Point Cook Senior

Year 11 Physics Unit 1

Special Area of Study 1
Energy from the nucleus

Chapter 12

Outcome

On completion of this chapter, you should be able to describe and explain typical fission and fusion reactions, energy transfer and transformation phenomena of importance in stars and in the production of nuclear energy, and the benefits and risks of the use of nuclear energy as a power source for society.

By the end of this chapter should be able to describe

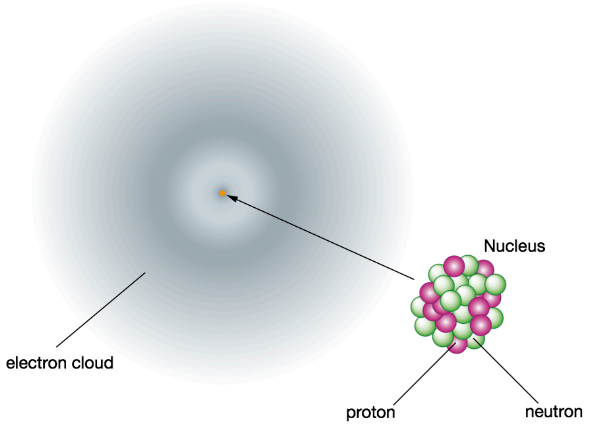
You will have covered material from the study of energy from the nucleus including:

- The nuclear model of the atom
- Nuclear fission in uranium-235 and plutonium-239
- Nuclear fusion reactions and stars
- Conditions for fission chain reactions
- Neutron absorption in uranium-238 and plutonium-239
- The transformation of nuclear energy into electrical energy

Splitting the atom—nuclear fission

The nucleus contributes most of the mass of the atom but accounts for almost none of the atom’s size. The diameter of a nucleus is typically about one ten-thousandth of the diameter of the electron cloud.

In this section, we will be examining the structure of the *nucleus* and the forces that exist within it.



This model of the atom was first developed in the early decades of the last century. protons and neutrons are found in the nucleus. electrons orbit the nucleus and this electron cloud comprises most of the atom’s size. If a tennis ball were used to represent the nucleus of an atom, the electron cloud would have a diameter of about 600m!

Inside the nucleus

Uranium is one of the largest atoms. It has 92 protons and over 140 neutrons in its nucleus. Even so, about 100 000 000 000 such uranium nuclei could be lined up across 1 mm!

A model known as the 'liquid drop model', proposed by Niels Bohr in 1936, is a useful way of visualising a nucleus. Nuclei are generally spherical in shape, but are quite fluid and can wobble like jelly.

Within the nucleus, there are protons in close proximity with other protons. This should seem odd since protons exert strong *electrostatic forces* of repulsion on each other. Shouldn't the nucleus simply blow apart? It obviously doesn't—so there must be something else going on. Another force, known as the *strong nuclear force*, is also acting and this is a force of attraction that acts to hold the nucleus together.

• **Electrostatic forces** act between *charged particles* and can act over relatively *large distances*. Within a nucleus, this means that each proton is strongly *repelling* every other proton, so this force is trying to make the nucleus disintegrate. Neutrons are unaffected by electrostatic forces.

• **The strong nuclear force** is a force of *attraction* that acts between *every* nucleon. This force acts like a nuclear cement. However, this force only acts over relatively *short distances*. Neutrons are attracted to nearby neutrons and protons. Protons are similarly attracted to nearby neutrons and protons. However, for nucleons on opposite sides of a large nucleus, this force is not significant.

When two protons are side by side in a nucleus:

- The forces of attraction and repulsion are acting at the same time.
- The strong nuclear force of attraction is much greater than the electrostatic force of repulsion that they exert on each other.
- When the protons are on opposite sides of a large nucleus, the short-range strong nuclear force will be weaker than the electrostatic force.

In small nuclei, where the protons and neutrons are all relatively close together, the strong nuclear forces are dominant. The nucleus is held together very strongly and so is very stable.

In large nuclei, the size of the nucleus reduces the influence of the strong nuclear force.

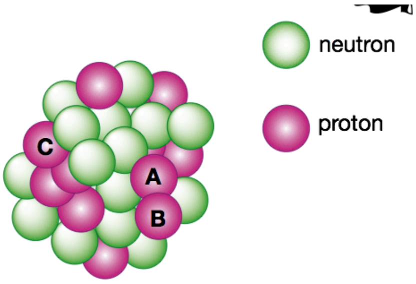


Figure 12.3 Proton A both attracts and repels proton B, but the attraction is greater because the strong nuclear force is very strong over short distances. Proton A also both attracts and repels proton C, but because of the greater distance between them, the force of repulsion is larger.

Now let us imagine that you were trying to construct a uranium nucleus, so you attempted to combine 92 protons and 92 neutrons. As shown in Figure 12.4, your attempt at a nucleus would spontaneously blow apart. It is inherently unstable because there are 92 protons all repelling each other and the size of the nucleus means that the effect of the strong nuclear force of attraction is diminished. To make your nucleus reasonably stable, more neutrons are required.

In nature, uranium nuclei are only ***reasonably*** stable when they have over 140 neutrons (though still radioactive).

