hearth*

WELDING

Welding is a process for joining metals, plastics, etc. by heating them locally until they can be joined by fusion or forging. The main methods of fusion welding are: electric arc, gas torch, friction and resistance welding.

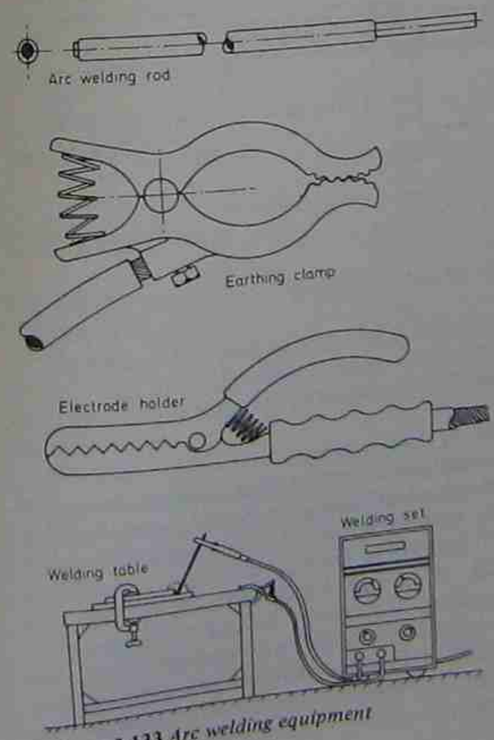


Figure 3.133 *Arc welding equipment*

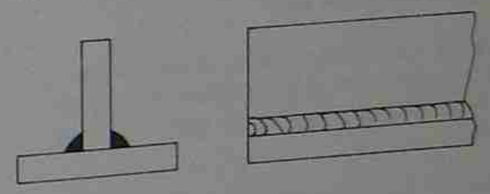
ARC WELDING

In this process the heat of fusion is generated by an electric arc struck between two electrodes, one of which is the workpiece and the other a welding rod. The welding rod is made of a material similar to that of the parts being welded and is coated with a solid flux which melts when heated. It is used to 'fill' the welded joint.

Power is obtained from an a.c. or d.c. *welding set* providing a regulated low voltage, high current supply to an *electrode holder* and an *earthing clamp*. The work is done on a special *welding table* made of steel on which the work is clamped and to which the earthing clamp is attached to complete the electric circuit.

TYPES OF WELD

Most welds in machine elements are fillet welds although butt welds are used a great deal for pressure vessels. These and other types of weld commonly used are described in the following:



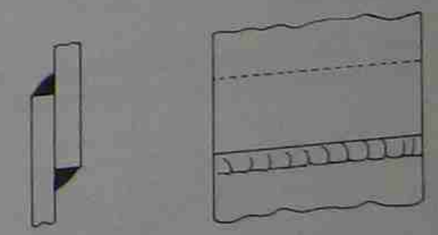


Figure 3.134 *Fillet welds*

Fillet weld A weld joining two plates at right angles, or overlapping plates. The weld is formed in the corner and is of approximately triangular shape.

Intermittent weld In the interests of economy and to reduce distortion, fillet welds are often intermittent.

Butt weld A weld joining two plates end to end to form a continuous plate. The plates are usually prepared by chamfering and the weld may be on one side or both sides of the plates (*see* Flash weld).

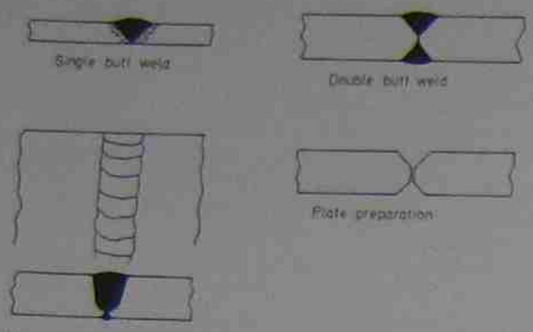


Figure 3.135 *Butt welds*

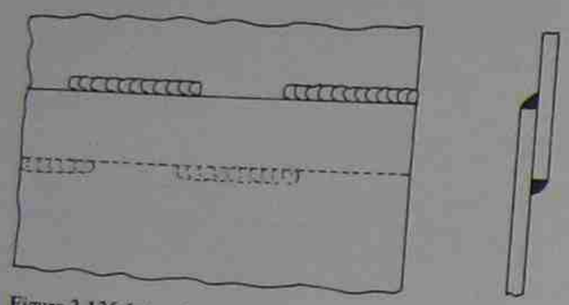


Figure 3.136 *Intermittent weld*

Plug weld A method of joining plates in which a series of holes in one plate are filled with weld to join it to the other plate to give a result similar to riveting.

Slot weld A similar method to plug welding using slots instead of holes.

Tack weld A short intermittent weld used to hold parts together temporarily before further welding.

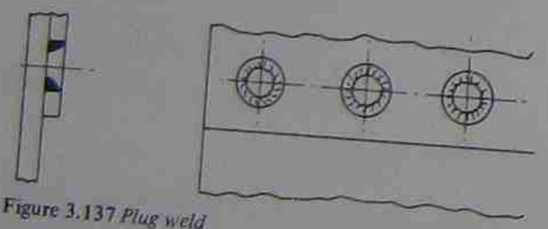


Figure 3.137 *Plug weld*

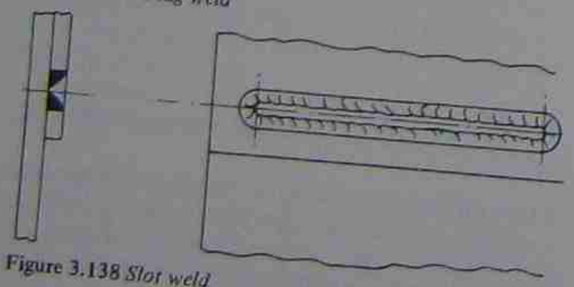


Figure 3.138 *Slot weld*

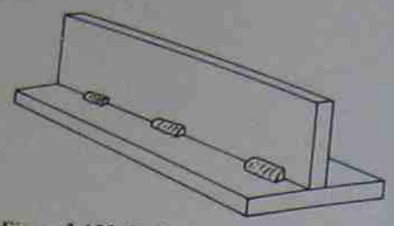


Figure 3.139 *Tack weld*

RESISTANCE WELDING

Welding is produced by fusion due to the heavy current flowing between two metal objects when they are held in close contact by electrodes. The current depends upon the nature of the surface and the contact pressure. This method is used for joining sheet metal and for attaching studs, rods and bosses etc. to plates.

