

7 Fission

In 1939 Hahn and Strassman, while bombarding U-235 nuclei with neutrons, discovered that sometimes U-235 splits into two nuclei of medium mass. There are two important results:

1. Energy is produced.
2. More neutrons are released.

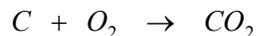
The process was named fission, which can be defined as the splitting of a heavy nucleus into two lighter nuclei. Immediately after hearing about this discovery, Lise Meitner and Otto Frisch recognized that neutrons produced by fission might be made to cause fission, one fission after another, releasing enormous energy.

7.1 Energy Released by Fission

Before the twentieth century, mass and energy seemed to be separate unrelated quantities, each governed by its own conservation law.

- a) Conservation of Mass states that mass cannot be created or destroyed.
- b) Conservation of Energy states that energy cannot be created or destroyed.

Burning carbon illustrates both laws. A carbon atom reacts chemically with a molecule of oxygen according to the equation:



Each reaction releases almost 5 eV of energy. If a quantity of carbon is burned and all the carbon dioxide (CO₂) gas is collected and weighed its weight equals the combined weight of the carbon (C) and the oxygen (O₂). Mass is conserved.

The 5 eV of heat energy released comes from chemical potential energy, converted to heat in burning. One form of energy is changed to another, but no energy is created or disappears. The amount of energy does not change, so energy is conserved.

The two conservation laws can still be applied to most processes, but fission and other nuclear reactions defy these separate laws.

Destruction of mass creates energy, and destruction of energy creates mass. Einstein predicted conversion between mass and energy in 1905. He uncovered contradictions in classical physics and showed that mass and energy are related by the formula:

$$E = mc^2$$

where: E = energy (joules)
 m = change in mass (kilograms)
 c = speed of light (approximately 3×10^8 m/s)

This relationship is likely true in general, but chemical reactions do not show it. The following example shows why. Consider the complete combustion of one kilogram of coal:

Energy from complete combustion of 1 kg of coal
 = 3.36×10^7 joules, which, in other units, is almost 10 kWh.
 (3.6×10^6 J = 1 kWh)

From, $E = mc^2$

$$m \text{ (converted)} = \frac{E}{c^2} = \frac{3.36 \times 10^7 \text{ J}}{(3 \times 10^8 \text{ m/s})^2} = 3.7 \times 10^{-10} \text{ kg}$$

This is a very small fraction of the initial 1 kg and impossibly small to measure.

A similar calculation shows that burning one atom of carbon converts only a few billionths of a mass unit to energy.

Energy from converting one C atom to CO_2 = 5 eV

Using the mass to energy conversion factor $931.5 \text{ MeV} = 1 \text{ u}$ yields the mass converted to energy as

$$5 \times 10^{-6} \text{ MeV} / 931.5 \text{ (MeV/u)} = 0.000\ 000\ 005\ 4 \text{ u}$$

This is about 1/10 000 of an electron mass and technology is not yet able to measure such a small mass loss.

For comparison, consider the complete fissioning of 1 gram of U-235.

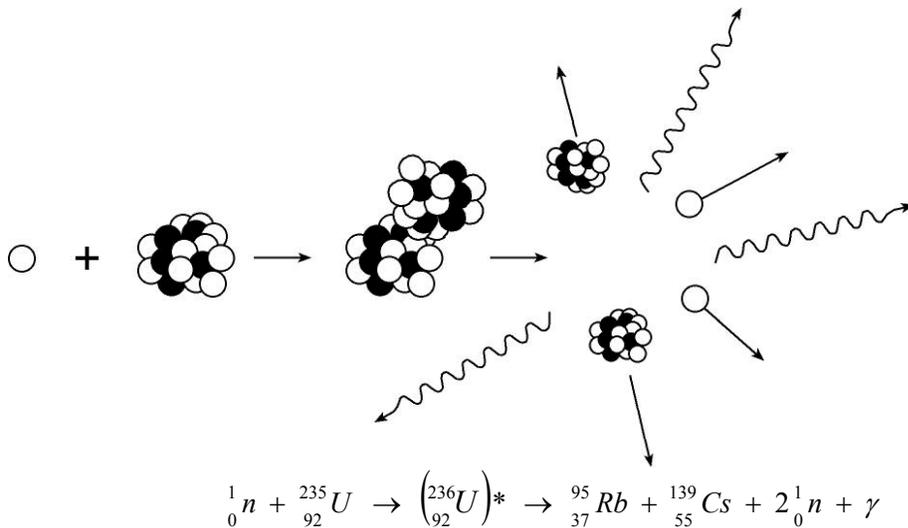
Energy from fissioning of 1 gram of U-235 = 8.2×10^{10} joules.
 This is very nearly 1 MWd (megawatt-day) of heat energy. (24 000 kWh = 1 MWd)

