# PHY140Y

## 36 Fission

### 36.1 Overview

- Neutron-Induced Fission
- Chain Reactions
- Example: The CANDU Reactor

### 36.2 Neutron-Induced Fission

The stability of a nucleus has been one of the mysteries of nuclear physics. Besides the decay modes we have already described, it became clear in the 1930's that there was at least one other means by which certain unstable nuclei decay – through a process known as fission. The nuclei that can experience this sort of decay are called "fissile," and include $^{235}$U and $^{239}$Pu.

The process itself is catalyzed by a relatively slow moving neutron. In the case of $^{235}$U, the neutron is absorbed by the nucleus to form a very unstable nucleus of $^{236}$U. Within a space of about $10^{-12}$ s, this nucleus breaks up into two approximately equal size daughter nuclei and a number of neutrons. The two daughter nuclei are usually unstable themselves and decay further to stable isotopes. There are on average 2.7 neutrons released in each $^{235}$U decay. An example decay would be

$$^{235}\mathrm{U} + n \rightarrow ^{102}\mathrm{Mo} + ^{131}\mathrm{Sn} + 3n. \tag{1}$$

The end products of this reaction are therefore:

- two unstable, radioactive nuclei (molybdenum and tin in the example above),
- a number of neutrons, and
- some energy.

The energy released in the decay is considerable, being on average about 200 MeV. However, most of this energy cannot be associated with the binding energy of the nucleus or the energy arising from the radiation. In fact, the energy that is released comes from

- 5 MeV in the form of the kinetic energy of the neutrons,
- 25 MeV in the form of subsequent radioactivity of the daughter nuclei, and
- 165 MeV arising from the electrostatic potential energy of the two daughter nuclei.

One can see why this latter energy is so large. For example, if we take the decay described above, and assume that the daughter nuclei are produced a distance $r = 2 \times 10^{-12}$ m apart, then the electrostatic potential energy will be

$$\begin{aligned} U &= \frac{kq_{\mathrm{Mo}}q_{\mathrm{Sn}}}{r} && (2) \\ &= \frac{(9.0 \times 10^9)(42 \times 1.60 \times 10^{-19})(50 \times 1.60 \times 10^{-19})}{2 \times 10^{-12}} = 2.4 \times 10^{-13}\ \mathrm{J} = 151\ \mathrm{MeV}. && (3) \end{aligned}$$

## 36.3 Chain Reactions

In itself, this decay is an interesting nuclear physics problem. However, what is perhaps more intriguing about a fission reaction is that it has the potential to sustain itself. Since it releases 2-3 neutrons in the resulting fission, any of these neutrons potentially can induce a second fission event, resulting in what is known as a “chain reaction.”

### 36.3.1 Moderating the Neutron Energies

It was realized in the late 1930’s that the potential for a chain reaction was very real. However, it seemed that nature did not favour this. Why? The answer came when people examined the effect of neutrons on $^{235}$U. it turns out the probability that a neutron is absorbed to form $^{236}$U depends strongly on the energy of the neutron: The faster the neutron is travelling, the less likely it is for the neutron to induce a fission. Most of the neutrons released in the fission had energies of a few MeV. This turns out to be a much higher energy that is optimal for inducing fission and so most of these neutrons simple escape from the sample of material.

The fix to this involved figuring out a mechanism for slowing down the neutrons without absorbing them. To achieve this, the neutrons that escape are allowed to interact in a material known as a “moderator.” Through elastic collisions with the nuclei in the moderator, the neutrons slow down to the optimal energies for inducing fission. Some of these neutrons then bounce out of the moderator back into the uranium sample and can now induce a fission. Good moderators are light nuclei that will quickly allow neutrons to transfer energy to them through elastic collisions, but are unlikely to absorb one of the neutrons through some other form of nuclear interaction. Thus, a material like water forms a good moderator.

### 36.3.2 Critical Mass

Once one has the neutrons slowed down, one still is left with making sure that enough of these slow neutrons interact with a $^{235}$U nucleus. This involves having a sufficiently large amount of uranium around. It turns out that one needs of order 15 kg of $^{235}$U in order to have enough fissile nuclei around that the average number of neutrons that are released in a fission and that induce a second fission event is greater than one. Once this is achieved, one has a chain reaction that is self-sustaining. The amount of $^{235}$U that is required is known as a “critical mass.”

This all being said, the natural abundance of $^{235}$U is only 0.72%. This means that for a chain reaction to occur with natural uranium, one would need something like

$$\frac{15\ \text{kg}}{0.0072} = 2.1\ \text{tonnes} \tag{4}$$

of natural uranium. To get around this problem, one has to refine the natural uranium to selectively reduce the fraction of $^{238}$U in the material, forming what is known as "enriched" uranium. The process of enrichment is technologically very challenging, as one is attempting to separate out one isotope from another, where the only discernable difference is their atomic mass (a 1% effect). The most effective techniques involve very high-performance centrifuges that use this mass difference to seperate out the heavier nuclei from the lighter ones. There are two levels of enrichedment: 1) reactor grade uranium that is typically enriched to 3% $^{235}$U, and 2) weapons grade uranium that is enriched to over 90% $^{235}$U.