Spot weld A type of resistance weld where thin plates are joined by local spots of fusion. It is used extensively for lightly-loaded light metal parts.

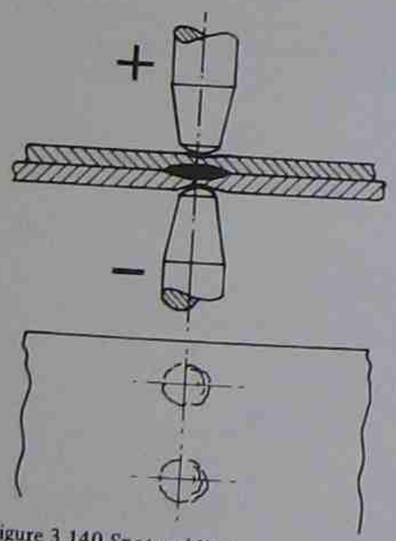


Figure 3.140 *Spot welding*

Resistance seam weld A continuous process in which two overlapping plates are joined by fusion due to the current flowing between two rotating wheels.

Flash weld A method of butt welding bars by resistance welding. The ends of the bars are connected to an electrical supply and brought together under pressure to complete the circuit. The arc produced causes fusion and the power is cut off to allow the joint to solidify.

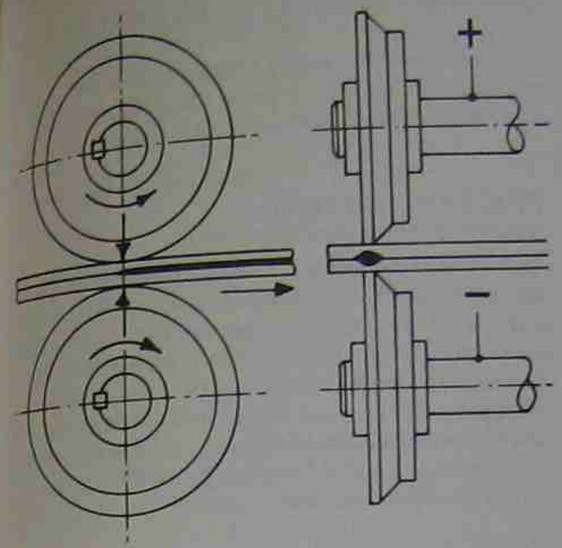


Figure 3.141 *Resistance seam welding*

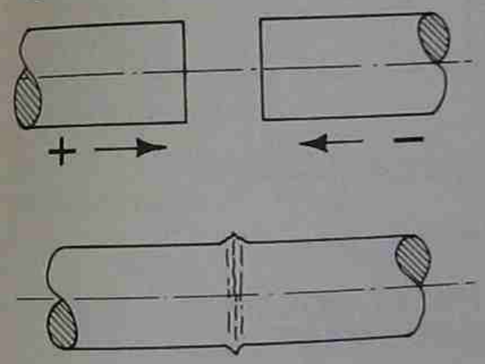


Figure 3.142 *Flash welding*

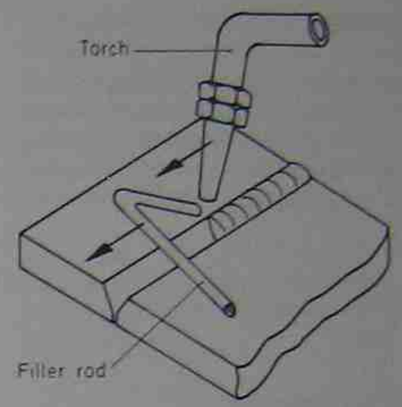
GAS WELDING

Gas welding is suitable for most sheet metals up to a thickness of a few mm.

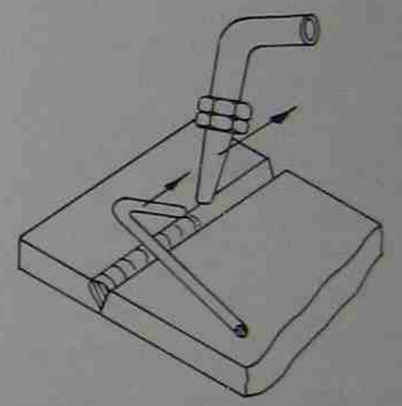
The heat of fusion is obtained by burning pure oxygen with gases such as acetylene, butane, propane or hydrogen in a specially designed torch. A filler rod is fed by hand.

Welding may be carried out to the left or right, these methods being known respectively as 'leftward welding' and 'rightward welding'. The former is used for metal thickness of up to 3mm and the latter for over 3mm, but gas welding is not often used for plate over 3mm.

Gas welding equipment The welding torch, fitted with gas and air control valves and interchangeable nozzles, is connected to gas cylinders by flexible hoses leading from regulators on the bottles.



Leftward welding



Rightward welding

Figure 3.143 *Gas welding*

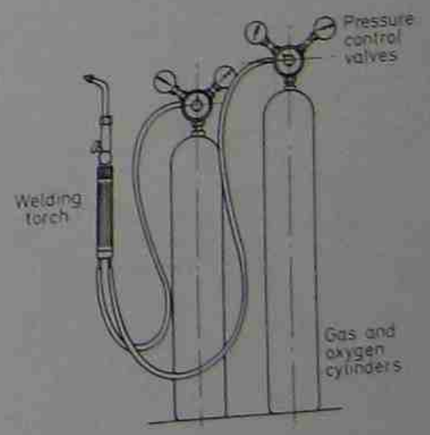


Figure 3.144 *Gas welding equipment*

FLAME CUTTING

Flame cutting is a method of producing shaped flat parts cut from steel plate, especially of large thickness. The torch may be hand-held or mounted in a welding machine in which a template of the required shape is followed by the cutting flame.