$$m \text{ (Converted)} = \frac{E}{c^2} = \frac{8.2 \times 10^{10} \text{ J}}{(3 \times 10^8 \text{ m/s})^2} = 9 \times 10^{-4} \text{ g}$$

The actual mass converted to energy to generate 1 MWd is almost 1 mg, nearly 0.1% of the original mass, and can be measured.

The example shows that the complete fissioning of all the atoms in one gram of U-235 would produce 1 MWd of thermal energy. A single fission does not create much energy but a gram of natural uranium contains 1.8×10^{19} U-235 atoms, and a CANDU reactor can fission about $\frac{3}{4}$ of these. (Compare fission of 1 g of U-235 with burning 1 kg of coal).

We now look at the fission of a single U-235 atom in more detail. A neutron enters the U-235 nucleus to form a highly excited compound nucleus, U-236, which in turn fissions. The following figure shows a typical fission:



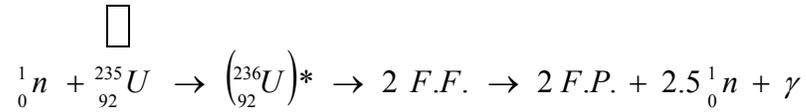
The mass of the reactants	236.05 u
The mass of the products	<u>235.865 u</u>
Mass converted (subtract)	0.19 u

The transformation of 0.19 u of mass releases nearly 180 MeV of energy immediately. Adding the energy released later by the

radioactive decay of the fission products brings the total to about 200 MeV.

7.2 Fission Fragments

The general equation for the fissioning of uranium is:



The compound nucleus, after capturing the thermal neutron, has a huge excess of energy. The asterisk indicates an excited state of U-236. The equation shows the immediate break-up (fission) of the compound nucleus into two fission fragments (F.F.).

The initial fission fragments leave the fission site with velocities around 9×10^6 m/s (that is, 32 million kilometres per hour). Most of the energy from fission ($\approx 84\%$) is in the form of kinetic energy of the fission fragments.

The fragments are highly positively charged and stop quickly, depositing their energy in a very short distance (5×10^{-4} cm). Ionization transfers most of the energy to the surrounding fuel. Excitation of nearby atoms and some direct collisions of the fragments with atomic nuclei also transfer some energy. The fuel gets hot as the motions of its atoms and molecules increase by these interactions.

The initial fragments are highly excited and unstable. They decay almost instantly into longer lived, unstable nuclei known as fission products, (F.P), illustrated in the equation above. The fission neutrons and prompt gamma rays shown in the above fission reaction are emitted in this process.

Fission products have a neutron/proton ratio similar to the U-235 nucleus ($n:p = 143/92 = 1.55$), yet are much lighter nuclei. The neutron/proton ratio required for stability is smaller, near 1.3 for the light fragment with $A \approx 95$ and near 1.4 for the heavy fragment, with $A \approx 140$. Fission products are neutron rich and consequently decay by beta-gamma emission.

The mass of the fission products falls within the narrow range shown in figure 7.1. A typical fission produces a heavy fragment and a lighter one that carries the largest proportion of the kinetic energy.