Remember every nucleus with more than 83 protons, i.e. above bismuth (Bi) in the periodic table, is radioactive.

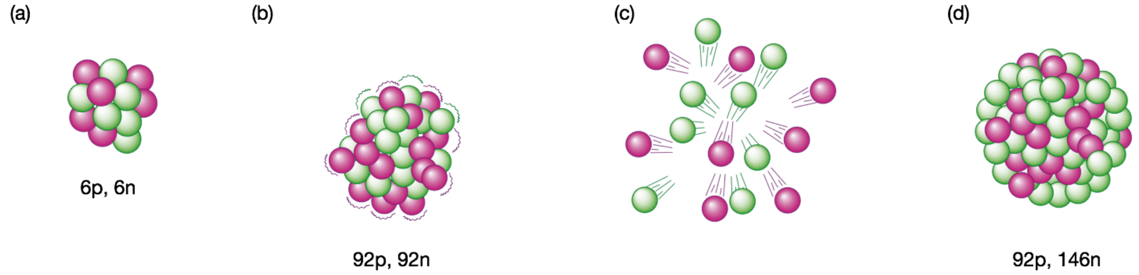


Figure 12.4 (a) A small nucleus such as carbon-12 is stable. This is because the electrostatic force of repulsion that acts between the protons is overwhelmed by the strong nuclear force of attraction. (b) and (c) A large nucleus with equal numbers of protons and neutrons cannot exist. The electrostatic forces of repulsion between the protons would overwhelm the strong nuclear forces. (d) Additional neutrons increase the stability of large nuclei. The extra neutrons increase the influence of the strong nuclear force and act like a 'nuclear cement', holding the nucleus together.

Nuclear fission

Early nuclear experiments were performed using alpha particles as high- speed 'bullets', bombarding target nuclei, and the resulting interactions were analysed (i.e. Rutherford's model of the atom gold foil experiment). The problem with this method was that both the alpha particles and target nuclei were positively charged and so repelled each other. It was possible for very energetic alpha particles to actually smash into the nuclei of small atoms such as nitrogen and aluminium. However, target nuclei with atomic numbers above 19, i.e. larger than potassium, repelled the alpha particles so strongly that collisions were not possible.

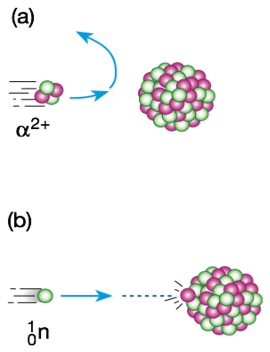


Figure 12.6 (a) Alpha particles are repelled so strongly by large atomic nuclei that collisions are not possible. (b) Neutrons, having no charge, are capable of colliding directly with the nucleus of an atom.

In 1934, Enrico Fermi, conducted an experiment where he bombarded uranium nuclei with neutrons and obtained some unexpected results. Some of the uranium nuclei absorbed the neutrons and split in two! Fermi was the first to observe *nuclear fission*, although the mechanics of this process was not determined until 1938.

NUCLEAR FISSION occurs when an atomic nucleus splits into two or more pieces. This is often triggered by the absorption of a neutron.

Nuclides that are capable of undergoing nuclear fission after absorbing a neutron are said to be **fissile**. Fissile nuclides are very uncommon. Uranium-235 and plutonium-239 are readily fissile. Uranium-238 and thorium-232 are only slightly fissile, requiring a very high-energy neutron to induce fission.

The release of neutrons during fission

When a uranium-235 or plutonium-239 nucleus absorbs either a slow- or a fast-moving neutron, it becomes unstable and spontaneously undergoes fission.

A typical fission reaction for uranium-235 is:

$${}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{91}_{36}\mathrm{Kr} + {}^{142}_{56}\mathrm{Ba} + 3{}^{1}_{0}\mathrm{n} + \text{energy}$$

Krypton-91 and barium-142 are known as the fission products or **fission fragments**. Three neutrons are freed from this uranium nucleus when it splits.

Usually either two or three neutrons are released. For uranium-235, an average of 2.47 neutrons per fission has been determined.

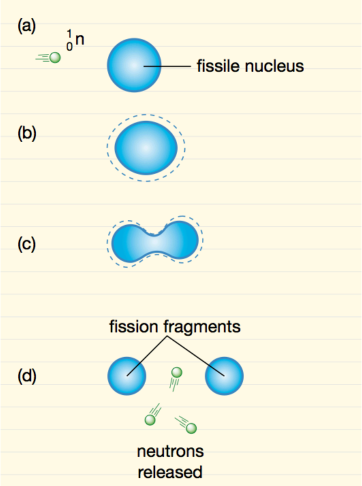


Figure 12.8 When a fissile nucleus such as uranium-238 is (a) struck by a neutron, the nucleus actually (b) wobbles about like a water droplet and (c) elongates. (d) If the nucleus stretches beyond a critical point, the electrostatic forces will overcome the strong nuclear forces and it will break into two. This is nuclear fission. Several neutrons are also released during this process. The fission fragments and neutrons have a large amount of kinetic energy.