The two obvious examples of technology that employ nuclear fission are nuclear power generation and nuclear explosives. In the first case, one initiates a chain reaction in a controlled manner and uses it as a source of thermal power. In the second case, the chain reaction is initiated in such a way as to release as much energy as possible before the energy of the reaction disasembles the critical mass of fissile material through the explosive energy release.

## 36.4 Example: The CANDU Reactor

As a concrete example, let's see how these basic principles are applied to the CANDU reactor, sketched in Fig. 1. Most nuclear reactors employ reactor grade fuel and "light water" (light water is what we would consider normal water, $H_2O$). The CANDU reactor is unique in that it is designed to use unenriched uranium as a fuel and employs heavy water ($D_2O$ where the hydrogen has been replaced by the hydrogen isotope deuterium or $^2_1$H) as the moderator. The chain reaction is controlled through the use of control rods consisting of a neutron-absorbing material like cadmium. The heavy water acts both as a moderator and a coolant, carrying the heat from the reactor vessel to a separate light water steam loop in which the heat is then used to turn light water into steam, which then turns a series of turbines to generate electrical power.

There are a number of advantages to this approach to nuclear reactor design:

- The use of natural uranium means that operation of the reactor does not depend on having uranium enrichment technology. Since the latter is a requirement of a nuclear weapons programme, avoiding the need for enrichment technology is seen as an anti-proliferation step.
- The use of heavy water as both a moderator and a coolant implies that in case there is a coolant system failure and the reactor core loses this system, the loss of the heavy water immediately halts the chain reaction. This is in contrast to many light water reactor and graphite reactor designs, where it is not possible to readily separate the fissile material from the moderator in the case of the failure of a key system.
- The use of natural uranium allows the reactor to be designed with a continuous refuelling system, allowing the fuel to be replaced as the reactor continues operation. Most other reactor designs require the reactor to be shut down and disassembled to replace the uranium fuel.

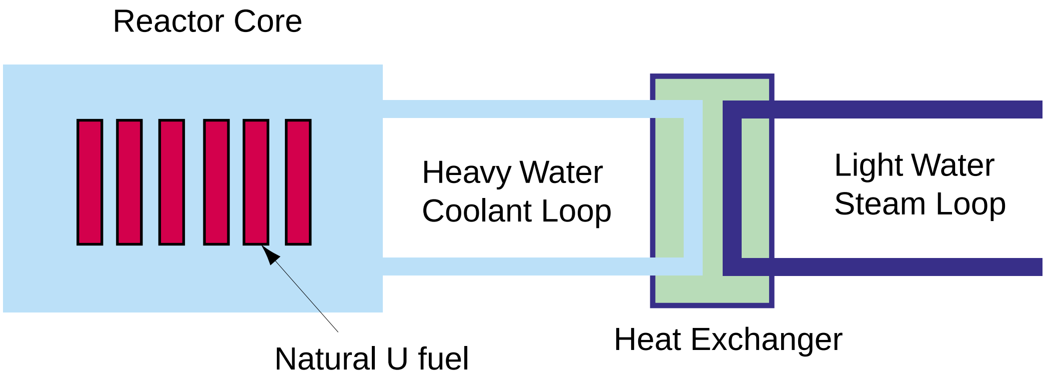

Figure 1: A sketch of the CANDU reactor.

These advantages and strong federal goverment support have made CANDU a competitive technology on a world scale. However, it is by no means a perfect technology. Two of the significant drawbacks are:

- Although the use of natural uranium avoids the need for enrichment facilities, the reactor does produce a militarily interesting fissile material, $^{239}$Pu. Because there is so much $^{238}$U around in the reactor, the following set of reactions occur:

$$\begin{aligned} {}^{238}\mathrm{U} + n &\rightarrow {}^{239}\mathrm{U} && (5) \\ {}^{239}\mathrm{U} &\rightarrow {}^{239}\mathrm{Np} + e^- + \bar{\nu_e} && (6) \\ {}^{239}\mathrm{Np} &\rightarrow {}^{239}\mathrm{Pu} + e^- + \bar{\nu_e}. && (7) \end{aligned}$$

  The problem with this is that $^{239}$Pu is the most fissile material known and is therefore the most popular material for use in a nuclear weapon. The CANDU reactor becomes a "breeder" for this isotope.

- The large amount of deuterium in the reactor core allows for the formation of tritium ($^3_1$H), a radioative isotope of hydrogen which has a half-life of a few years. We occasionally hear about accidental releases of tritium from Ontario Power Generation's CANDU plants, raising environmental concerns.

Besides these two concerns, the issue of long-term storage of the very long-lived radioactive waste that is a by-product of any nuclear reactor technology remains an unresolved issue.

What this short discussion illustrates is that it is difficult if not impossible to keep the "genie in the bottle." Nuclear technology is here to stay in one form or another. The issue is how we best manage it.