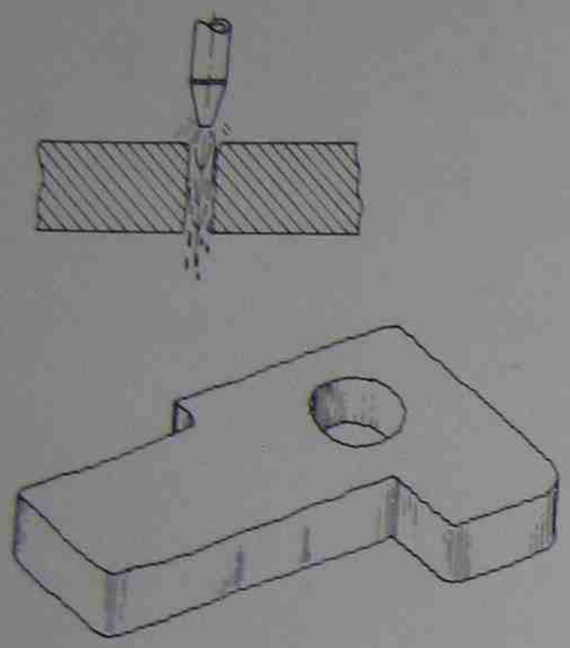


Figure 3.145 *Flame cutting*

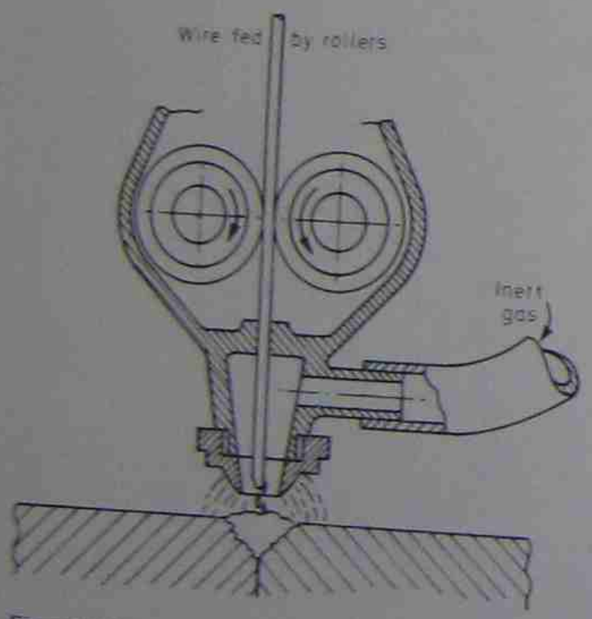


Figure 3.146 *Gas metal arc welding*

GAS SHIELDED METAL ARC WELDING

In this process, also called Metal Inert Gas (MIG), an inert gas such as argon is used as a flux for arc welding. The electrode is a continuously-fed consumeable wire.

FRICTION WELDING

Parts may be welded by the heat generated by mechanical friction. One of the parts is rotated in a chuck and the other part, which does not rotate, is brought into contact with it under pressure. When the resulting friction has produced sufficient heat to fuse the contacting surfaces, the non-rotating part is freed and allowed to rotate. On cooling, the parts are joined. This method is useful for joining dissimilar metals which are otherwise difficult to weld.

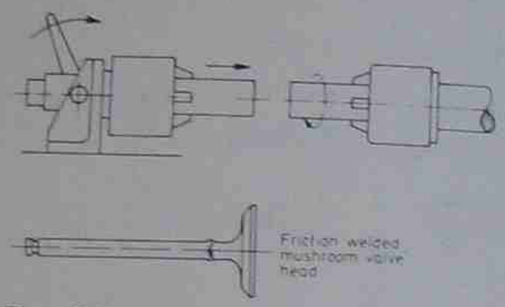


Figure 3.147 *Friction welding*

3.4 METAL-FORMING EQUIPMENT

CASTINGS

A casting is produced by pouring molten metal, or any other material, into a suitably shaped mould and allowing it to solidify. The term 'casting' also refers to the actual process.

Most castings are *sand castings* which are made in a mould using a special moulding sand. The mould is made in a *moulding box* divided horizontally into halves which are located with dowels and bolted together during casting. A wooden replica, or *pattern*, of the part to be cast is embedded in the sand to produce a cavity. Any holes required in the casting are produced by inserting *cores* into the mould. These cores are previously made in a *core box* out of baked sand. The molten metal is poured into the mould through runners until it fills the cavities and appears in risers. When the metal has set the sand is removed, the sticks of metal in the runners and risers are removed, and the casting is cleaned by chipping, grinding and sandblasting.