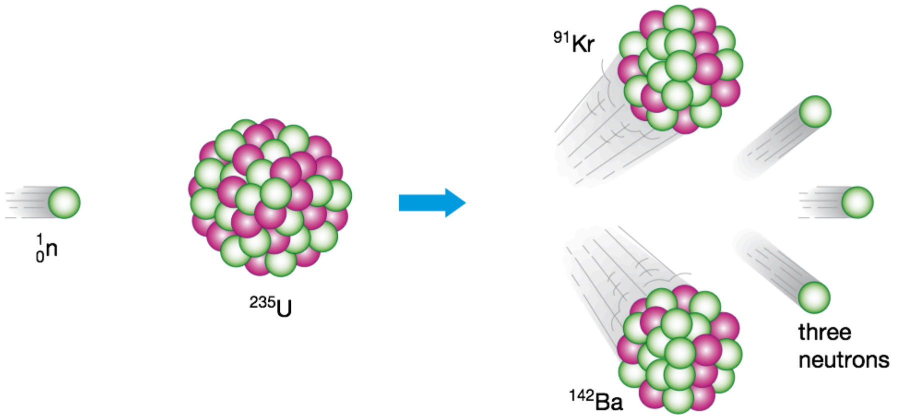


Figure 12.9 When a uranium-235 nucleus absorbs a neutron, nuclear fission occurs. The uranium nucleus splits in two, forming in this example krypton-91 and barium-142. Three neutrons are released.

The energy released during nuclear fission

The chemical reactions that you have probably performed at school typically release only a few electron volts of energy. Compared with this, an enormous amount of energy, about 200 MeV, is released during each fission reaction. This energy is mainly in the form of the kinetic energy of the fission fragments, with the neutrons and emitted gamma radiation also having some energy. It was Albert Einstein who provided the explanation of the origins of this energy. He showed that *mass* and *energy*, instead of being completely independent quantities, were in fact *completely equivalent*.

This does not mean that mass can be transformed into energy, rather that mass has energy and energy has mass.

In any fission reaction, the combined mass of the incident neutron and the target nucleus is always greater than the combined mass of the fission fragments and the released neutrons. For example, in Figure 12.9 the mass of the incident neutron and the uranium-235 nucleus is greater than the combined masses of the fission products—barium-142, krypton-91 and three neutrons. The energy released as a result of this mass decrease is given by Einstein's famous equation:

$$E = mc^2$$

It is important to note that only a very small proportion of the original mass of nuclei is available as usable energy—typically around 0.1%. The energy released during the fission process is usually expressed in either joules (J) or electronvolts (eV).

Now complete Questions 1 to 10 of Section 12.1

Point Cook Senior

Year 11 Physics Unit 1

Special Area of Study 1
Energy from the nucleus

Chapter 12.2

Aspects of fission

The properties of uranium-235, uranium-238 and plutonium-239

Uranium-235 is most likely to undergo fission when struck by a slow- moving or **thermal neutron** with energy as low as 0.01 eV. A slow- moving neutron can be absorbed into a uranium-235 nucleus, forming the highly unstable uranium-236 isotope. This then undergoes *fission* and releases energy.

A fast, high-energy neutron is not easily captured by a uranium-235 nucleus and so is less likely to induce fission. It is difficult for the nucleus to capture a **fast neutron** because the neutron does not stay close to it long enough for the strong, short-range nuclear force to drag it in.

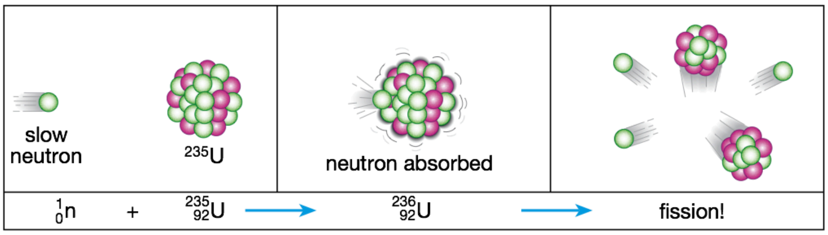


Figure 12.14 A slow neutron is absorbed by a uranium-235 nucleus, converting it into uranium-236, which is highly unstable. This nucleus then undergoes nuclear fission.

Uranium-238 is only slightly fissile. It requires a neutron with a large amount of energy (about 1 MeV) to cause fission in a uranium-238 nucleus. Because of its effectively non-fissile nature, uranium-238 is not suitable for use as a nuclear fuel, but it does have a role to play in nuclear energy production. A uranium-238 nucleus is far more likely to simply capture a neutron and become uranium-239. This then goes through a series of radioactive decays to become plutonium-239, itself a fissile substance. Uranium-238 is known as a **fertile** material because of this ability to capture a neutron and transform into a fissile substance.

Plutonium-239 is fissile in the same manner as uranium-235. However, plutonium nuclei require *fast neutrons* to bring about nuclear fission. Slow- moving, or thermal, neutrons do not cause fission in plutonium-239 nuclei.

