CHAPTER 16

The nucleus and nuclear reactions

The work of Chadwick and Fermi in producing artificial transmutations led to practical applications of nuclear physics

Introduction

Chapters 14 and 15 discussed the various models of the atom, concentrating on the electrons around the nucleus. This chapter studies the structure, as well as the components, of the nucleus.

16.1 The nucleus

■ *Define the components of the nucleus (protons and neutrons) as nucleons and contrast their properties*

Rutherford was the first person to use the term ‘nucleus’ as part of the conclusion of his alpha particle scattering experiment described in Chapter 14. Now it is known that there are two types of particles that exist inside the nucleus: protons and neutrons. Protons and neutrons are collectively called **nucleons**. The properties of the types of nucleons are summarised in Table 16.1.

Table 16.1

Properties	Proton	Neutron
Location	Inside the nucleus	Inside the nucleus
Mass	1.673×10^{-27} kg	1.675×10^{-27} kg
Charge	1.602×10^{-19} C	0

The development of the knowledge of the nucleus

The nucleus described by Rutherford was simply a concentrated mass of positive charge. No one at the time really knew what it was composed of and what its internal structure was. Again, just like the electron models, it took the work of many scientists, over a few decades, to determine the structure and components of the nucleus.

Protons were the first nucleons to be discovered, in a similar fashion to the way electrons were discovered. The charge-to-mass ratio of the protons was measured in a discharge tube containing hydrogen ions. (Hydrogen ions are simply protons: Why?) Neutrons were discovered later and are discussed in the next section.

16.2 The discovery of neutrons

■ *Discuss the importance of conservation laws to Chadwick's discovery of the neutron*

Soon after learning about the existence of the nucleus and protons, some scientists started to speculate that the nucleus should possess ***A*** (mass number) of protons and ***A* – Z** (atomic number) of electrons. For example, for sodium atoms, there should be 23 protons (A = 23), and 23 – 11 (Z) = 12 electrons in the nucleus. This hypothesis worked well for two main reasons:

1. It successfully explained why atoms had a larger mass number compared to the actual number of positive charges (protons). Note that the 12 electrons in the nucleus cancelled out the positive charges of the 12 protons, leaving a net charge of positive 11 rather than 23.
2. It explained beta emission, a radioactive decay where electrons were ejected from the nucleus. (This is discussed later in this chapter.) Although incorrect, scientists at the time thought the only way to account for this phenomenon was if there were electrons inside the nucleus.

However, other scientists believed that there existed another type of particle inside the nucleus. They hypothesised that these particles had a similar mass to protons and were neutral in charge; these particles were **neutrons**.

Chadwick's discovery of neutrons

In 1930, the German scientist Walther Bothe (1891–1957) noted that when the element beryllium was bombarded with alpha particles (helium nuclei), a neutral but highly penetrative 'radiation' could be obtained. However, he could not explain the nature of this 'radiation'.

James Chadwick

In 1932, Englishman James Chadwick (1891–1974) proposed that the unknown radiation obtained from the alpha particle bombardment of beryllium were in fact neutrons. He then set out an experiment to try to quantitatively study this unknown 'radiation'. The neutral charge of this 'radiation' was easily demonstrated as it was not deflected by electric fields or magnetic fields. To measure the mass of the proposed neutrons, Chadwick directed the neutrons produced towards a block of paraffin wax (see Fig. 16.1).

Paraffin wax is rich in hydrogen atoms, and hence protons. The proposed neutrons, when directed towards the paraffin wax, should have a good chance of colliding with those protons and knocking them out. As a result, protons would be ejected from the paraffin wax and could be measured by the detector, which allowed the energy and the velocity of the ejected

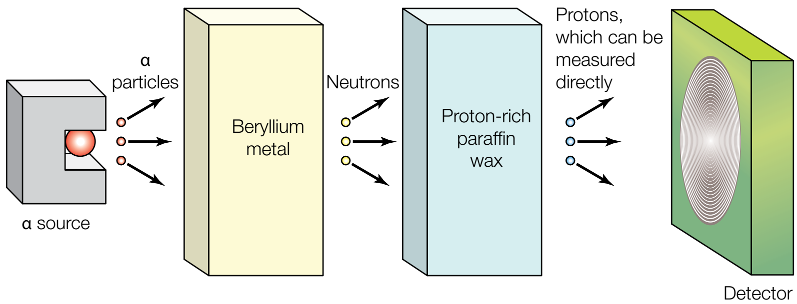


Figure 16.1
Chadwick's experiment

protons to be assessed. By applying the law of conservation of momentum and the law of conservation of energy, Chadwick was able to calculate backwards to determine that the mass of the neutron was approximately equal to that of the proton. The existence of the neutron was experimentally shown! Chadwick demonstrated the existence of neutrons without directly observing them; rather, it was done through demonstrating neutrons' properties.

NOTE: The calculation itself is not required by the syllabus, however, students should appreciate that it would be similar to that for the collision between two cars described in the Preliminary Course.

It is important to point out that neutrons are difficult to assess directly as they do not have any charge and therefore cannot be manipulated easily. The clever part of Chadwick's experiment is that it translates the difficult-to-measure neutrons to the easily measured protons. Since protons have charges, they can be easily manipulated, just as electrons can be manipulated in cathode ray tubes to allow their properties to be assessed.

To summarise the reaction taken place in Chadwick's experiment, make use of a nuclear equation:

$$^{4}_{2}\text{He}\ (\alpha) + {}^{9}_{4}\text{Be} \rightarrow {}^{12}_{6}\text{C} + {}^{1}_{0}\text{n}$$

NOTE: When writing nuclear equations, the total mass number on the left-hand side of the equation should equal to the total mass number on the right, that is, $4 + 9 = 12 + 1$; similarly the atomic numbers should also be equal on both sides: $2 + 4 = 6 + 0$.

The cloud chamber

The cloud chamber was originally developed by Scottish physicist, Charles Wilson (1869–1959), therefore it is sometimes called the Wilson cloud chamber.

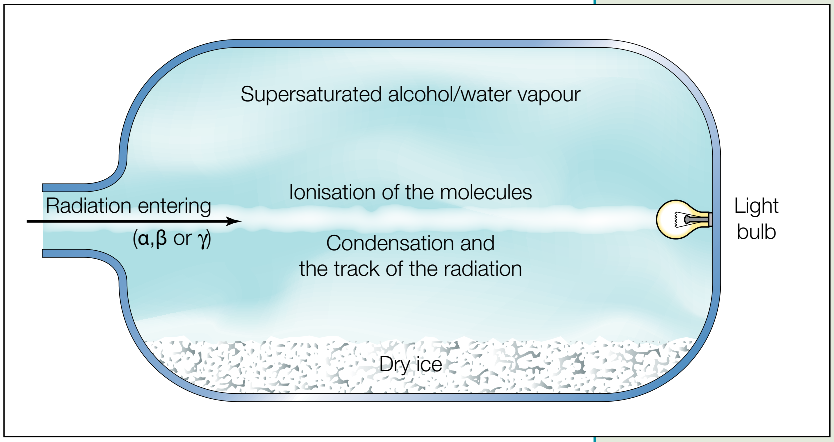
Definition

A **cloud chamber** is a device used to detect the presence of radiation. It also allows for observation and manipulation of radiation in order to assess its properties.

A cloud chamber consists of a glass tube, usually cylindrical in shape, filled with dry ice at its base. To one side there is a light bulb that illuminates the chamber. On the other side there is an entrance for the radiation. This is shown in Figure 16.2. The tube is super-saturated with alcohol and water vapour and the dry ice is used in order to maintain a cool temperature inside the tube.