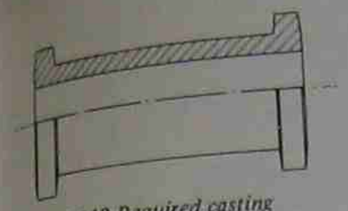


Figure 3.148 *Required casting*

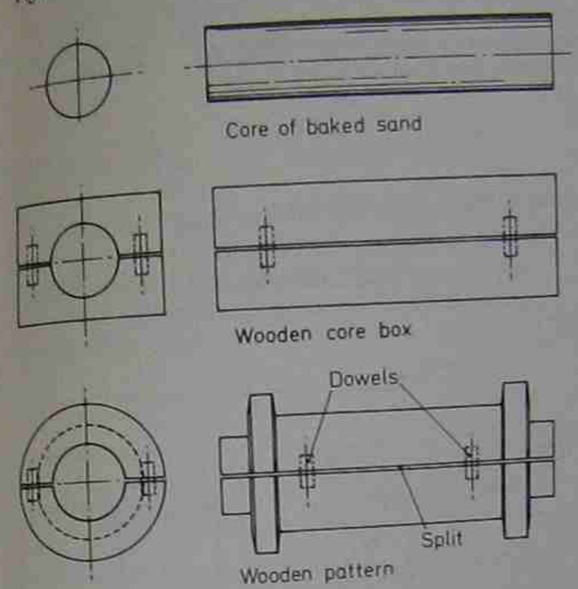


Figure 3.149 *Casting*

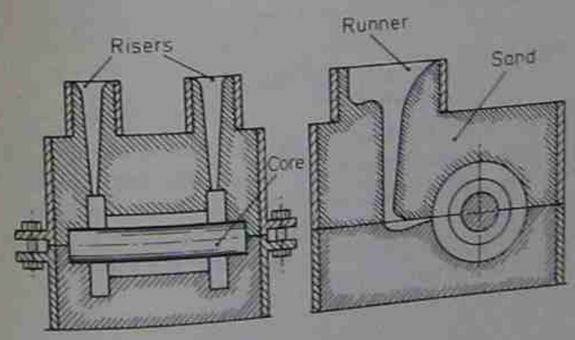


Figure 3.150 *Moulding box*

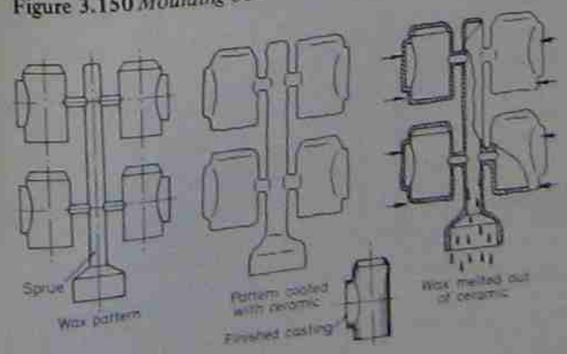


Figure 3.151 *Investment casting*

Investment casting (lost wax casting) A permanent metal mould is made and from it wax patterns are produced. These are coated with several layers of ceramic slurry, each layer being allowed to harden. The coated patterns are baked and the wax melts and runs away leaving a cavity which is filled to give a precision casting.

Die casting The mould is made of steel in several parts dowelled together. Molten metal is fed into the mould under gravity or pressure and when solid it is ejected by pins.

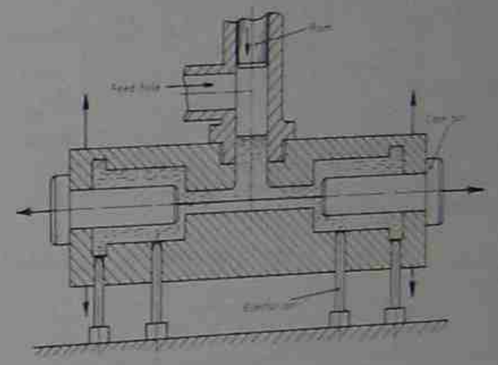


Figure 3.152 *Die casting*

Centrifugal casting Cylindrical and circular components, such as piston rings, cylinder liner pipes, gear wheels and locomotive wheels, may be cast in a rotating mould in which centrifugal pressure in the molten metal produces a fine-grain high-quality casting. Molten metal is poured into the mould while it is rotating and allowed to solidify before rotation ceases.

Wheel-shaped objects are cast with the axis vertical whereas pipes are cast with a horizontal axis.

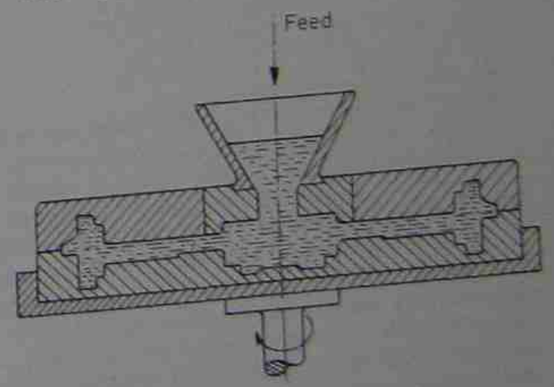


Figure 3.153 *Centrifugal casting – vertical axis*

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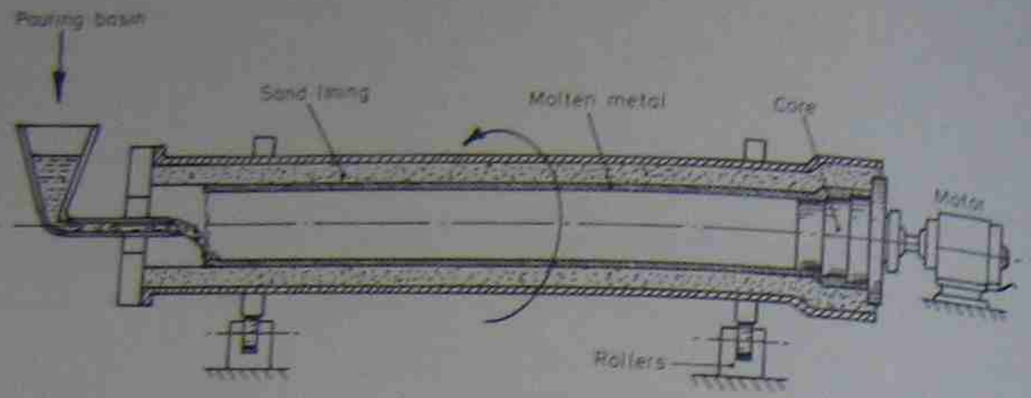
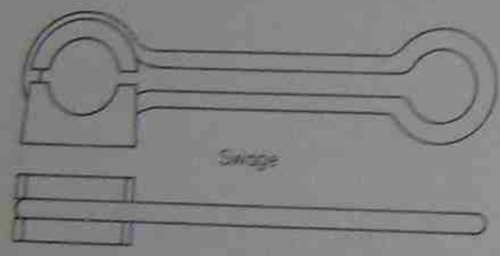


Figure 3.154 *Centrifugal casting of pipe – horizontal axis*

FORGING

Forging is the forming of metal parts by hammering, pressing or bending to the required shape, usually while the metal is at red heat.



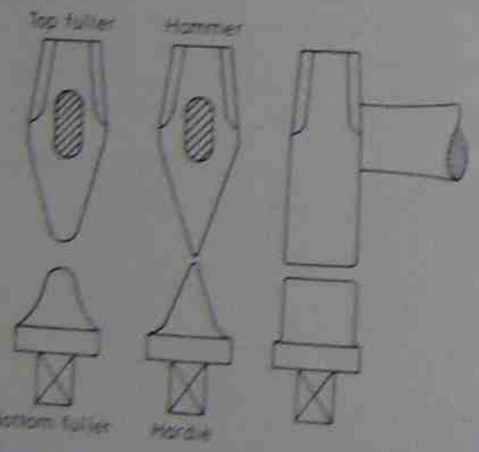


Figure 3.155 *Hand forging tools*

Hand forging This is the process used by a blacksmith where parts are formed on an *anvil* using special hammers, chisels and swages. The anvil has a hardened top face used for cutting on and a soft 'beak' for bending bars. In the top face is a square hole called a 'Hardie hole' used for holding various tools.