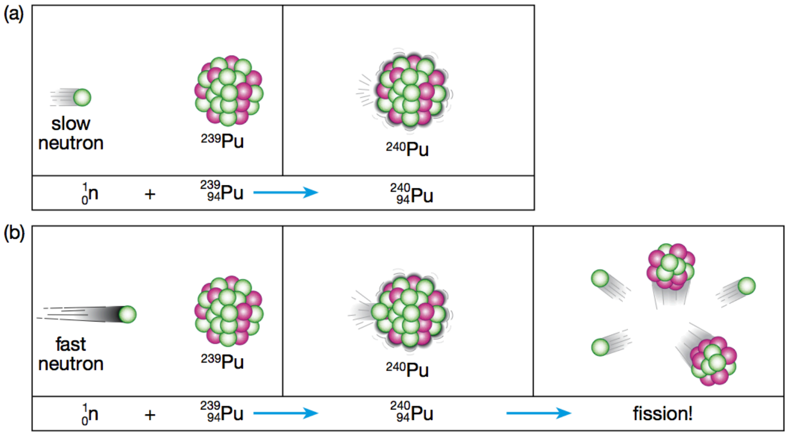


Figure 12.15 (a) When a plutonium-239 nucleus absorbs a slow neutron, the isotope plutonium-240 is formed. (b) The additional energy possessed by a fast-moving neutron causes the plutonium-240 nucleus to distort and split into fission fragments.

Chain reaction

The scientists working on the Manhattan Project during World War II knew that nuclear energy could be released from a single fissile nucleus. The problem that they faced was how to obtain energy from a vast number of fissile nuclei. The nuclear fission bomb that was dropped with such devastating effect over Hiroshima in 1945 exploded as a result of an *uncontrolled chain reaction* in its uranium-235 fuel. When uranium-235 undergoes fission, it releases two or three neutrons each time. Each of these neutrons is then able to cause fission in another uranium-235 nucleus, which in turn will also release two or three neutrons. Within a very short time, the number of released neutrons and fission reactions has escalated in a process known as a *chain reaction*.

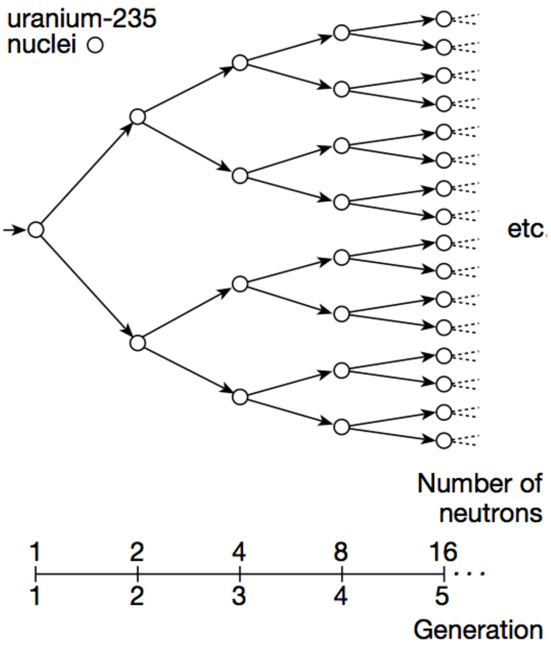


Figure 12.16 A single slow-moving neutron causes fission, and two neutrons which are both capable of splitting another nucleus are released. After five nuclear generations, 16 neutrons are capable of triggering fission.

In Figure 12.16, two neutrons are released during the fission reaction. The number of nuclei undergoing fission doubles each generation and within a small fraction of a second an enormous number of nuclei have undergone fission. Only a miniscule amount of energy (of the order of 10^{-13} J) is released by each fission reaction, but in this uncontrolled chain reaction there are so many reactions occurring in such a short time that an explosion results. In 1 kg of uranium-235, so many reactions occur that about 8×10^{13} J of energy is released in just over one-millionth of a second!

Nuclear fuel

In the 4.5 billion years since the Earth was formed, the radioactive isotopes that are naturally present in the Earth itself, its oceans and the atmosphere have been decaying to form more stable isotopes. By far the two most common isotopes of uranium present in the Earth's crust are uranium-238 and uranium-235. These have half-lives of 4.5 billion years and 710 million years respectively, and so uranium-235 has been decaying at a faster rate than uranium-238. This means that far less uranium-235 remains in the Earth's crust so that today the uranium that is mined from the ground consists of:

• 99.3%uranium-238—thenon-fissileisotope • 0.7%uranium-235—thereadilyfissileisotope. This means that a chain reaction cannot occur in a sample of uranium taken from the ground because the proportion of fissile uranium-235 is too low. To be useful as a nuclear fuel, uranium ore has to be *enriched*. This involves increasing the proportion of uranium-235 relative to uranium-238, a very difficult and expensive process. The slightly different masses of the isotopes enables separation to be achieved. The three common enrichment methods are the ultracentrifuge, electromagnetic and gaseous diffusion separation techniques.

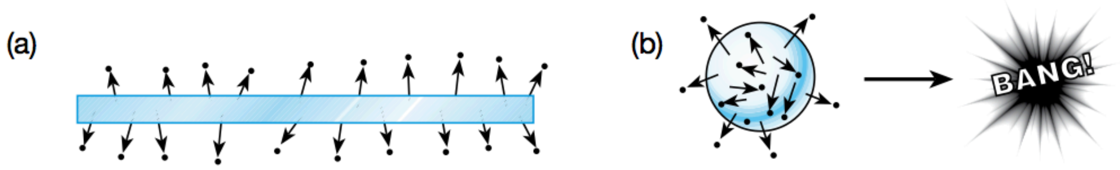
Nuclear weapons require fissile material that has been enriched to over 90% purity. The bomb that was dropped over Hiroshima contained 40 kg of 95% purity uranium-235. Nuclear reactors require fissile material enriched to about 3% uranium-235.