As radiation travels through the chamber, it ionises some of the molecules inside the chamber by knocking out their electrons. The ionised molecules then act as nucleation centres for the condensation of the super-saturated vapour to occur.

Figure 16.2
A cloud chamber



NOTE: A nucleation centre is where condensation can occur.

As the radiation passes through the chamber and ionises the molecules along the way, it will create a track of nucleation centres for the vapour to condense on, thereby outlining the pathway of the radiation. The nature of the radiation can be easily distinguished by the nature of the pathway created. The alpha particles (see the next section), being those that ionise the most, will create the thickest pathway, whereas the gamma rays, which ionise the least, will create the thinnest track. Furthermore, manipulation can be carried out using electric fields or magnetic fields in order to assess the properties and make measurements of the radiation.

16.3 Radioactivity and transmutation

- ***Define the term 'transmutation'***
- ***Describe nuclear transmutations due to natural radioactivity***

Definition

Radioactivity is the spontaneous release of energy or energetic particles from unstable nuclei. In nature, there are three types of radioactivity (radioactive decay): alpha (α), beta (β) and gamma (γ). α and β are particles while γ is electromagnetic radiation.

Definition

Transmutation is the phenomenon in which one element changes its identity to become another element.

Transmutation can be either natural, through α, β or γ decays, or artificial. This chapter will first examine in detail the nature of α, β or γ decays and their associated transmutations. It will then examine examples of artificial transmutations.

Examples of radioisotopes

Alpha (α) radiation or decay

Alpha decay refers to an unstable nucleus emitting an alpha particle (α). Alpha radiation (particles) are energetic helium nuclei, in other words, helium atoms without their two electrons, and are written as $^{4}_{2}\mathbf{He}$. Obviously, an alpha particle has two protons and two neutrons, and is doubly positively charged due to the two protons.

What happens when alpha decay occurs?

For each alpha particle emitted, two neutrons and two protons (hence four nucleons) are lost. This reduces the mass number by four and the atomic number by two and results in transmutation. This transmutation is a natural process. A general equation for an alpha decay is:

$$\underbrace{{}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y}_{\text{transmutation}} + {}^{4}_{2}He\ (\alpha)$$

Why does alpha decay occur?

As a general rule, unstable elements become more stable through the process of radioactive decay. When alpha decay occurs, the size of the nucleus reduces and becomes more stable. Hence it may be concluded that alpha decay occurs for elements that are too 'big'; elements are considered too 'big' if their atomic number is equal to or greater than 83.

Some examples include:

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

$${}^{241}_{95}Am \rightarrow {}^{237}_{93}Np + {}^{4}_{2}He\ (\alpha)$$

NOTE: Both ${}^{238}_{92}U$, ${}^{241}_{95}Am$ are elements beyond element 83, and therefore are too large to be stable.

Beta (β) radiation or decay

There are two types of β decay: β^- decay and β^+ decay. β^+ decay is not required by the 'From Quanta to Quarks' syllabus, and therefore is not discussed in this chapter. (Also note an alternative to β^+ decay is electron capture.)

β^- decay occurs when an unstable nucleus breaks down to emit β^- radiations (particles). β^- particles are fast-moving electrons and have the symbol of ${}^{0}_{-1}e$. The β^- particle is derived from the conversion of a neutron into a proton and electron inside the nucleus; the electron is ejected from the nucleus whereas the proton stays within the nucleus: ${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e$

What happens when β^- decay occurs?

For each β^- particle emitted, a neutron is converted to a proton, therefore the total number of nucleons, and hence the mass number, does not change. However, because there is now an added proton, the atomic number increases by one. This again results in natural transmutation. A general equation for β^- decay is:

$$\underbrace{{}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y}_{\text{transmutation}} + {}^{0}_{-1}e\ (\beta)$$

Why does β^- decay occur?

Through β^- decay a neutron is converted into a proton and the element is now more stable. Hence β^- decay occurs when there are too many neutrons compared to protons, or too few protons compared to neutrons. Generally, for small atoms, the neutron-proton ratio should be about 1:1, whereas for larger atoms such as uranium, the ratio can be as high as 1.5:1. You may need to consult the periodic table to determine whether the number of neutrons in a particular atom is too many.

Some examples include:

$${}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e\ (\beta)$$

$^{90}_{38}Sr \rightarrow ^{90}_{39}Y + ^{0}_{-1}e$ (β)

$^{60}_{27}Co \rightarrow ^{60}_{28}Ni + ^{0}_{-1}e$ (β)

Note that $^{14}_{6}C$, $^{90}_{38}Sr$ and $^{60}_{27}Co$ all have more neutrons compared to their stable isotope listed in the periodic table. **Isotopes** refer to the same element with different numbers of neutrons; isotopes of the element that may undergo radioactive decay are referred to as **radioisotopes**.

There is another small particle accompanying β^- decay. This will be discussed in the next section.

Gamma (γ) radiation or decay

Gamma (γ) radiation is the highest frequency electromagnetic radiation in the EMR spectrum. Gamma decay occurs when atoms try to discharge the excessive amounts of energy from the nucleus. The nucleus would have the excessive amount of energy usually as a result of some kind of prior disturbance, such as having been bombarded by neutrons from an external source or having previously undergone alpha or beta decay. Gamma radiation is pure energy so by itself does not cause transmutation. Nevertheless, through gamma decay, the element becomes more stable.

Some examples include:

(a) $^{60}_{27}Co \rightarrow ^{60m}_{28}Ni + ^{0}_{-1}e$

And immediately $\underbrace{^{60m}_{28}Ni \rightarrow ^{60}_{28}Ni}_{\text{No transmutation}} + \gamma$

m = metastable/excited, indicating that the nucleus has excessive amounts of energy.

Overall equation: $^{60}_{27}Co \rightarrow ^{60}_{28}Ni + ^{0}_{-1}e + \gamma$

(b) $^{99}_{42}Mo \rightarrow ^{99m}_{43}Tc + ^{0}_{-1}e$

After a while $\underbrace{^{99m}_{43}Tc \rightarrow ^{99}_{43}Tc}_{\text{No transmutation}} + \gamma$

Note that for cobalt-60, because the gamma radiation occurs immediately after the beta decay, sometimes the two forms of radiation are said to occur together and cobalt-60 is described as a co-emitter of beta and gamma radiations. However, in the second example, the gamma decay for technetium-99m is a delayed process. Consequently, technetium-99m is described as pure gamma emitter and its parent isotope molybdenum-99 is described as a beta emitter. Nevertheless, the principle of the gamma decay is the same in both cases and in particular, gamma decay by itself does not cause transmutation.

Some examples of artificial transmutations

Both alpha and beta decays lead to natural transmutation. However, as mentioned before, transmutations can also be done by artificial means. These include:

1. Bombarding elements with α particles, as seen in Chadwick's experiment.
2. Bombarding elements with slow neutrons, which will be discussed in detail later in this chapter.
3. Bombarding elements with charged particles at high speeds in a particle accelerator. This is covered in Chapter 17.