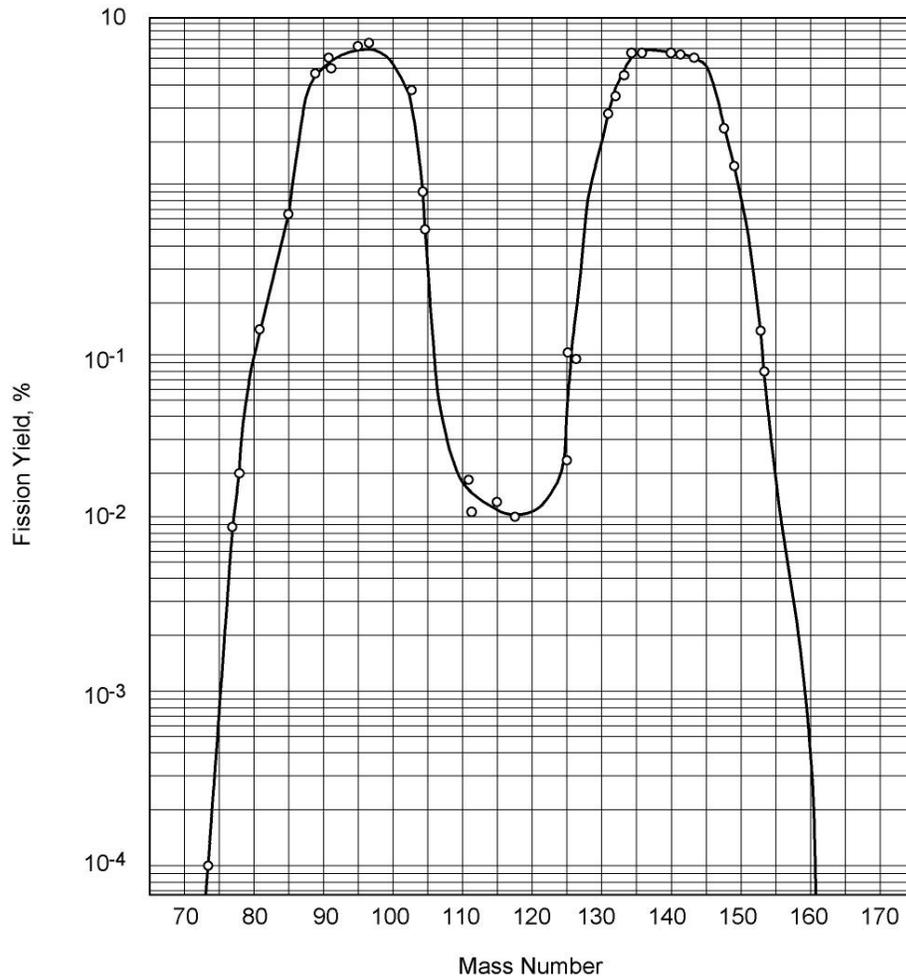


Figure 7.1
Yield of Fission Products

7.3 Chain Reaction

A typical fission produces between 0 and 5 neutrons. The average is approximately 2.5 neutrons per U-235 fission. Under the right circumstances, these neutrons will produce further fissions. Figure 7.2 shows that if one neutron makes two, two give four, four give eight, and so on. This results in over one thousand fissions in ten generations.