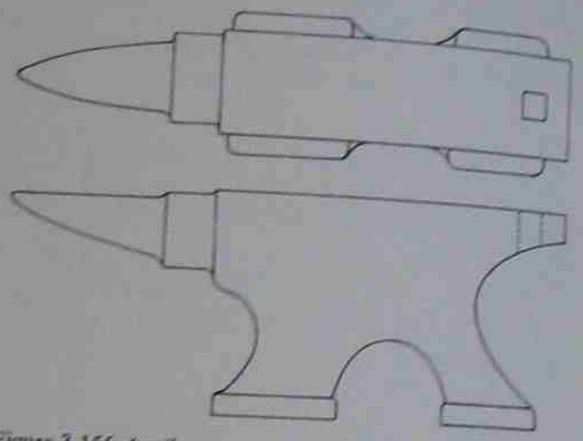


Figure 3.156 *Anvil*

Drop forging machine This is a machine used for forging in which pneumatic or hydraulic pressure is used to provide the force. Hot metal blanks are compressed between hard steel dies one of which is attached to the powered hammer and the other to the machine table.

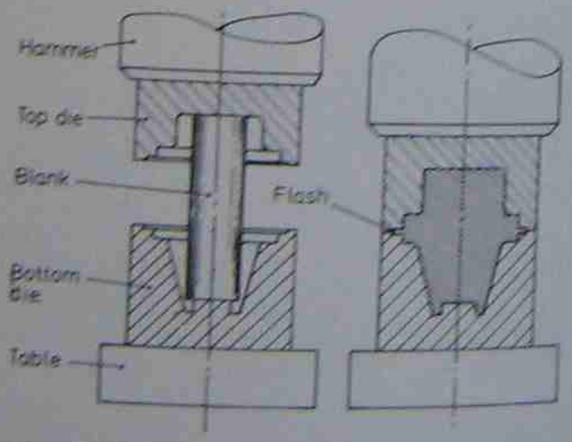


Figure 3.157 *Drop forging machine*

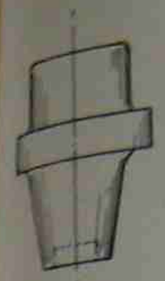


Figure 3.158 *Forging with flash removed*

ROLLING MILL

Red-hot ingots of steel, or other metals, are passed through successive pairs of rollers specially shaped to produce flat sheet, I, T, channel, angle or any other section bar. Final cold rolling is sometimes carried out to give a better finish.

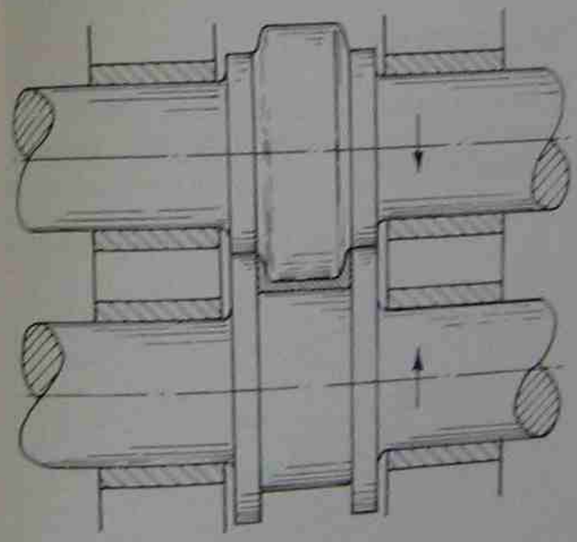


Figure 3.159 *Rolling mill (rolling channel)*

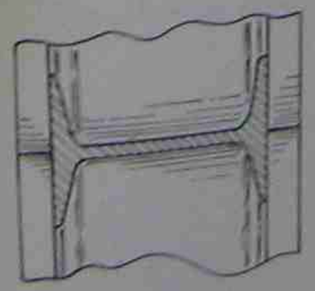


Figure 3.160 *Rolls for I section*

EXTRUSION

When metal is sufficiently soft, either at normal temperatures or when heated, it can be forced under pressure to flow through a die like toothpaste from a tube to form bars of any desired cross-section.

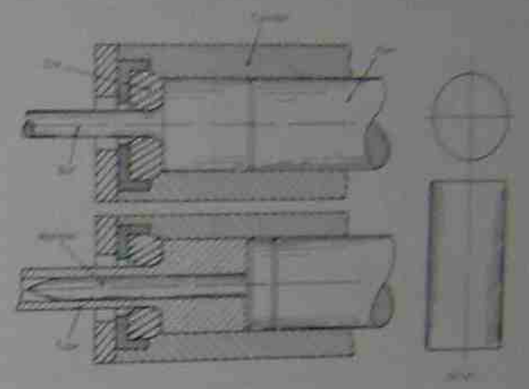


Figure 3.161 *Hot extrusion*

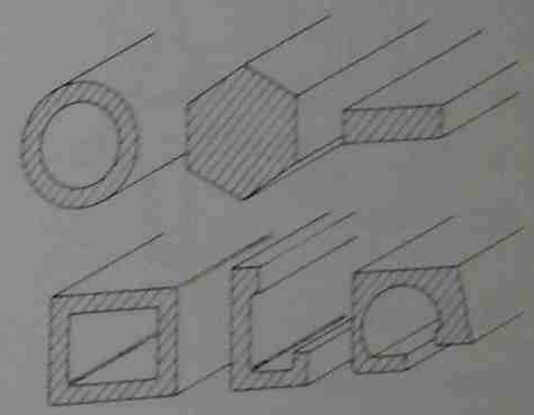


Figure 3.162 *Hot extruded sections*

Hot extrusion A piece of metal bar, or *billet*, is heated to the desired temperature and fed into a cylinder. It is then forced by a ram through a die of the correct shape to produce long lengths of bar which can be cut to the required length. Hollow sections can be made using a mandrel placed in the orifice.

Cold extrusion Soft metals such as copper, zinc and aluminium can be extruded when cold, and sometimes it is necessary to carry out the process in several stages.