16.4 Wolfgang Pauli and the discovery of neutrinos

■ *Discuss Pauli's suggestion of the existence of neutrino and relate it to the need to account for the energy distribution of electrons emitted in β-decay*

When radioisotopes undergo alpha decay, the ejected alpha particles either have energy that is identical or varying in a predictable way. However, when beta decay occurs, the energy of the ejected electrons exhibits a wide range, from a minimum of approximately 0.02 MeV to a maximum of approximately 1.2 MeV, as shown in the graph in Figure 16.3. An obvious question is that if a beta particle can achieve a maximal energy of 1.2 MeV, then what accounts for the missing energy for those beta particles with a sub-maximal energy level? In other words, if no energy loss can be identified, then all of the beta particles should have the same maximal energy. This puzzle led some scientists, including Niels Bohr, to start questioning the validity of the law of conservation of energy at the atomic level. It was the Austrian physicist Wolfgang Pauli who solved this by proposing that there was another small particle that was co-emitted during beta decay that would carry away the missing energy. This particle was later termed the **neutrino**.

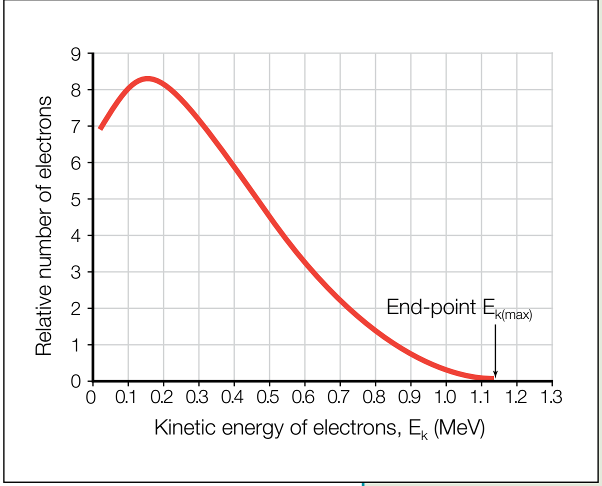


Figure 16.3 The energy profile of beta decay: this graph shows that the beta particles emitted during a beta decay exhibit a whole range of energy levels

NOTE: 1 MeV is one mega electronvolt.

1 electronvolt = 1.6×10^{-19} J

Therefore, 1 MeV = 1.6×10^{-13} J.

An electronvolt is an alternative unit of energy.

Properties of the neutrino

The proposed neutrino was hypothesised to be electrically neutral and have no rest mass. However, it carried energy and momentum and travelled at the speed of light. The neutrino carried away a variable fraction of energy during beta decay so that the total energy of the decay is always conserved—if the beta particle carries more energy, then the neutrino carries less and vice versa.

Billions of neutrinos from the Sun pass through the Earth every day undetected. This is because neutrinos have almost no mass and are electrically neutral, therefore causing minimal interactions with matter.

Taking the existence of neutrinos into account, the equations for beta decay should be written as:

β^- decay: ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e\ (\beta) + \overline{v}$ Anti-neutrino

β^+ decay: ${}^{18}_{9}F \rightarrow {}^{18}_{8}O + {}^{0}_{+1}e\ (\beta^+) + v$ Neutrino

Remember that an anti-neutrino is associated with the emission of the electron (β^-), whereas a neutrino is associated with the release of the anti-electron (positron) (β^+). Neutrino and anti-neutrino, as well as electron and positron, are known as **matter and anti-matter pairs**.

The detection of neutrinos

The detection of neutrinos can be extremely difficult for three reasons:

1. Neutrinos have no charge, and hence do not cause ionisation. So they cannot be detected by conventional detectors such as a cloud chamber.
2. Neutrinos have a mass of virtually zero, and therefore will not undergo any collisions like neutrons would in Chadwick's experiment.
3. Neutrinos are invisible; unlike photons, neutrinos cannot be seen.

The existence of neutrinos was predicted in 1934 by Pauli but it took about 20 years for the technologies to evolve to enable the detection of neutrinos experimentally.

NOTE: When matter meets anti-matter, they annihilate each other's mass completely. This mass is converted into energy in the form of gamma rays, according to the equation $E = mc^2$.

16.5 Strong nuclear force

- ***Evaluate the relative contributions of electrostatic and gravitational forces between nucleons***
- ***Account for the need for the strong nuclear force and describe its properties***

The nucleus contains protons and neutrons. Protons are positively charged particles, therefore when they are placed next to each other, they tend to repel. The following example illustrates the force of interaction between protons when they are placed next to each other inside the nucleus.

Example

On average, two nucleons (protons) are separated by a distance of 1.30×10^{-15} m. Calculate:

(a) The repulsive force between two protons due to their electric charge.
(b) The gravitational attraction force between these two protons.

Solution

(a) The equation used to calculate the size of the electrostatic force:

$$F_q = \frac{(9 \times 10^9) \times q_1 \times q_2}{d^2}$$

Known quantities:

$q_1 = 1.602 \times 10^{-19}$ C
$q_2 = 1.602 \times 10^{-19}$ C
$d = 1.30 \times 10^{-15}$ m

Unknown F_q

Substituting into the equation:

$$F_q = \frac{(9 \times 10^9) \times 1.602 \times 10^{-19} \times 1.602 \times 10^{-19}}{(1.30 \times 10^{-15})^2}$$

$= 137$ N Repulsion

(b) The equation used to calculate the size of the gravitational attraction force:

$$F_g = \frac{(6.67 \times 10^{-11}) \times m_1 \times m_2}{d^2}$$

Known quantities:

$m_1 = 1.673 \times 10^{-27}$ kg

$m_2 = 1.673 \times 10^{-27}$ kg

$d = 1.30 \times 10^{-15}$ m

Unknown F_g

Substituting into the equation:

$$F_g = \frac{(6.67 \times 10^{-11}) \times 1.673 \times 10^{-27} \times 1.673 \times 10^{-27}}{(1.30 \times 10^{-15})^2}$$

$$= 1.10 \times 10^{-34} \text{ N Attraction}$$

You can see from the above example that the gravitational attraction force that tries to hold the protons together is nowhere near as strong as the repulsive electrostatic force. Consequently, it will seem to be impossible for the nucleus to hold together its protons unless there exists another holding force. This is the **strong nuclear force**.

The strong nuclear force is one of the four fundamental forces in the Universe. Fundamental forces are **gravitational force**, **electromagnetic force**, **strong nuclear force** and **weak nuclear force**. Gravitational force is the force resulting from mass. Electromagnetic force is the force due to the interaction between electric fields and/or magnetic fields. (The weak nuclear force will not be described in this book, as it is not a part of the HSC syllabus.)

Definition

The **strong nuclear force** is the force that is responsible for holding the nucleons together inside the nucleus.

Two important properties of the strong nuclear force:

1. The strong nuclear force acts equally between proton–proton, proton–neutron and neutron–neutron. This means that the strong nuclear force is responsible for holding all nucleons together, although it is obvious that such a force is more important for the protons, since neutrons are neutral and do not repel. The strong nuclear force is essential for counteracting the electrostatic repulsive force between the protons.

   The fact that the strong nuclear force has an equal action between all nucleons also explains the role of neutrons in stabilising the nucleus. Inside a nucleus, neutrons are placed between protons, holding the protons together via the strong nuclear force while separating the protons from each other so that the size of the repulsive force is reduced. Larger elements need to have relatively more neutrons compared to protons to allow the neutrons to be interspersed among the protons so that the repulsive forces between the protons are reduced as the protons are separated.