Critical mass

In their efforts to produce an explosion, the scientists working on the Manhattan Project during World War II had to establish a nuclear chain reaction in a sample of nuclear fuel. They found that the explosive ability of a sample of fissile material depended on its *purity* and *size*.

In a sample of nuclear material in which the *concentration* of uranium-235 or plutonium-239 is too low, a chain reaction cannot be established. This is because the neutrons have only a small chance of being absorbed by a fissile nuclei and causing a further fission reaction. The chain reaction will die out. The fuel used in nuclear fission weapons is enriched to a high degree of purity so that a chain reaction can be sustained.

The *shape* of the nuclear fuel is an important factor in its explosive ability. A 20 kg sample of enriched uranium-235 in the shape of a sphere will spontaneously explode, whereas 20 kg of enriched uranium-235 flattened into a sheet will not. The flat piece has a very large surface area and so an enormous number of neutrons are able to escape from the uranium into the air. These neutrons do not cause further fission reactions and so the chain reaction will die out. In the spherical piece of uranium, the surface area is much smaller and a greater proportion of neutrons remain in the uranium to sustain the chain reaction.



20 kg ^{235}U: subcritical

20 kg ^{235}U: supercritical!

The explosive ability of a fissile material also depends on its *physical size*. For example, a piece of uranium-235 the size of a marble will not explode but a piece the size of a grapefruit most definitely will. The small piece has more surface area compared with its volume than the large piece. In the marble-sized lump, a greater proportion of neutrons escape into the air and so the chain reaction dies out. This is a *subcritical mass*. In the sample the size of a grapefruit, a higher proportion of neutrons is available to continue the chain reaction within the material. This is a *supercritical* piece, capable of causing a nuclear explosion.

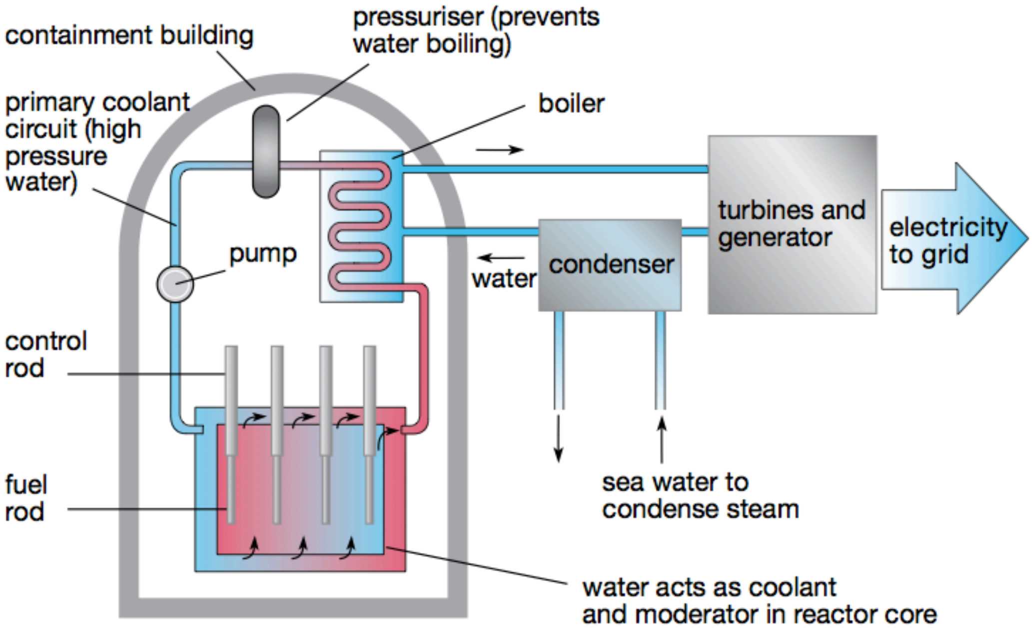
The minimum amount of enriched fissile material in the shape of a sphere that leads to a sustained chain reaction is known as the *CRITICAL MASS*.

12.3 Nuclear Fission Reactors

- Since the 1950s, controlled nuclear fission has been used (within a **nuclear reactor)** to produce electricity.
- Australia does not have any, but about 30 countries do and have about 400 nuclear power plants in operation. About 230 of these are pressurised water reactors (PWR).
- Many more reactors have been constructed for medical, military and research purposes.
- A nuclear power plant will produce electricity in much the same way as a coal-burning power plant. **The primary difference is how the heat is produced.**
- The power stations in the La Trobe Valley generate electricity by burning coal to produce heat that creates the steam which is used to turn the generator turbines.
- A nuclear power station simply has a different way of producing heat—nuclear fission.