Impact extrusion A metal which is plastic when cold may be formed by the impact of a high velocity punch to form a tube. A 'slug' of metal is given a single blow which 'splashes' it up the sides of the punch. This process is used for the manufacture of toothpaste tubes, battery cases, ignition coil cans, etc.

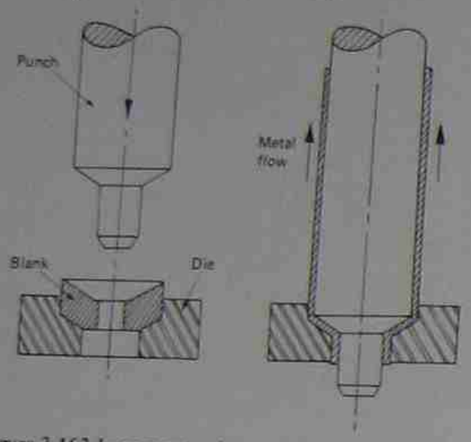


Figure 3.163 *Impact extrusion*

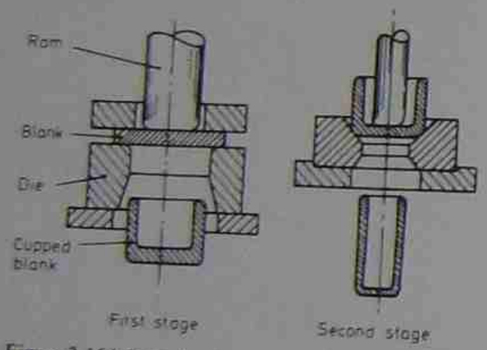


Figure 3.164 *Deep drawing*

DEEP DRAWING

Deep drawing is the forming of sheet or plate into box- and cup-shaped articles by pressing it with a shaped punch into a die. It involves considerable plastic deformation of the material. The process is used for cartridge cases, washing machine tubs and many electrical fittings.

PRESS

A press is used for a wide range of processes such as punching, piercing, blanking, notching, bending, drawing, folding, flanging, etc. It may be operated by means of a crank connected to a heavy flywheel or by hydraulic power.

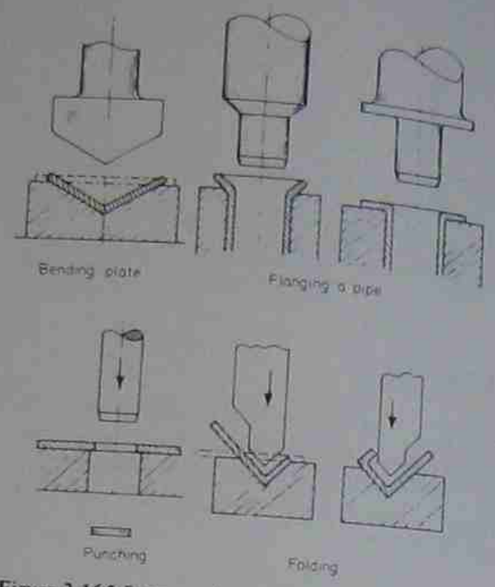


Figure 3.165 *Press work*

SHEARING MACHINE

A shearing machine consists of a fixed blade and a manually- or power-operated moving blade used for cutting sheet metal.

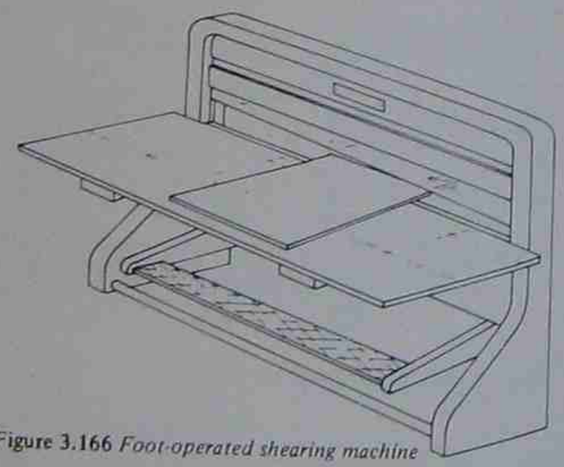


Figure 3.166 *Foot-operated shearing machine*

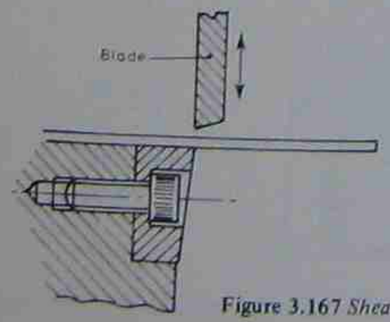


Figure 3.167 *Shearing operation*

WIRE DRAWING

A method for producing small diameter wire by drawing it while cold through successively smaller dies. Because of work hardening, the yield strength of the material of the wire increases at each drawing.

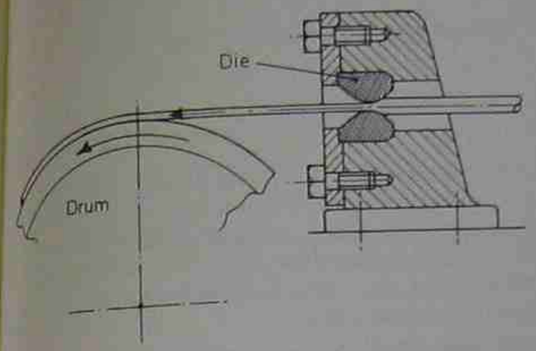


Figure 3.168 *Wire drawing*

SPINNING

Spinning is the forming of items out of sheet metal by rotating a thin metal disk at high speed, usually in a lathe, and pressing it into a cup or cone shape over a former using either a forming tool or a roller.