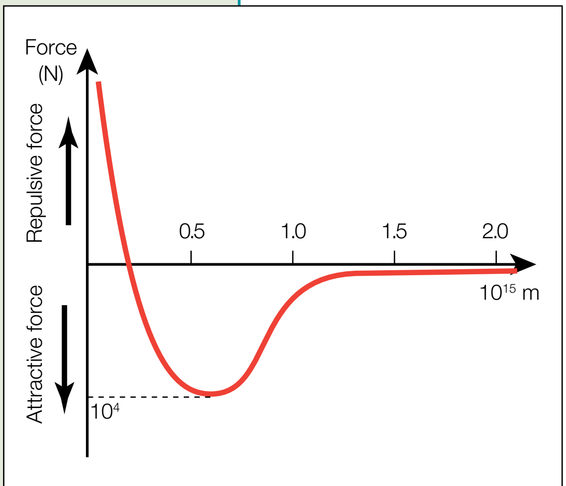


Figure 16.4 The profile of the strong nuclear force: the force is very strong but acts over a very short distance; the force becomes repulsive when acting over extremely short distances

2. The strong nuclear force is a very powerful force; however, it only acts over a very short distance. The best way to illustrate the size and profile of this force is by using a graph as shown in Figure 16.4. As you can see, the strong nuclear force is at its greatest strength, about 10^4 N, when it is acting over a distance of approximately 1.3×10^{-15} m, which is the average distance of separation between the nucleons. This force is very adequate in holding the nucleons together. However, the size of the force declines very quickly and reaches almost zero when acting at a distance of 2×10^{-15} m. Also, note that at a distance less than 5×10^{-16} m, the force becomes repulsive. This is also significant as the repulsiveness of the force prevents the nucleons getting too close or fused together. In other words, the force profile of the strong nuclear force is such that it tries to hold the nucleons apart at an approximately constant distance of 1.3×10^{-15} m.

Nuclear reactions

It is important to point out that the structure of the nucleus is far more complex than that discussed so far. In the remainder of this chapter, other reactions the nucleus can undergo are dealt with in addition to natural radioactive decay.

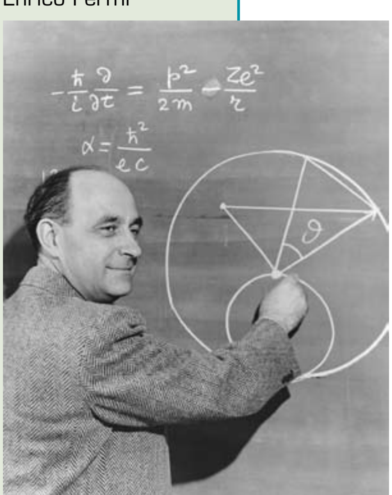
16.6 Fermi's artificial transmutation experiments

Soon after the discovery of neutrons by Chadwick, Italian scientist Enrico Fermi (1901–1954) realised that neutrons, due to their lack of charge, would have great potential to reach the nucleus of atoms to cause reactions. Between 1934 and 1938, Fermi bombarded many elements with neutrons. In the majority of the cases, heavy isotopes of the same element were formed. For example:

$$^{12}_{6}C + ^{1}_{0}n \rightarrow ^{13}_{6}C$$

In some cases, these heavier isotopes were actually unstable and would undergo radioactive (beta) decay to form new elements.

Enrico Fermi



NOTE: The reason for beta decay is that the element now has an excessive number of neutrons.

For example:

$$^{103}_{45}Rh + ^{1}_{0}n \rightarrow ^{104}_{45}Rh$$

Then $^{104}_{45}Rh \rightarrow ^{104}_{46}Pd + ^{0}_{-1}e + \overline{v}$

A change in the identity of the element has been achieved. This has been done via an artificial means. This is an example of **artificial transmutation**.

Fermi went on to postulate that if the same was to be done with uranium—the largest naturally occurring element—a new element with an atomic number one larger than uranium could be produced. This can be demonstrated in the following equations:

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

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

Through these reactions, Fermi produced element 93, named neptunium, which was the first artificially produced element. Neptunium was also the **first human-made element** beyond uranium and so it was referred to as the first **transuranic element**. Not surprisingly, transuranic reactions are another example of artificial transmutations.

Definition

Transuranic elements are elements that have atomic numbers larger than that of uranium. Since uranium is the largest naturally occurring element, all transuranic elements are human-made.

Also, neptunium-239 would undergo a further beta decay to form plutonium-239 and thus create the **second transuranic element**:

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

The need for slow neutrons

During the neutron bombardment experiments, Fermi noticed the bombardment was much more efficient when the neutrons used were slowed down. This is because fast neutrons tend to go through the nuclei without being captured, and thus do not cause nuclear reactions.

To slow down neutrons, a **moderator** needs to be used. Moderators are materials that possess the property of slowing down the neutrons as the neutrons pass through them. They facilitate the neutron-capturing by the nuclei—hence transmutations. Some examples of materials used as a moderator are:

- D_2O (heavy water) (where D is deuterium)
- H_2O
- graphite (carbon)
- beryllium or beryllium oxide

16.7 The accidental discovery of nuclear fission reactions

- ***Describe Fermi's initial experimental observation of nuclear fission***

There was no doubt that during Fermi's neutron bombarding experiments, transuranic elements were produced and detected. However, Fermi and his team were puzzled when they found that apart from the anticipated transuranic elements, there were also many other isotopes produced. All were beta emitters with different measurable half-lives. Clearly, this indicated that another process must be taking place at the same time but they could not understand the nature of this process.

It was not until 1939 that Austrian physicists Lise Meitner (1878–1968) and Otto Frisch (1904–1979) explained this observation by stating that the neutron bombardment led to the breaking down of uranium-235 into two smaller nuclei of roughly equal size. The term **nuclear fission** was coined to describe this process.

Definition

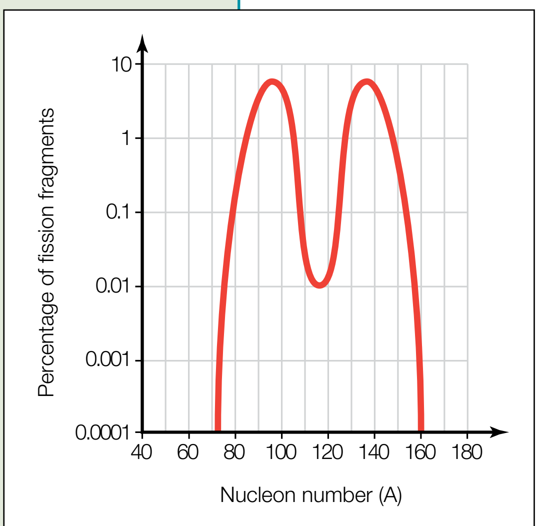
Nuclear fission refers to the process when a large atom, such as uranium, is hit by a slow neutron. It breaks down to give two smaller nuclei of roughly the same size (daughter isotopes) and at the same time, emit a few more neutrons and release energy.

For example:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3(^{1}_{0}n) + energy$$

Some examples of the elements that can undergo fission include uranium-235 and plutonium-239. Note that the two daughter isotopes of the fission reaction are randomly generated as a probability function. For uranium, this can be any pair from hydrogen (Z = 1) and protactinium (Z = 91) to two of palladium (Z = 46). (Both give a total of 92, the atomic number for uranium.) Nevertheless, the most likely pairs formed will be ones that include one relatively smaller element and another that is relatively heavier. Such a pattern can be represented by a graph as shown in Figure 16.5.

Figure 16.5 Mass distribution pattern of products of nuclear fission



To provide explanation for Fermi's initial observations, uranium has two naturally occurring isotopes: uranium-238 and uranium-235. Uranium-238 was the isotope that was capable of undergoing neutron capturing and transuranic reaction; this was expected by Fermi and his team. Uranium-235 on the other hand was to undergo fission having been hit by a neutron, and those puzzling beta emitters with variable half-lives were in fact various pairs of daughter isotopes produced by the fission reaction.