Physics file

Australia's only nuclear reactor is located at Lucas Heights, a suburb of Sydney. The HIFAR (High Flux Australian Reactor) operated here from 1958 to 2007, but has now been replaced by a new research reactor known as OPAL (Open Pool Australian Lightwater reactor). About 7 kg of uranium enriched to 20% U-235 is immersed in a pool of water almost 13 metres deep. Radioisotopes that are used in industry and in the nuclear medicine departments of Australia's hospitals are created here. Another important application is the irradiation of silicon chips, creating high conductivity silicon for the computer industry.



A schematic diagram of a pressurised water reactor: the heat is removed from the core of the reactor by the coolant water. The coolant then heats the water in the boiler (heat exchanger) turning it into steam that turns the turbine that drives the generator. In this way, electricity is generated. A typical 1000 MW power plant consumes about 6 000 000 tonnes of black coal each year, or about 25 tonnes of enriched uranium that has been obtained from around 75 000 tonnes of ore.

Fast breeder reactors

- Of the 400 nuclear reactors operating, a handful of these are fast breeder reactors.
- Thought to be the solution to the Earth's energy problems.
- They make use of the most abundant isotope of uranium, uranium-238, to breed another fissile element, plutonium-239, for use in further nuclear reactions.
- However, they have safety and technical problems and have proved very expensive to operate. (The political climate and concerns about terrorist groups obtaining the plutonium and producing nuclear weapons have also been major factors in governments deciding not to construct this type of reactor.)

Disposing of nuclear waste—the nuclear fuel cycle

A major problem facing the nuclear power industry is the disposal of the unstable radioactive waste. There are about 400 nuclear reactors generating electricity around the world, producing large quantities of radioactive waste.

- A typical 1000 MW reactor will produce about 25 tonnes of spent fuel rods annually.
- A 1000 MW coal-fired power station produces millions of tonnes of carbon dioxide and sulfur dioxide annually, gases that are major contributors to the greenhouse effect.

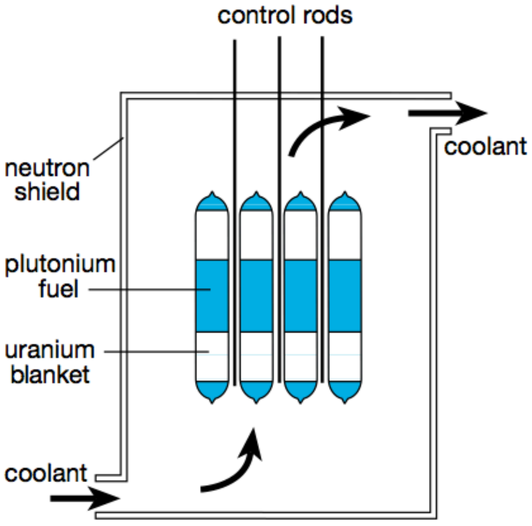
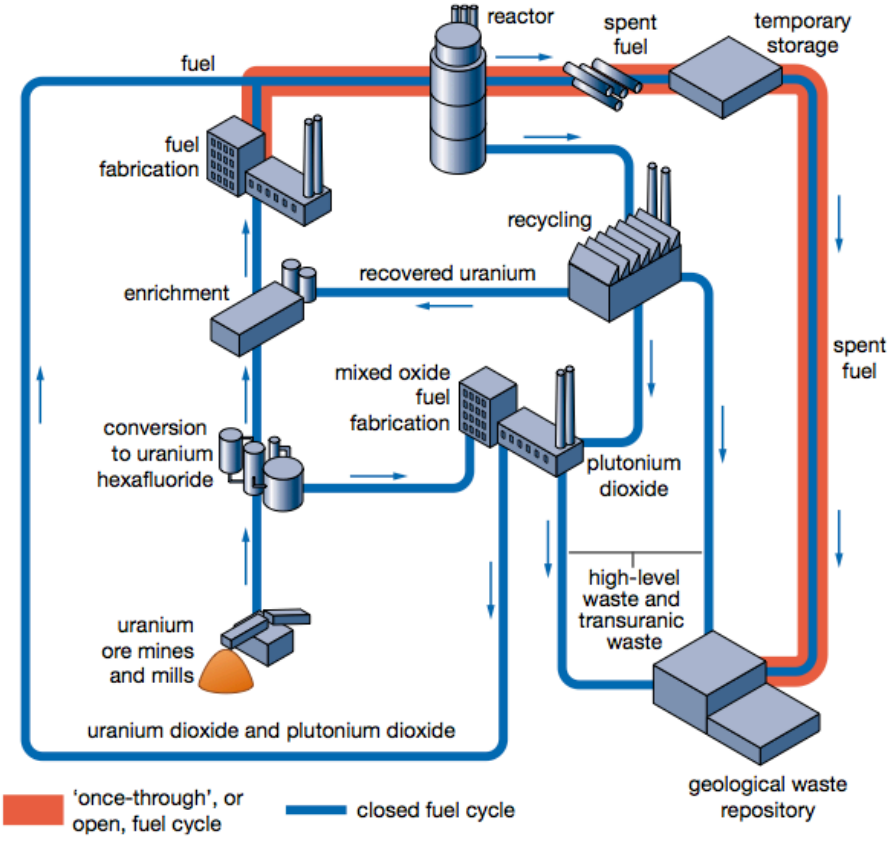


Figure 12.23 The core of a fast breeder reactor does not include a moderator. The plutonium in the fuel rods is surrounded by uranium. It is here that new plutonium is bred.