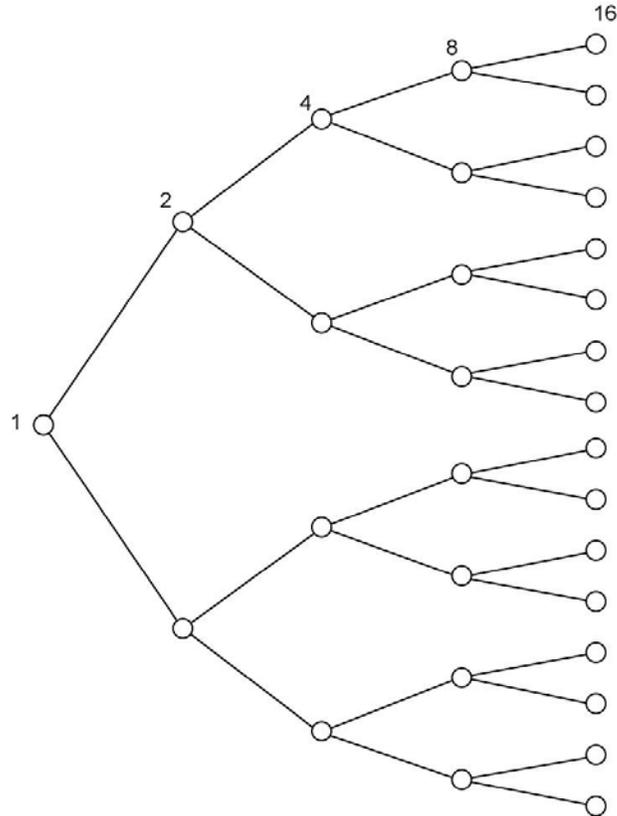


Figure 7.2
The Chain Reaction

his type of multiplication is unsuitable for a power reactor where steady power production is required. For a power reactor, we want each fission to cause just one other fission; so 1.5 neutrons must meet some fate other than causing fission. This special condition, where each fission causes one more, is called a "self-sustaining chain reaction" and will be discussed in detail in a later module.

7.4 Neutrons

7.4.1 Prompt and Delayed Neutrons

Most (99.35%) of the neutrons from the fission of U-235 are born at the time of the fission (10^{-14} seconds after the neutron is absorbed). A small number of the fission products emit a neutron while decaying. These decaying fission products yield the remaining 0.65% of the neutrons.

The neutrons born "instantly" at the time of fission are called prompt neutrons. The average lifetime before neutron emission from the fission products is 13 seconds. These neutrons are called delayed neutrons and will be seen to be indispensable to reactor control.

7.4.2 Neutron Energy

Neutrons from fission have relatively high energies near 2 MeV. High-energy neutrons travel at speeds a few percent of the speed of light and are called fast neutrons. They slow by undergoing elastic and inelastic collisions with surrounding nuclei until they reach energy equilibrium with their surroundings.

Once slowed, the neutrons diffuse through the core, jostled by surrounding molecules. (In subsequent collisions with neighbouring molecules the neutron is just as likely to pick up a bit of energy as to lose some). Such neutrons, in thermal equilibrium with their surroundings, are called thermal neutrons. A thermal neutron has energy of 0.025 eV at 20°C. Thermal neutrons are also slow neutrons.

7.4.3 Neutron Flux

Thermal neutrons are much more likely to interact with nuclei than are fast neutrons. The effect of the thermal neutrons at any point in the reactor depends on both the number of neutrons and their speeds. The quantity that relates these properties is the neutron flux, represented by the Greek letter ϕ (phi). Neutron flux measures the number of neutrons crossing a volume each second (moving in random directions). In this course, neutron flux can be thought of as a function of neutron population, that is, higher flux means more neutron “visits” to potential targets. Figure 7.3 shows the thermal neutron flux in a Bruce reactor. Flux distributions will be discussed later in more detail.