16.8 Fermi's discovery of chain reactions

It is apparent from the fission equation $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3(^{1}_{0}n) + energy$, that fission produces more neutrons than it consumes. If these extra neutrons are then allowed to cause more fission reactions, even more neutrons will be produced, thus leading to even more fission reactions. A **chain reaction** is set up. Using the above equation as an example, one neutron gives rise to three neutrons, which will then cause three uranium atoms to undergo fission to produce nine neutrons, thus the number of neutrons and the number of uranium atoms undergoing fission increases by a factor of 3^n. This is shown in the Figure 16.6 (a).

If this is allowed to proceed *uncontrolled*, then very quickly the number of uranium atoms undergoing fission will be very high. At the same time, a huge amount of energy will be released and an explosion will occur. This forms the basis of nuclear bombs. In cases where a steady rate of energy production is required, such as in nuclear power plants, this chain reaction needs to be *controlled*. To achieve this, a neutron-absorbing substance is used to take away the extra neutrons produced, so that the number of neutrons involved to initiate each of the subsequent fission reactions remains constant. This results in a steady rate of fission, and therefore energy liberation. This is shown in Figure 16.6 (b).

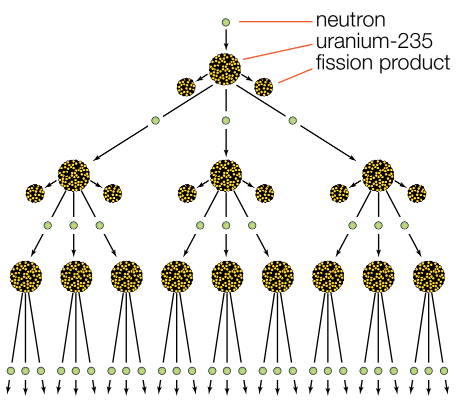


Figure 16.6 (a) Uncontrolled fission chain reaction: all neutrons produced by the fission reaction are allowed to strike more uranium atoms to cause more fission

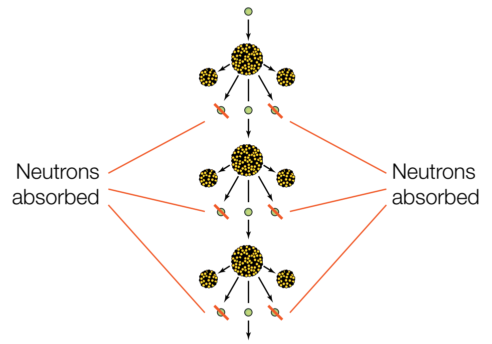


Figure 16.6 (b) Controlled fission chain reaction: some neutrons produced by the fission reaction are absorbed so that the number of neutrons involved in the fission reaction is constant

16.9 Comparing controlled and uncontrolled fission reactions

■ ***Compare requirements for controlled and uncontrolled nuclear chain reactions***

Definition

Uncontrolled fission reactions are fission reactions where all the neutrons produced during the reaction are allowed to strike more fissionable material to cause further nuclear fission so that the process continues exponentially. These reactions are adopted in nuclear weapons.

Definition

Controlled fission reactions are fission reactions that allow the extra neutrons produced during the reaction to be absorbed, so that approximately the same number of neutrons will be present for each of the subsequent fission reactions; in these cases, the rate of fission is steady. These reactions are adopted in nuclear power plants to produce heat energy at a steady rate.

Nuclear power station at Three Mile Island, Pennsylvania, USA

A mockup of the Fat Man nuclear device

The concept of controlled and uncontrolled nuclear fission is demonstrated in Figure 16.6. Although the two types of fission reactions are different, they share common features. These are discussed below.

The similarities

Both controlled and uncontrolled fission reactions require:
- fuel
- moderator

Fuel

Both controlled and uncontrolled fission reactions require either fissionable uranium-235 or plutonium-239 as fuels. Natural uranium ore only contains less than 1% fissionable uranium-235 compared to the 99% of uranium-238. (Recall that uranium-238 is not fissionable, rather it undergoes transuranic reactions.) In the case of the controlled chain reactions, processes are required to concentrate the fissionable uranium-235 to a concentration of at least 5%; whereas in the case of uncontrolled nuclear fission reactions, such as those for nuclear bombs, the required concentration may be as high as 95%. The processes for concentrating uranium-235 will be discussed in the next chapter. Plutonium-239 on the other hand does not occur naturally, thus extra effort is required to 'breed' it through transuranic reactions.

In addition to the required concentration, the fissionable fuels also need to have their mass above the **critical mass**.

Definition

Critical mass is the smallest amount of fissionable material that would sustain a chain reaction.

In simple terms, the amount of fissionable material needs to be sufficiently large so that a chain reaction can be sustained. This is because:
- There is a possibility that neutrons can be captured by the fissionable atoms (fuel) without causing fission.
- There is a possibility that neutrons will be captured by other non-fissionable elements mixed within the fuels.
- Also, there is a possibility that the neutrons will escape without being captured.

Thus there needs to be a sufficiently large amount of fissionable material so that the probability of the neutrons striking the fissionable atoms is sufficiently high to sustain a continuous fission process.

In most controlled fission reactions, enriched uranium (concentration of about 5%) is made into separate rods that together exceed the critical mass. These are called **fuel rods**. Each fuel rod is enclosed in a gas-tight aluminium case. The fuel rods are inserted into the reaction core for nuclear fission to take place to produce energy. Once the uranium is used up, the rods are removed and new ones are inserted.

In the case of uncontrolled nuclear fission reaction, fragments of fissionable material are brought together very quickly so that the total mass exceeds the critical mass before the bomb explodes. This is discussed in the next chapter.

Moderator

A moderator is used to slow down a neutron, as discussed. Slow neutrons are more efficient in causing nuclear reactions than fast neutrons.

The differences

Controlled nuclear fission reactions have extra requirements:

- control rods
- coolant
- radiation shield

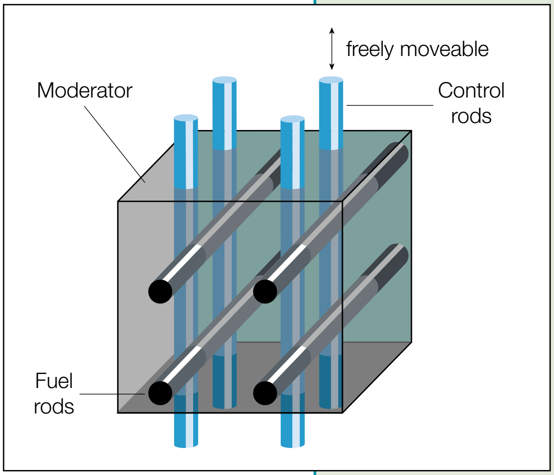


Figure 16.7 Control rods being inserted in between the fuel rods within a moderator

Control rods

In a controlled fission reaction, extra neutrons produced by the fission reaction are absorbed by the control rods so that the number of neutrons present for each of the subsequent fission reactions remains roughly constant. Some materials that can be used to make control rods are cadmium or boron. Control rods are designed to be able to move into and out of the reactor core freely. When they are moved further into the core, they absorb more neutrons, and therefore slow down the reaction, whereas when they are removed from the core, they absorb fewer neutrons, so the reaction speeds up. The movement of the rods is controlled by a computer system such that the rate of fission reaction is always controlled tightly. An illustration of how the control rods can be set up along with the fuel rods is shown in Figure 16.7.