Radioactive waste products are classified into the following three categories: *low level, intermediate level* and *high level.*

- *Low-level waste* is generated primarily from hospitals, industry and laboratories and consists mostly of tools, clothing, used wrapping material and other items. These materials make up 90% of the volume but only 1% of the radioactivity of all radioactive waste.
- *High-level waste* is waste from contaminated reactor parts

The open fuel cycle in which the uranium is used once in a reactor, then disposed of as waste is shown in red. This system is used in the USA and Canada. The closed fuel cycle is shown in blue. In this system, spent fuel rods are reprocessed and the retrieved uraniumand plutonium are re-used as nuclear fuel. this approach of recycling uranium is used in France, UK, Russia, Japan and Germany.



In Summary,

Nuclear fission reactors

- A nuclear reactor uses enriched uranium as its fuel. The fuel rods in a nuclear reactor contain uranium that has been enriched to about 3% uranium-235.
- The core of the reactor consists of a material (e.g. graphite, water) that acts to slow the neutrons that are emitted during fission. This material is called a moderator. These slowed neutrons are then able to induce fission in the uranium-235 nuclei.
- The rate of the nuclear reaction in the reactor core is determined by the control rods. These consist of a material (e.g. cadmium, boron steel) that absorbs neutrons. The control rods are raised and lowered to control the chain reaction and so produce a steady release of energy.
- The coolant is a fluid that flows through the reactor core. It extracts heat energy from the core. This energy is then used to produce steam that drives turbines to produce electricity.
- A fast breeder reactor uses plutonium as its fuel. Plutonium-239 is fissile when struck by fast-moving neutrons. A fast breeder reactor does not need a moderator.
- Uranium-238 is also placed in the core of a fast breeder reactor. It absorbs neutrons and transmutes into plutonium-239 which can then be used as fuel for a fast breeder reactor.
- Large quantities of nuclear waste are produced by the nuclear industry each year. This is to be weighed up against the millions of tonnes of CO2 and other greenhouse gases that are released into the atmosphere each year by coal-fired power stations.
- Low-level radioactive waste is generally burnt or buried in pits, intermediate-level waste is buried in deep trenches, and high-level waste is either permanently stored in ponds of water or reprocessed before being stored in reinforced stainless steel drums.

12.4 Nuclear fusion

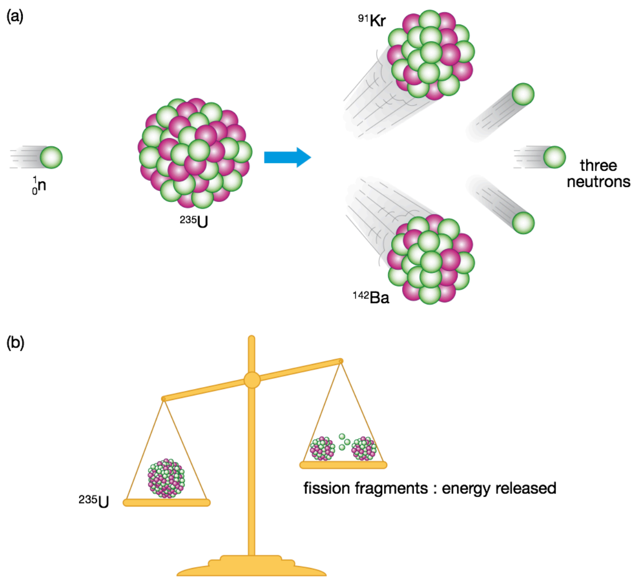


Figure 12.29 (a) Each fission of a uranium-235 nucleus releases about 200 MeV of energy. (b) The fission fragments have a lower combined mass than the uranium nucleus. The missing mass is related to the 200 MeV of energy by the equation $E = mc^2$.

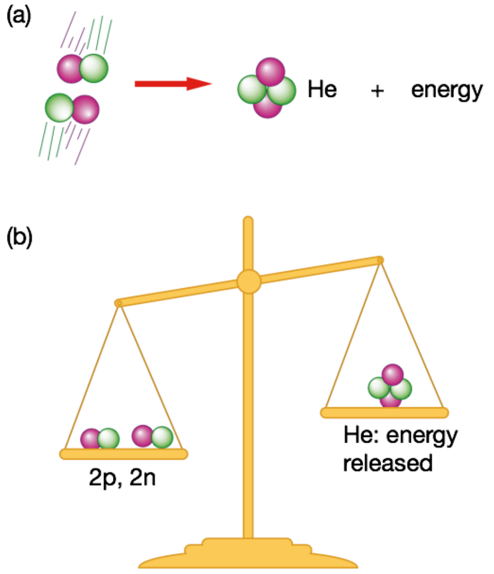


Figure 12.30 (a) When two isotopes of hydrogen (deuterium) are fused together to form a helium nucleus, energy is released. (b) The binding energy of the nucleus appears as a loss in mass, which can be calculated using $E = mc^2$.