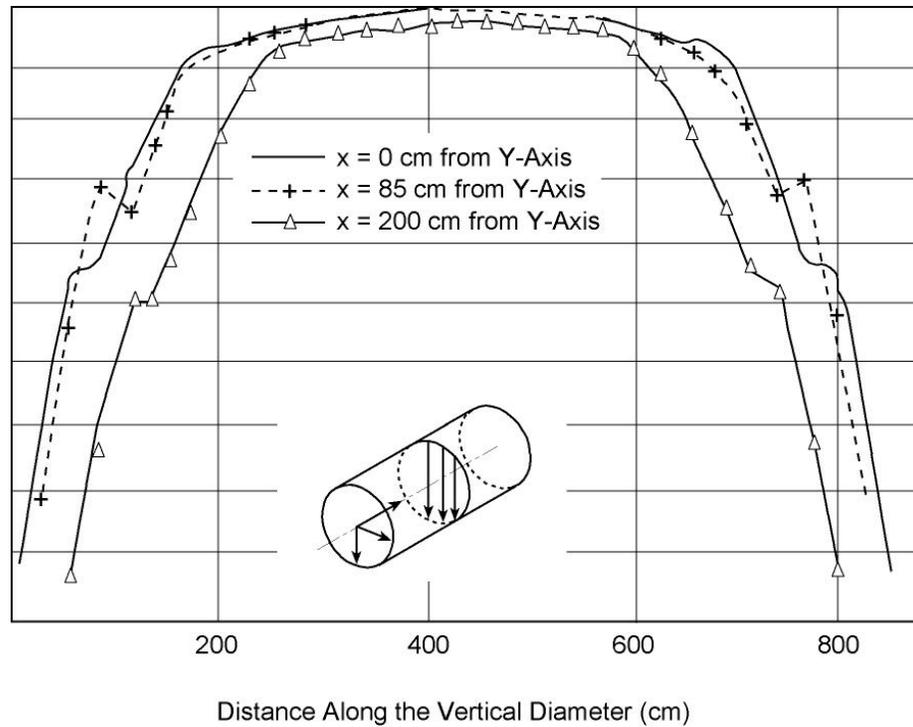


Figure 7.3
Neutron Flux

7.5 Neutron Cross-Sections

Module five examined two types of neutron reaction: scattering and absorption. Different nuclei have different probabilities of reacting with a neutron. A given target nucleus, struck by a neutron, has a different likelihood of undergoing these different reactions.

Neutron cross-section represents the probability that a reaction occurs when neutrons bombard a target nucleus. The Greek letter sigma (σ) denotes the cross-section. A nucleus has different cross sections for different reactions; subscripts denote the type of cross-section. For example, σ_a is the absorption cross-section and σ_f is the fission cross-section. The unit for cross-section is a barn ($1 \text{ barn} = 10^{-24} \text{ cm}^2$). To a neutron, an area of 10^{-24} cm^2 appears "as easy to hit as the broad side of a barn".

You can think of the neutron cross-section, with the dimension of area, as the effective target area of the nucleus for an incoming neutron, although the cross-section has no simple relationship with the actual geometry of the nucleus. The size of the cross section depends on:

1. The composition of isotopes in the target.
2. The energy of the incoming neutron.

The next two sections cover these two effects.

7.5.1 Effect of Composition

Uranium-235 has a fission cross-section of 580 barns for thermal neutrons, but makes up only 0.7% of natural uranium. The other 99.3% is U-238, which has a zero fission cross-section for thermal neutrons. Thus, the fission cross-section of natural uranium (used in CANDU fuel) is:

$$\sigma_f^{Nat.U} = 0.993 \times 0 + 0.007 \times 580b \approx 4 \text{ barns}$$

Enriched fuel with U-235 (typical for a light water reactor) has a fission cross-section:

$$\sigma_f^{2\% \text{ enriched}} = 0.98 \times 0 + 0.02 \times 580b \approx 11.6 \text{ barns}$$

As you can see, enrichment increases the fission cross-section of the fuel. Fission is a more probable fate for a neutron entering enriched fuel, almost 3x as likely as for CANDU fuel.

One hundred tonnes of uranium fuel (typical for a large reactor) contains about 700 kg of U-235 if the fuel is natural uranium, 2 tonnes of U-235 if it is 2% enriched. Enrichment allows the fission process in light water reactors to compete effectively with neutron absorption by light water. CANDU accommodates a lower fission probability with a reactor design that is neutron efficient, that is, wastes few neutrons. However, we are getting ahead of ourselves. The next section describes how this is done.