Coolant

In a controlled fission reaction, the coolant is pumped to circulate through the reaction core. The role of the coolant is to first carry away the heat from the reactor core so that the core, which is where the nuclear fission takes place, will not melt down as a result of the extreme heat produced. Second, as the coolant carries the heat away, it is able to move the energy from inside the reactor core to somewhere else where the energy can be utilised to do useful work. This can, for example, be to heat up water to produce steam, which is in turn used to power a turbine attached to a generator. Some examples of the coolants used are molten sodium or molten sodium chloride, both of which are able to carry away sufficient amounts of energy quickly enough to be effective.

Radiation shield

The radiation shield of a nuclear fission reactor consists of an inner layer, which is made of lead, and an outer layer, which is a thick layer of high-quality concrete. The inner lead layer is designed to reflect most of the neutrons produced by the fission reaction back into the reaction core. This will not only result in fewer neutrons reaching the outer environment to do damage but also ensure that there are more neutrons in the nuclear reactor core to facilitate the nuclear reaction. The outer concrete layer acts as a biological shield to further block the radiation coming out of the reactor core. The principal role of the radiation shield is therefore to ensure that the radiation is contained within the reactor core so that the surrounding environment is not affected.

Although the most important application of a controlled nuclear fission reaction is to produce energy, there are other important uses for it. The fission products themselves may have extensive applications in various industries, medicine and agricultural settings. As well, the neutrons produced by the fission reaction can be used to carry out transmutations via neutron capturing. In Australia, these take place at the Australian Nuclear Science and Technology Organisation (ANSTO) facility at Lucas Heights, near Sydney.

PFA

H4

'Assesses the impacts of applications of physics on society and the environment.'

TR

PFA scaffold H4
Mapping the PFAs

■ *Compare requirements for controlled and uncontrolled nuclear chain reactions*

What are the applications of physics in this case?

Nuclear fission, as first observed by Fermi, has been utilised for nuclear weapons, large scale nuclear-powered electricity generation as well as nuclear-powered naval vessels and satellites for more than 60 years. Many radioactive isotopes used in medicine and industry require a nuclear reactor for their production.

What impacts have there been on society?

There have been significant and major impacts on society due to controlled and uncontrolled nuclear chain reactions.

The first impact on society was brought about by the dropping of the two atomic bombs (both fission bombs but of slightly different designs) on the Japanese cities of Hiroshima and Nagasaki. The subsequent deaths of tens of thousands of civilians, the destruction of large parts of these cities and the release of radioactivity shocked the world. It was the reason Japan surrendered, ending the war in the Pacific, even though the US had no more atomic bombs ready at the time. Should the Japanese have decided to fight on, thousands more allied and Japanese soldiers would have been killed using conventional warfare.

The arms race and the Cold War, during which the US and the USSR produced sufficient nuclear weapons to destroy the major cities of the world many times over, caused the release of radioactivity into the atmosphere and oceans from the many hundreds of test bombs detonated by both sides.

The production of electricity harnessing the heat energy from controlled nuclear chain reactions has been used widely in many countries, particularly in Europe, the USSR (now Russia and smaller states), Scandinavia, Canada, Japan and the US. With a few exceptions, this source of electricity has been reliable and affordable; however the Three Mile Island (US) and the far worse Chernobyl (Ukraine) accidents had serious adverse effects. The Chernobyl accident released large amounts of highly radioactive material, resulting in deaths, birth defects and cancers for many years after the event.

Small power generators using nuclear fission to develop heat and thus electricity have been used to power satellites and space probes successfully for many years. The use of radioactive isotopes in medicine and industry is possible partly due to their production using neutron bombardment. The neutrons required for this are sourced from nuclear reactors. The ANSTO facility at Lucas Heights in Sydney's southern suburbs is Australia's only operating nuclear reactor, and is used for the production of radioisotopes and for research.

What impacts have there been on the environment?

The immediate environments surrounding the Hiroshima and Nagasaki detonation sites have remained contaminated by radioactive fallout (although the cities themselves have been rebuilt). Radioactive contamination surrounds the test sites near Woomera in South Australia and the Monte Bello islands off Western Australia. Numerous similar sites around the world remain uninhabitable.

Radioactive waste from controlled nuclear chain reactions within nuclear power plants is a major concern to the countries faced with its disposal. The waste remains dangerous for thousands of years. Australia has been at the forefront of developing safe methods for its storage. In the past, some countries simply dumped the waste at sea in metal drums, which have since begun to rust and leak.

One positive side to nuclear power plants that has gained increased attention over recent years is that they do not produce carbon dioxide gas in order to generate heat. Coal, gas and oil-fired power stations are the major source of this greenhouse gas worldwide. However, the mining operations and transporting of the uranium fuel used in nuclear power stations does produce carbon dioxide.

The assessment of these impacts

There is no doubt that uncontrolled and controlled nuclear chain reactions have made significant and major impacts on society and the environment over the past 60 or so years. These impacts have been positive and negative. The debate about the merits or otherwise of using controlled nuclear chain reactions will continue well into the future.

USEFUL WEBSITES

WWW

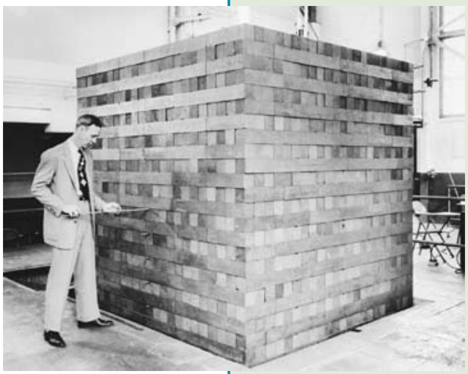
The Australian Nuclear Science and Technology Organisation website:
http://www.ansto.gov.au

Information and background to the social and environmental consequences of the Chernobyl disaster:
http://www.chernobyl.info/index.php

16.10 Fermi's first controlled chain reaction

■ ***Describe Fermi's demonstration of a controlled nuclear chain reaction in 1942***

In 1942 the first sustained fission chain reaction was observed. A team of scientists led by Fermi built a nuclear pile in a converted squash court at the University of Chicago. The pile consisted of graphite blocks surrounding a core of uranium. The quantity of uranium required, approximately 60 tonnes, represented almost all the US reserves of the material at the time. To prevent an uncontrolled reaction that would cause an explosion, cadmium rods, which absorb neutrons, were inserted between the blocks of the uranium fuel. Radioactivity monitors were used to detect the sustained reaction, which continued once the cadmium control rods had been slowly withdrawn from the uranium core.



Fermi's first nuclear fission pile in 1942

16.11 Mass defect and binding energy

■ ***Explain the concept of a mass defect using Einstein's equivalence between mass and energy***

The total mass of the neutrons, protons and electrons that make up an atom is greater than the mass of the same atom as a whole. This discrepancy in mass is summarised in Figure 16.8. Two new terms require attention: **mass defect** and **binding energy**.

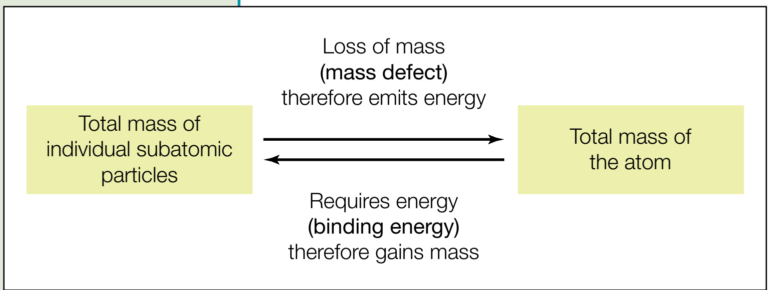


Figure 16.8 Relationship between mass defect and binding energy

Definition

Mass defect is the loss in mass when the mass of an atom as a whole is compared to the mass of its made-up components individually—protons, neutrons and electrons.