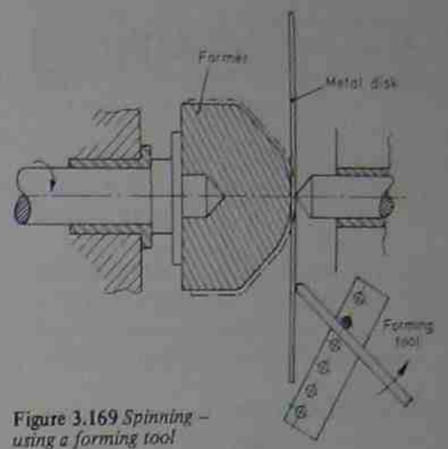


Figure 3.169 *Spinning – using a forming tool*

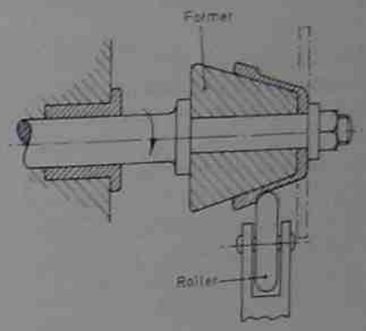


Figure 3.170 *Spinning – using a roller to form*

4. Engineering Materials

4.1 METALS

CAST IRON

Cast iron contains a considerable amount of carbon (2.4–4.5%) and is too brittle for 'working'. It is, however, very fluid when molten and is suitable for intricate castings.

Though quite strong in compression it is weak in tension and shear, but the strength can be increased considerably by the addition of alloying materials such as nickel, chromium and copper. These alloy cast irons can be used for gears, camshafts and crankshafts and are cheaper than steel.

SPHEROIDAL GRAPHITE (SG) IRON

In this iron (also called Nodular Iron) the graphite is in the form of small spheres resulting in increased ductility. The mechanical properties approach those of steel combined with good castability.

MALLEABLE CAST IRON

This is tougher and more shock-resistant than cast iron and is suitable for automobile parts, such as levers and pipe fittings.

There are three main types, *white heat* with superior castability, *black heat* with superior machineability, and *pearlitic* superior to the other two but difficult to produce.

STEEL

Steel is essentially an alloy of iron and iron carbide with small amounts of other elements in controlled quantities. A wide range of steels is available with properties varying considerably depending upon the alloying elements and subsequent heat treatment.

Carbon steel The amount of carbon determines the strength of steel. The main types are: dead mild (or low carbon), mild, medium carbon and high carbon.

Dead mild (low carbon) The carbon content is 0.07–0.15%. It is used for pipes, wire, nails, boiler plates, chains, etc., and it is worked when hot but does not machine easily.

Mild The most widely used of engineering materials whose carbon content of 0.15–0.25% allows it to be easily worked, machined and welded. Typical applications are ships' plates, forgings, nuts and bolts, gears and shafts.

Medium carbon A type which can be heat-treated to give greater strength, medium carbon steel is also easily machined. Its uses are machine parts, forgings, castings, springs and drop hammer dies.

High carbon This type contains 0.5–1.5% carbon which gives it great strength when heat-treated. At the lower carbon content it is used for screwdrivers, hammers, spanners, chisels, forging and pressing dies, while the highest carbon content is used for drills, lathe tools, hacksaws, ball bearings, taps and dies.

Alloy steels The addition of alloying elements to steel makes it more responsive to heat treatment, and this results in increased hardness, strength and toughness and greater resistance to corrosion. The main alloying elements are nickel, chromium, manganese, molybdenum, vanadium, tungsten, silicon and cobalt.

Nickel-chrome Nickel-chromium steels are among the most important alloy steels used in engineering. Heat treatment gives a wide range of properties with good resistance to shock and good ductility. They are used for high-tensile bolts, hardened gears, machine tools, etc.

Stainless A corrosion-resistant steel with about 12% chromium and other elements, used for turbine blades, and in sheet form for chemical and food containers.

Silver A bright-drawn high-carbon steel in the form of circular rod, containing manganese and chromium.

Tool High carbon steel to which manganese, tungsten and chromium have been added. When hardened it is used for dies, and to a limited extent for machine tools having been largely replaced by tungsten carbide inserts or brazed tips.

TUNGSTEN CARBIDE

An extremely hard material used for machine tool tips.

COPPER

A reddish, ductile metal of low strength but which is a very good conductor of heat and electricity. It is used for making pipes, electricity cables, gaskets and washers for fluid sealing, and is extensively alloyed with zinc, tin, aluminium, etc.

Copper nickel alloys There is a wide range of these alloys with amounts of nickel varying from 2–70%. Alloys with 40–45% nickel are used for resistance wire, e.g. Constantan, and they have a high resistivity and small resistance/temperature coefficient. Alloys containing about 70% nickel are known as *monel metal*. These are as strong as steel and have excellent resistance to corrosion by sea water, salt solutions and organic acids. They are suitable for steam turbine blades and condenser tubes.

Beryllium copper If 2% beryllium is added to copper the result is a very hard alloy as strong as tool steel. It is used for springs, bellows, bourdon tubes in pressure gauges and for non-sparking tools.

BRASS

This is the most widely used alloy of copper. It consists of 30–50% zinc and the remainder copper, to which a small amount of lead may be added to improve machinability. Brasses with a low zinc content are used for cold working in the production of condenser tubes, cartridge cases, gas and electric light fittings. Brasses with 39–46% zinc are easily hard worked and are used for extruded sections, pump parts, hydraulic fittings, nuts, bolts and screws.

BRONZE

'Bronze' refers to a copper-tin alloy which is used for electrical parts, hydraulic components, bearings and gears.

Gunmetal This is a bronze with 2% zinc added to improve the fluidity when casting and increase hardness. It is used extensively for castings, particularly those of a complicated form.

Lead bronze The addition of lead improves machinability in bronzes and improves the wear resistance of bronze bearings.

Phosphor bronze Phosphor bronze contains from 0.1–1.0% phosphorus. It is used for heavy-duty bearings, gears and non-ferrous springs, and is hard with good resistance to wear and corrosion.

Manganese bronze This is a bronze to which ferromanganese has been added. It is used for very high strength castings.

ALUMINIUM

A light, ductile metal which is a good conductor of heat and electricity. It is used for electrical conductors and parts of switchgear, kitchen utensils, wrapping foil, window frames and as a base for many alloys.

Aluminium is extremely soft and ductile but is difficult to cast. Its properties can be greatly improved by adding small amounts of copper, silicon, manganese, magnesium, iron, zinc, nickel, bismuth and titanium. Aluminium alloys are classed as *wrought* and *casting* and may be *heat-treatable* or *non-heat-treatable*.

Silicon lowers the melting point and improves castability. Copper, magnesium, manganese, zinc, titanium and nickel increase the strength. Lead and bismuth increase machinability.