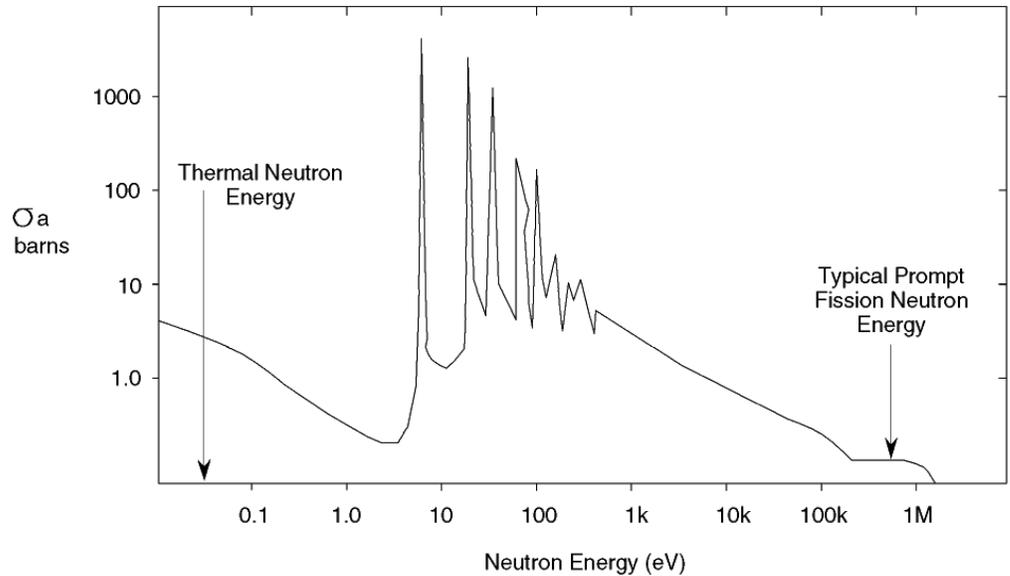


Figure 7.4 - Variation of the Absorption Cross Section of U-238 with Neutron Energy

7.5.2 Effect of Neutron Energy

For absorption reactions, cross-section decreases overall as neutron energy increases. For example, the fission cross-section for U-235 is 580 barns for thermal neutrons and only 2 barns for fast (2 MeV) neutron. This means fission is more probable (made 290 times more likely) if the neutrons are thermalized.

Figure 7.4 shows the absorption cross-section for U-238. For neutron energies near the thermal neutron energy, the cross-section falls off smoothly as neutron energy increases. This is typical of absorption cross-sections for most nuclei. As thermal neutrons travel at faster speed the apparent size of the target decreases, but the frequency of neutron “visits” increases. For many materials (but not all), these effects offset each other so the amount of absorption in the material is not much affected by thermal neutron speed.

The peaks in the energy range of ≈ 10 eV to ≈ 1 keV of figure 7.4 are called Resonance Absorption Peaks. The highest peak is over 6 000 barns. The peaks represent the only time absorption in U-238 is significant. U-238 is almost certain to absorb neutrons that enter the fuel in this energy range. Most nuclei have resonances, but the U-238 resonances are particularly important to us because there is so much U-238 in a CANDU core.

7.6 Summary of Key Ideas

- Fission of a nucleus results in releasing energy and more neutrons.
- The energy released comes from the conversion of mass following Einstein's famous formula $E = mc^2$.
- A single fission results in about 200 MeV of energy.
- 85% of the energy shows up as kinetic energy of the fission products.
- The rest of the energy is divided between gammas emitted at the time of the fission and kinetic energy of the neutrons.
- More energy is released after the fission when the fission products decay.
- A chain reaction occurs when the neutrons released by one fission cause fissions in other nuclei.
- Prompt neutrons appear at the time of fission.
- Delayed neutrons appear after the fission when certain the fission products decay.
- Almost all nuclides will absorb neutrons. The probability that a neutron is absorbed is called the neutron cross section. The unit of cross section is the barn.

7.7 ASSIGNMENT

1. Explain where the energy released by fission comes from.
2. Write the general fission reaction for ${}_{92}^{235}\text{U}$.
3. State how much energy a fission releases and how the majority of this energy shows up.
4. Explain a self-sustaining chain reaction.
5. Define:
 - a) thermal neutron
 - b) prompt neutron
 - c) delayed neutron
6. Define neutron cross-section and state its units.
7. How does the probability of fission in U-235 vary with neutron energy?
8. Why are delayed neutrons important, although they contribute only a small fraction of the neutrons in the reactor core?