It follows that if mass is lost, energy must be liberated according to Einstein's equation $E = mc^2$. On the other hand, the same amount of energy must be put back if one is to separate the atom into its individual components and at the same mass is restored. This energy is known as binding energy.

Definition

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

The concept of mass defect and binding energy can be further illustrated through the follow example:

Example 1

Calculate the mass defect for a helium (He) atom and its corresponding binding energy, given that the rest mass of the helium atom is 4.002602 u. Express the energy in mega electronvolts (MeV).

Solution

Mass defect = total mass of the separate parts that make up the helium atom – mass of the helium atom

= (mass of a neutron × 2 + mass a proton × 2 + mass of an electron × 2) – mass of the helium atom

Because we are working with the atomic mass unit (u), we need to convert the mass of the neutrons, protons and electrons from kg to atomic mass unit (either using the values from Table 16.1 or from the HSC data sheet) . This can be done by dividing the mass in kg by 1.661×10^{-27}, since 1 u = 1.661×10^{-27} kg. Hence:

$$\text{Mass defect} = \left(\frac{1.675 \times 10^{-27}}{1.661 \times 10^{-27}}\right) \times 2 + \left(\frac{1.673 \times 10^{-27}}{1.661 \times 10^{-27}}\right) \times 2 + \left(\frac{9.109 \times 10^{-31}}{1.661 \times 10^{-27}}\right) \times 2 - 4.002602$$

$$= 0.0298013 \text{ u}$$

Therefore, an energy equivalent of this mass that needs to be put back in if we need to separate this atom back into its separate parts is governed by the equation $E = mc^2$. To use this equation, the mass must be converted back to kg by multiplying by 1.661×10^{-27}. Hence:

$$E_{binding} = 0.0298013 \times 1.661 \times 10^{-27} \times (3 \times 10^8)^2 \text{ J}$$

Converting the unit from joules to electron volt (eV) can be done by dividing the value in joules by the charge of an electron: 1.602×10^{-19}. Dividing this by 10^6 will convert the value from eV to MeV. Hence:

$$E_{binding} = 0.298013 \times \frac{1.661 \times 10^{-27} \times (3 \times 10^8)^2}{1.602 \times 10^{-19} \times 10^6}$$

$$E_{binding} = 27.8 \text{ MeV}$$

In fact, $\frac{1.661 \times 10^{-27} \times (3 \times 10^8)^2}{1.602 \times 10^{-19} \times 10^6}$ give rises to a constant, which is 933.1.

(Note that the HSC data sheet quotes 931.5, which is calculated from non-rounded off data.)

Binding energy per nucleon

It might seem logical to say that the larger the binding energy, the more energy is required to break down the atom into its separate parts, implying the atom is more stable. However, the problem is, as the atom gets bigger, its binding energy will naturally increase as there are now more separate parts put together. This large binding energy does not reflect how strong the atom is held together but rather the size of the atom. To make a fair comparison, one must be able to eliminate the effect of the size of the atom on binding energy. To do this, the binding energy is divided by the number of nucleons the atom has to give **binding energy per nucleon**. Since this is the energy per nucleon, the effect of the size of the atom on binding energy is eliminated and this gives an accurate reflection of the level of energy required to split the atom, and hence the stability of the atom.

A higher binding energy per nucleon means an atom or a nucleus is more stable. More energy is required to break it apart.

Example 1

Calculate the binding energy per nucleon for the helium atom.

Solution

Helium has two neutrons and two protons, therefore altogether four nucleons. Using the previous value obtained for the binding energy of He:

$$E_{binding\ per\ nucleon} = \frac{27.8}{4} = 6.95 \text{ MeV/nucleon}$$

Example 2

Calculate the binding energy per nucleon for magnesium-24 with a mass of 23.98504 u.

Solution

Mass defect = total mass of the separate parts that make up the magnesium atom – mass of the magnesium atom

= (mass of a neutron × 12 + mass a proton × 12 + mass of an electron × 12) – mass of the magnesium atom

$$\text{Mass defect} = \left(\frac{1.675 \times 10^{-27}}{1.661 \times 10^{-27}}\right) \times 12 + \left(\frac{1.673 \times 10^{-27}}{1.661 \times 10^{-27}}\right) \times 12 + \left(\frac{9.109 \times 10^{-31}}{1.661 \times 10^{-27}}\right) \times$$

$$12 - 23.98504$$

$$= 0.20938 \text{ u}$$

$$E_{binding} = 0.20938 \times \frac{1.661 \times 10^{-27} \times (3 \times 10^{8})^{2}}{1.602 \times 10^{-19} \times 10^{6}}$$

$$E_{binding} = 195.38 \text{ MeV}$$

Since magnesium has 24 nucleons, therefore:

$$E_{binding\ per\ nucleon} = \frac{195.38}{24} = 8.14 \text{ MeV/nucleon}$$

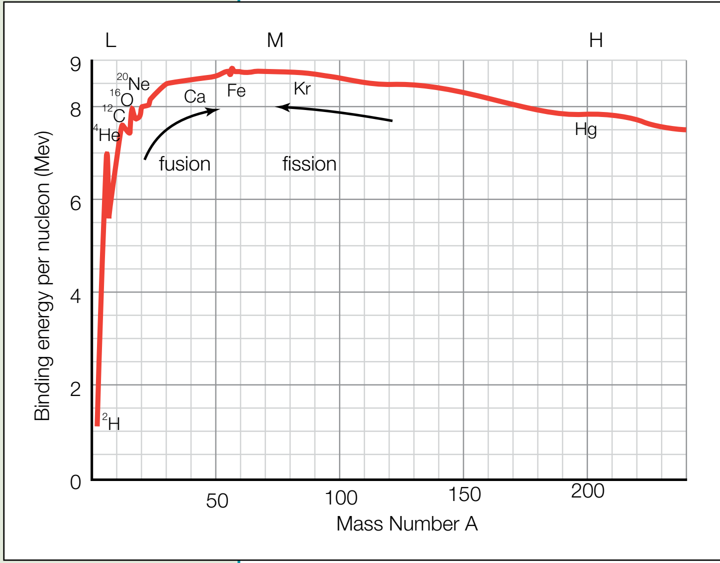


Figure 16.9 The binding energy per nucleon versus the atomic number

If the binding energy per nucleon is plotted against the atomic number, a graph as shown in Figure 16.9 is obtained.

Using this graph, some of the phenomena happening at a nuclear level can be explained. First, the graph can be used to explain the emission of alpha particles (helium nucleus, also see Chapter 16). When a nucleus is too large so that it is unstable, it emits small ‘packs’ of particles as a part of its decaying process. These ‘packs’ consist of two protons and two neutrons, therefore are helium nuclei. The reason for this is that as shown in Figure 16.9. Helium has a very high binding energy per nucleon compared to other small elements, therefore it is easiest and most energy efficient for the unstable nucleus to release protons and neutrons in the form of a helium nucleus. Although many other elements, for example carbon, have a larger binding energy per nucleon, they are generally too large to be released from an unstable nucleus.