Duralumin This most important of aluminium alloys contains copper, manganese, magnesium and silicon. It is as strong as mild steel with a third of the weight and is used for forgings, stampings, bar, sheet and rivets.

Aluminium-copper-zinc alloys These have a low melting point and are easily cast. They are cheap and are used for gearboxes and crankcases.

Y alloy This is an aluminium alloy containing 4% copper, 2% nickel and 1.5% magnesium. It is used extensively for castings such as cylinder heads and pistons for IC engines.

MAGNESIUM ALLOYS

Magnesium is only two thirds the weight of aluminium, and its alloys are useful for producing lightweight forgings and castings.

NIMONIC ALLOYS

An important range of alloys composed mainly of nickel and chromium with small amounts of titanium and carbon. They are very strong up to temperatures of 900°C and are therefore suitable for gas-turbine and jet-engine applications.

ZINC

Zinc is used as a protective coating for sheet metal, wire, nails, etc. It is also used in alloys with aluminium, copper and magnesium. Zinc alloys are used for die castings.

CHROMIUM

Chromium is used in electroplating to provide a surface with a high polish and high corrosion-resistance. It is alloyed with steel to give extremely high strengths.

CADMIUM

A fairly expensive metal used for plating and in certain types of battery.

TITANIUM

An expensive metal used in the production of aircraft parts alloyed with aluminium, vanadium, manganese, tin, etc. It has high strength, low weight, good heat- and corrosion-resistance.

LEAD

Lead is a heavy, soft, ductile metal with little mechanical strength. Because of its good resistance to corrosion it is used for roofing, cable sheathing and lining chemical apparatus. It is used extensively in nuclear work for radiation shielding and is alloyed with other metals for bearing metals and solders.

WHITE METAL (BABBITT METAL)

The name given to a range of tin-based alloys containing copper and antimony and sometimes lead. The antimony is important in ensuring low friction in bearings. These alloys are expensive and used only in high performance applications.

FUSIBLE ALLOYS (LOW MELTING POINT ALLOYS)

Alloys of bismuth, lead and tin have very low melting points and are used for solders and fusible plugs.

4.2 PLASTICS AND OTHER NON-METALLIC MATERIALS

PLASTICS

The term 'plastics' covers a wide range of man-made materials which can be moulded to the required shape by the application of heat and pressure.

There are two main types of plastic, *thermoplastic* and *thermosetting*. Thermoplastic materials become soft and pliable when heated and can be moulded into the required shape. They can be reheated and re-moulded repeatedly. Thermosetting plastics suffer a chemical change when subjected to heat and pressure and they cannot be softened by reheating.

PVC (POLYVINYL CHLORIDE)

Rigid PVC is a thermoplastic material used for pipes and ducts, plasticised PVC is used for cable covering, mouldings, fabric and flexible sheet. It is flame- and water-resistant.

PERSPEX (ACRYLIC RESIN)

Perspex, a thermoplastic material, is one of the most common acrylic resins. It can be made very clear or coloured and has good optical properties. It is available in sheet, bars, tubes, etc.

POLYSTYRENE

A thermoplastic which can be moulded into complicated shapes with fine detail. It is an excellent electrical insulator but is not weather resistant.

POLYTHENE (POLYETHYLENE)

A thermoplastic polymer with good electrical properties, especially at high radio frequencies, which is suitable for use as weatherproof sheeting.

POLYPROPYLENE

This is similar to polythene but has greater heat resistance.

CELLULOSE PLASTICS

These include celluloid used for drawing office equipment, Cellophane used in film form for packaging, and rayon used for clothing, cements, petrol pipes and photographic film.

NYLON

A plastic used in fibre form for fabrics and also moulded into parts requiring light weight, low friction and flexibility. It has good self-lubricating properties when used for bearings.

EXPANDED PLASTICS

Polythene, polystyrene, polyurethane and PVC can be foamed by the introduction of gas bubbles during manufacture. These foam plastics are extremely light and are used for heat insulation, packaging and model making.

BAKELITE

A hard phenolic thermosetting plastic which is very cheap and is used for electrical insulated parts, tool handles, bonding material for grinding wheels, etc.

TUFNOL

A laminated plastic, i.e., one containing fabric, paper, etc. Available in sheet, rod and tube, and used widely in engineering for bearings, gears, pulleys and insulated parts.

PTFE (POLYTETRAFLUORETHYLENE)

Marketed under the names Fluon and Teflon this is a plastic with high chemical inertness and heat resistance used for extremely low-friction bearings and non-stick surfaces.

EPOXY RESINS

Polymers such as Araldite are widely used for structural plastics, adhesives and for encapsulation.

GLASS FIBRE

Fine threads of glass are used as a reinforcement in synthetic resin mouldings for boat hulls, pump impellers, roof lights, etc., and also as a structural material.

CARBON

Amorphous carbon is used for fluid seals in pumps and steam turbines. *Carbon fibres* are extremely strong and can be used to increase greatly the strength of epoxy resin mouldings and metal components.

DIAMOND

A form of carbon used for the tips of oil-well drills etc., and as a dust on dressing tools for grinding wheels.

RUBBER

Natural latex combined with sulphur, carbon black and other materials is widely used in engineering where flexibility is required. Examples of its use are tyres, flexible couplings and anti-vibration mountings.

SYNTHETIC RUBBER

A wide range of synthetic rubbers, such as Neoprene, Buna and butyl, are used for flexible mountings and couplings and oil seals, etc. In their properties they are often superior to natural rubber.

CERAMICS

This is a general name for all non-metallic, non-organic materials but usually it refers to materials which will withstand very high temperatures. They are extremely hard and also wear- and corrosion-resistant and can be moulded into a variety of shapes before firing. They are used for burner nozzles, gas-turbine parts and electrical insulation.

ASBESTOS

A natural mineral material used for fireproofing. It can be woven into cloth or made into board. Sindanyo is the name of a form of asbestos board used for low voltage insulation.

PORTLAND CEMENT

A material made by burning a mixture of clay and lime. Mixing it with sand, aggregate and water produces concrete, and this is usually reinforced with steel bars to make structural columns and beams.

ABRASIVES

Materials such as carborundum and emery are used for making grinding wheels and sharpening stones.

WOOD

Wood is used in engineering in its natural form, and also in plywood, chipboard and blockboard.