Binding Energy

In order to change water into vapour, it is necessary to add lots of energy to the water. This energy acts to break the bonds between the water molecules so that they are able to move around freely. This added energy is a kind of 'binding energy'. The free molecules of water vapour have more energy than the liquid water molecules and so, as described by Einstein, have slightly more mass.

In order to change a helium nucleus into individual protons and neutrons, you would also need to add an amount of energy. This energy would act to separate the particles, enabling them to move around freely, and is called the *binding energy* of the nucleus. The free particles have more energy and so, according to Einstein, have greater mass.

NUCLEAR FUSION **occurs when two light nuclei are combined to form a heavier nucleus. This is the process by which energy is produced in stars.**

Even though the number of protons and neutrons is the same both before and after fusion, the mass per nucleon is lower after fusion has occurred. The binding energy of the nucleus corresponds to this missing mass and can be calculated by using $E = mc^2$.

It would seem as though obtaining energy from nuclear fusion should be quite straightforward. Unfortunately this is not the case. The main problem with nuclear fusion is that *nuclei* are *positively* charged. They exert an electrostatic force of *repulsion* on each other and so it is not easy to force the nuclei together. Remember that the electrostatic force is a long-range force and the strong nuclear force of attraction acts at much shorter distances.

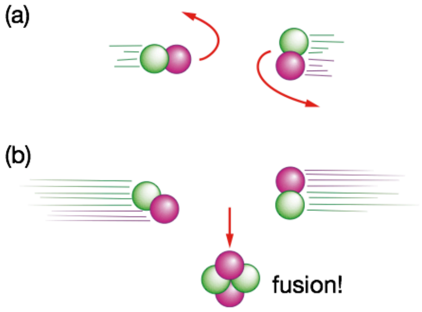


Figure 12.31 (a) Slow-moving nuclei do not have enough energy to fuse together. The electrostatic forces cause them to be repelled from each other. (b) If the nuclei have plenty of kinetic energy, they will overcome the repulsive forces and move close enough together for the strong nuclear force to come into effect. At this point, fusion will occur and energy will be released.

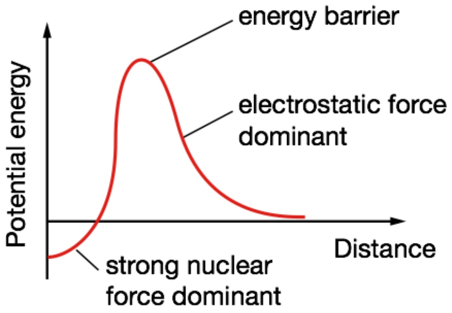


Figure 12.32 If hydrogen (deuterium) nuclei are to get close enough for the strong nuclear force to act, they must overcome the energy barrier presented by the electrostatic force. Temperatures of around 400 000 000 K are required to provide this amount of energy!

Fusion in the Sun and similar stars

In our sun, about 657 million tonnes of hydrogen and hydrogen isotopes are fused together to form about 653 million tonnes of helium each second. The missing 4 million tonnes is related to the energy released by the equation $E mc^2$. A tiny proportion of this energy reaches Earth and sustains life as we know it.

Nuclear fusion reactors

Replicating the reactions that take place on the Sun is extraordinarily difficult. This is because extremely high densities, temperatures and pressures are required. Fusion researchers are instead using two isotopes of hydrogen, deuterium ${}_1{}^2H$ and tritium ${}^3{}_1H$ as fuel. Deuterium can be extracted in vast quantities from lakes and oceans, but tritium is radioactive with a half-life of 12.3 years and must be artificially produced. The nuclear reactions used in current fusion reactors are as follows:

$$ {}_1^2H + {}_1^2H \rightarrow {}_2^3He + {}_0^1n $$
$$ {}_1^2H + {}_1^2H \rightarrow {}_1^3H + {}_1^1H $$
$$ {}_1^2H + {}_1^3H \rightarrow {}_2^4He + {}_0^1n $$

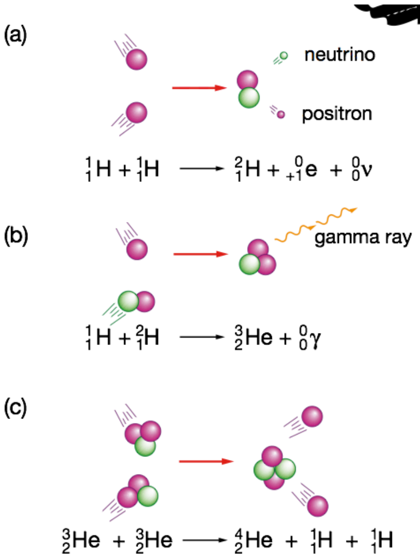


Figure 12.33 These are three of the main fusion reactions that are taking place on the Sun right now. (a) Two protons (hydrogen nuclei) fuse together forming a hydrogen isotope, deuterium. Note that one of the protons has decayed, forming a neutron, a neutrino, a positron and releasing energy. (b) During the fusion of a proton and deuterium (${}^2H$) into helium-3, the nucleons lose mass and energy is released. (c) The fusion of helium-3 nuclei results in the formation of a helium-4 nucleus and releases two protons and energy.