From the graph it can also be seen that iron has the highest binding energy per nucleon, indicating that it is the most stable nucleus in the entire periodic table. It follows that for elements that are to the left of iron on the graph, if they are combined together at a nuclear level to form larger elements, they will become more stable, and in turn, energy will be released. This is basically the principle of **fusion reactions**, where smaller elements, when fused together, make heavier elements and release energy. This is the method by which stars generate their energy. Of course, the fusion process has to stop at iron, as beyond that, the elements gradually start to have lower binding energy per nucleon, thus their energy content is increased. To synthesise elements that are heavier than iron, energy input is required. This is also why even a large star will end its life once the fusion has reached iron, and elements that are heavier than iron are only formed during the supernova of the star—where the supernova provides the energy for the synthesis of elements beyond iron. Indeed, for elements that are to the right of iron on the graph, energy is only released when they are split to form small elements, that is, towards iron. This is the source of energy for fission reactions.

16.12 Energy liberation in nuclear fission

■ *Solve problems and analyse information to calculate the mass defect and energy released in natural transmutation and fission reactions*

Following from the previous section, when a large element is split to form smaller daughter elements, the atomic number moves to the left along the graph towards iron as shown in Figure 16.9. Consequently, the daughter elements will have lower energy content and thus energy will be liberated. The amount of energy liberated corresponds to the change in binding energy per nucleon between different elements, which is directly related to the change in mass between different elements—the reactants should have a larger total mass than the products. Use this concept to calculate the energy liberated during a nuclear fission reaction; this is shown in the example below.

Example

During a nuclear fission reaction, a slow neutron collides with and splits a U-235 nucleus. The product nuclei are Ba-141 and Kr-92 and a number of neutrons. If the kinetic energy of the colliding neutron is negligible, calculate the energy in MeV released by this nuclear reaction. Given that:
Mass of U-235: 235.0439 u
Mass of Ba-141: 140.9139 u
Mass of Kr-92: 91.8973 u

Solution

The first step is to write a balanced nuclear equation for this reaction. Knowing the reactants are $^{235}_{92}U$ and $^{1}_{0}n$ (neutron), and products are given to be $^{141}_{56}U$ *and* $^{92}_{36}Kr$, using the fact the mass number and atomic number have to be conserved, that is, equal on both sides, therefore three neutrons must be released as by-products. Hence the equation is written as:

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3({}^{1}_{0}n) + energy$$

The energy liberated is directly related to the loss in mass when the reactants go to form the products. Hence:

The mass loss in u = mass of reactants in u – mass of products in u
= mass of $^{235}_{92}U$ and one neutron – mass of $^{141}_{56}Ba$ *and* $^{92}_{36}Kr$ and three neutrons

$$= \left(235.0439 + \frac{1.675 \times 10^{-27}}{1.661 \times 10^{-27}}\right) - \left[140.9139 + 91.8973 + 3 \times \left(\frac{1.675 \times 10^{-27}}{1.661 \times 10^{-27}}\right)\right]$$

$$= 0.21584 \text{ u}$$

Therefore, the energy liberated can be calculated as:

$$E = 0.21584 \times \frac{1.661 \times 10^{-27} \times (3 \times 10^{8})^2}{1.602 \times 10^{-19} \times 10^{6}}$$

$$= 201.41 \text{ MeV}$$

NOTE: The concept used to calculate the binding energy from the mass defect is used here in the same way to calculate the amount of energy released from the mass loss. This is because under all circumstances, energy is always related to mass via Einstein's equation $E = mc^2$.

Observe radiation emitted from a nucleus using a Wilson cloud chamber

FIRST-HAND AND SECONDARY SOURCE INVESTIGATION

PHYSICS SKILLS

H12.1 A, B, C, D
H12.2 B

- ***Perform a first-hand investigation or gather secondary information to observe radiation emitted from a nucleus using Wilson cloud chamber or similar detection device***

The functional principle of the Wilson cloud chamber has already been discussed in this chapter, in the description of Chadwick's experiment.

You should be familiar with the set-up of a cloud chamber in a school laboratory. The trace that alpha, beta or gamma radiations would leave as they are going through the cloud chamber can be shown.

Condensation trails in a Wilson cloud chamber caused by emitted radiation

CHAPTER REVISION QUESTIONS

1. Define the term 'nucleons'.
2. (a) Describe Chadwick's experiment that allowed him to discover the existence of the neutron.
   (b) What was the significance of using the paraffin wax in his experiment?
   (c) There were two laws of conservation used in his experiment. What were they and why were they important for the discovery of the neutron?
3. Describe how a cloud chamber can be used to detect the presence of alpha, beta or gamma radiation.
4. Define 'radioactivity' and 'transmutation'.
5. (a) Determine whether the following elements are alpha emitters or beta emitters.
      (i) Potassium-40
      (ii) Thorium-232
      (iii) Radium 226
      (iv) Iodine-131
   (b) Write a nuclear equation to describe the decay of each of these elements.

6. Iron-59 undergoes gamma decay; write an equation to describe this reaction.

7. Under what circumstances were neutrinos discovered? Why was the law of conservation of energy important for the discovery of neutrinos?

8. (a) When aluminum is bombarded with alpha particles, a highly unstable isotope of phosphorus is formed. Write a nuclear equation to describe this reaction.
   (b) This radioisotope of phosphorus then undergoes a decay to form phosphorus-30 and another product. Identify this product and write a nuclear equation to describe this reaction.

9. Nitrogen-14 when bombarded with an alpha particle will give rise to oxygen-17 and one other element. Write a nuclear equation to describe this reaction.

10. A certain nucleus absorbs a neutron. It then undergoes beta decay and eventually breaks up to form two alpha particles.
    (a) Identify the original nucleus and the two intermediate nuclei.
    (b) Will there be any neutrino emitted? Explain.

11. (a) Define 'strong nuclear force'.
    (b) Describe two properties of strong nuclear force.
    (c) Why is strong nuclear force important in stabilising the nucleus?

12. What are control rods and why are they significant for nuclear fission reactions?

13. What are the key differences between a controlled nuclear fission reaction and an uncontrolled fission reaction?

14. The daughter isotopes for the fission of uranium-235 are caesium-141 and rubidium-93.
    (a) How many neutrons are released during this fission reaction?
    (b) Write a nuclear equation to describe this reaction.

15. When uranium-235 is bombarded by a slow neutron, xeon-139 and strontium-95 may be produced and a few neutrons are also released. Write a nuclear equation to describe this reaction.

16. Fermi was known as the father of nuclear physics. With the use of appropriate equations, describe his contributions to nuclear physics, making particular references to the production of transuranic elements and nuclear fission reactions.

17. Calculate the mass defect, binding energy and binding energy per nucleon for the following elements:
    (a) Lithium-7, mass = 7.016 003 u
    (b) Zinc-64, mass = 63.929 15 u
    (c) Radon-219, mass = 291.009 48 u

18. The energy released during normal radioactive decay can be calculated in the same way as to the energy released in a nuclear fission reaction. Essentially, the mass of the products will be less than the mass of the reactants, with the change in mass corresponding to the energy released. Calculate the energy released by an alpha decay of uranium-235, given that the mass of uranium-235 is 235.043 92 u and mass of thorium-231 is 231.03630 u. (Hint: an alpha particle is essentially a helium nucleus.)

19. When carbon-12 is bombarded by a proton, nitrogen-13 is produced. Write a nuclear equation to describe this reaction. Given that the mass of carbon-12 is 12.000 000 u and the mass of nitrogen is 13.005738 u. Calculate the energy released by this reaction in both MeV and J.

SR

Answers to chapter revision questions